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Technical Activities 1985

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U.S. DEPARTMENT OF COMMERCE, Malcolm Baldrige, Secretary
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ABSTRACT

This report summarizes the research and technical activities of the Center for Basic Standards during the Fiscal Year 1985. These activities include work in the areas of electricity, temperature and pressure, mass and length, time and frequency, quantum metrology, and quantum physics.

Keywords: Astrophysics; atomic and molecular physics; chemical physics; electrical standards; fundamental constants; gravity measurements; laser physics; length standards; mass standards; pressure and vacuum standards; temperature standards; time and frequency standards; X-ray and gamma-ray wavelength standards.

INTRODUCTION

This report is a summary of the technical activities of the NBS Center for Basic Standards (CBS) for the period October 1, 1984 to September 30, 1985. The Center is one of the four centers and operating units in the National Measurement Laboratory.

The summary of activities is organized in six sections, one for the technical activities of the Quantum Metrology Group, and one each for the five divisions of the Center. Each division or group tells its own story in its own way. In general, there is an overview followed by a series of short reports on current projects. Then the publications, invited, talks, committee participation and professional interactions during the year are listed.

More information about particular work may be desired. To obtain this, the reader should address the individual scientists or their division, c/o Center for Basic Standards, B160 Physics Building, National Bureau of Standards, Gaithersburg, Maryland 20899.

TABLE OF CONTENTS

QUANTUM METROLOGY GROUP
SUMMARY OF ACTIVITIES
FISCAL YEAR 1985

OVERVIEW

We are engaged in certain relatively clearly defined scientific enterprises and at the same time concerned with development and improvement of tools and measurement technology for future scientific work. This combination of efforts is not so unusual, and for the moment at least, appears advantageous. Indeed much of our current scientific program benefits from earlier technical development exercises and there are indications that this progression may continue in the future. Evidently we benefit from an absence of externally mandated programs and goals which makes planning and program articulation both more difficult and more important.

In the following sub-sections we have attempted to convey our sense of where the work now stands and where at least some of its future may lie. For purposes of internal management and in terms of the external groups and facilities with which we interact, we tend to see two major scientific thrusts: One of these concerns itself with precision measurement, especially of the spectroscopic variety predominantly in the x-ray and γ-ray regions, determination of fundamental constants and tests of basic symmetries and invariances. The second concerns itself with structure and dynamics in atoms, molecules and simple solids perturbed by the presence of one or more inner-shell vacancies. This work ultimately requires radiation fluxes only available at synchrotron radiation sources to separately characterize single vacancy and multiple vacancy processes. However, the ultimate aim is systematic investigation of smaller molecules and other simple systems to establish a stable basis for investigation of less well understood systems. Lastly in this report we indicate current efforts at new technology for scientific measurements. Although it is not easy to impose on these exercises a meaningful programmatic overlay, there are certain features which indicate an appropriateness to our presence in these areas. These indicators include: rather challenging technical obstacles, scientifically attractive potentiality, good local talent and either modesty of scale or effective external collaborative relationships.

TECHNICAL ACTIVITIES

Precision measurements & fundamental constants

Objectives and programs:

Ongoing work in this area is primarily on spectroscopic measurements in the region of x-rays and γ-rays but includes also work on the gravitational constant. Our spectroscopic efforts are focussed at the present time on tests of QED in high Z one- and two-electron systems, systematics of inner vacancy spectra and measurement of those γ-transitions which are directly connectable to fundamental constants and masses of elementary particles.

The overall scheme begins with optical interferometry of a crystal (Si) lattice spacing, dissemination of this result to other diffracting crystals and their use via absolute angle measurement for wavelength determination. Some of these wavelength determinations are of direct importance in and of themselves, as is the case for the n-p capture γ, while others provide markers for experiments where only relative measurements are feasible, e.g., those involving mesic atoms or one- and two- electron high Z systems. All aspects of this work are currently active and in aggregate involve significant numbers of NBS staff and visitors, as well as considerable resources both internal to NBS and at major international centers.

NBS personnel working in this area include R.D. Deslattes 2/3, E.G. Kessler, G.L. Greene 2/3, A. Henins 2/3, R.E. LaVilla 1/3, and M. Cutkosky 1/3. We have enjoyed visits from H. Börner and T. Manning, Institut Max Von Laue-Paul Langevin (ILL) and M. Tanaka, National Research Laboratory of Metrology (NRLM). Our activities take place at NBS in lattice interferometry and x-ray spectra while γ-ray work is carried out at ILL in Grenoble and one-and two-electron spectroscopy has proceeded at the Max-Planck Institute for Nuclear Physics (MPIKP) in Heidelberg and at the Gesellschaft für Schwerionenforschung (GSI) outside of Darmstadt, where there are also effective collaborators (Reinholdt Schuch, MPIKP and Heinrich Beyer, GSI).

Gravitational work carried out by Luther (2/3) aims to produce an improved value of G which has a measure of intrinsic interest, but in addition, confronts efforts to estimate this numeric a **priori** (Sternglass, 1984, Cohen, 1985). This work also aims to test equivalence of passive and active gravitational mass for alumina, silica and tungsten. Here there are also conflicts and questions (Stacey, et al. 1981, Jacobson, 1983).

Current Activities - accomplishments:

The biggest challenge confronting this whole area of work is the improbably large (10σ) apparent discrepancy between the 1975 NBS interferometric determination of a Si lattice spacing and that subsequently reported by the Physikalisch-Technische Bundesanstalt (PTB). First priority and maximum effort have been given and applied to (respectively) this question. The experimental capabilities were re-established by last year with additional diagnostic interferometric channels added to control the dominant source of systematic error. As reported last year this system appeared to be operational and had demonstrated sensitivity and accuracy adequate to accomplish the needed correction factor measurements. Unfortunately, it was not noticed at that time that a fundamental conceptual error prevented these (otherwise adequate) interferometric signals from giving the information needed to accomplish the required corrections. A revised "path curvature" interferometer was designed, fabricated (by Continental Optical and Perkin Elmer) and installed. This system began to operate in September 1985 and should have yielded significant results by the time of the Panel meeting.

Aside from the primary interferometric measurement, there is a need for rapid and sensitive intercomparison of lattice spacings among crystals having nearly the same lattice parameter. To address this need, a new goniometric facility was designed and built with major contributions from our long-term visitor Dr. M. Tanaka. Although x-ray sources are used, the classical limits on lattice parameter precision implied by x-ray wavelength spread are largely circumvented. As originally planned, this new facility, the DELTA-D (δd) machine, would have replaced the second generation x-ray interferometer experiment. It would have made use of the same x-ray sources, vibration isolated and temperature-controlled environment as well as computer controlled measurement apparatus. Because of the problems already noted above, this sequential model is no longer appropriate. We have therefore begun a process which should yield an independent δd machine within the month prior to the meeting of this panel. This process involves establishing a new (and previously unplanned) vibration isolated and temperature controlled environment. It also involves providing dual x-ray sources not previously contemplated and appropriate computer controlled data acquisition facilities.

The NBS-ILL precision gamma-ray wavelength facility has been significantly up-graded during the past year. This up-grade coincided with a one year shut down of the ILL reactor for maintenance. On the ILL side, the reactor source tube has been replaced with a tube of a new design which will permit three sources to reside in the high flux region simultaneously, a significant improvement for the precise but inefficient flat crystal spectrometer. The casement in which the spectrometer resides was removed in order to change the source tube. During reconstruction, the casement was enlarged to accommodate a larger more stable base for the spectrometer.

On the NBS side, the precision spectrometer was returned to the U.S. and significantly improved. The major improvements are: 1) a larger vibration isolation platform which will permit the spectrometer to be moved into and out of the gamma-ray beam without moving the vibration isolation platform, 2) a positioning system for the vibration isolation platform which allows reproducible positioning to within a few microns, 3) improved optics for the angle interferometers, 4) crystal and optical polygon supports which permit angle interferometer calibration without removal of crystals and automatic indexing of the polygon, 5) improved collimation and detection for better background suppression and 6) a controlled atmosphere chamber for the spectometer. The target accuracy for this spectrometer is 0.1 ppm for sources of a few counts per second (2nd or 3rd order). The spectrometer improvements are nearing completion. The vibration isolation platform will be shipped to ILL in November or December 1985 and the precision spectrometer in January 1986.

High precision gamma-ray data recorded in 1984 were analyzed and published during the past year. The measured wavelengths were produced in the reactions $^{35}Cl(n,\gamma)\ ^{36}Cl$ (517, 786, 788, 1165, 1951, 1958 keV) and $H(n,\gamma)D$ (2.2 MeV). The chlorine data showed that wavelength measurements accurate to ~ 0.1 ppm are possible for intense lines up to 2 MeV. The uncertainty of the weak hydrogen line ($\lesssim$ 0.5 counts/sec in first order) is ~0.9 ppm. The deuteron binding energy follows directly from this measurement and the neutron mass can be derived by combining the deuteron binding energy with mass spectroscopic data. The uncertainty on the mass of the neutron has been reduced by a factor of three.

One- and two-electron high Z studies are presently carried out at accelerator facilities in West Germany. All such work uses focusing crystal spectrometers and position sensitive detectors to compare e.g., Lyman α with an otherwise determined x-ray reference line measured on the (in-house) upgraded vacuum spectrometer. In the past we used recoil production (U^{+66} at 5-6 MeV/u) and x-ray standards; although the recoil spectra are free of Doppler correction, they remain troubled by spectator electrons. The latest generation of this work uses acel-strip-decel technology to produce relatively slow beams of naked ions whose upper levels are then populated selectively by single collision encounters with atomic H or He. A prototype of this procedure was run at MPIKP in Heidelberg and should give results limited by the x-ray reference line. New developments of crystal filter markers which have now been demonstrated should overcome x-ray line shape limitations in the future.

Gravitational activity over the past year focussed on an ultimately disappointing study of a new fiber material (Pt/W). It turned out to be a disaster. Even though its torsion constant and strength were ideal,its stability and the numbers it produced were just not good enough to generate any truly useable data, but were just good enough to warrant continued use in the hope of eventual success. This fiber has been abandoned and a fiber of chromium and gold-plated quartz is currently installed and is being readied for what is fervently hoped will be the last cut at this measurement. A hard disk has been installed on the computer system which controls the experiment and analyzes the data, allowing what is hoped will be easier data reduction and analysis.

A measurement of the equivalence of the active and passive mass of bronze and tungsten has been made. The results are consistent with Newton. A measurement of the equivalence of the active and passive mass of alumina and tungsten has been made with sufficient precision to be interesting, as pertaining to the measurement of Stacey and Tuck.

Three precision spheres of borosilicate glass have been manufactured. These spheres accurately duplicate the diameter of the tungsten spheres against which they are compared. Their sphericities are a few parts/million rms. A manuscript is being prepared outlining their construction.

Inner shell spectra-synchrotron radiation

Objectives and program:

Our long-standing efforts in x-ray spectroscopy have focussed on multi-vacancy and many-body effects. Aside from matters of intrinsic interest (which are considerable) these features are ubiquitous in both emission and absorption spectra making direct interpretation of these spectra less robust and informative than it should be absent these complexities. By studies of emission spectra under highly resolved monochromatic excitation we demonstrated an unambiguous separation of spectral features arising from-single vacancy and multi-vacancy processes [Phys. Rev. A 27 923 (1983)].

Such work is possible only with the use of an intense synchrotron radiation source. Furthermore, extension of our original demonstration experiment, carried out on atomic argon to families of molecular gases and simple solids and to include electrons as well as photons, requires a dedicated and highly specialized beamline. Design, construction and installation of such a line at the National Synchrotron Light Source (NSLS), Brookhaven has been a major effort of several people for more than a few years. As is well known, there were considerable delays in the x-ray ring startup at NSLS and there were surely problems in our development. However, as indicated in the next paragraphs, this has been the year for full operation of the ring, of our beamline and the beginning of its research program.

The time up to that of full operation at NSLS has not been without issue, due to work carried out at the Stanford Synchrotron Radiation Laboratory (SSRL) and the Hamburg Synchrotron Radiation Source (HASYLAB). These efforts have led toward previously unanticipated directions, some of which will fold into our ongoing program. Overall this is a large effort, both financially and in terms of personnel. Full time contributions come from P. Cowan, S. Brennan and B. Karlin (a Brookhaven National Laboratory (BNL) employee supported by NBS). Participation by T. Jach (1/2) and R. LaVilla (2/3), as well as significant contributions from R.D. Deslattes, E.G. Kessler and A. Henins rounded out the effort.

Current activities - accomplishments:

The past year can be divided roughly in two with regard to synchrotron radiation. On May 9, 1985 the National Synchrotron Light Source (NSLS) began a full schedule of operational beam time. Because of the long delay in the beginning of NSLS operation, we took advantage of available beam time at other synchrotron sources prior to March 1985. However, since April 1985 the principal efforts have been the installation, commissioning and operation of the X-24A beamline at NSLS.

In a collaboration with the Center for x-ray Optics of the Lawrence Berkeley Laboratory (LBL), we obtained 8 eight-hour shifts of beamtime February 17-20, 1985 at the Stanford Synchrotron Radiation Laboratory (SSRL). This experimental run was at SSRL Beamline VI-2 on the LBL/Exxon Wiggler, which is the world's brightest continuous beam x-ray source. The intention of the experiment was to observe photoelectron and Auger electron spectra from argon as a function of incident photon energy near the thresholds for single and multiple-vacancy production at ~3.2 keV.

This experimental run was plagued with difficulty: The promised eight shifts of beam were reduced to about one and one-half due to facility-related problems. In the remaining beamtime we were able to obtain detailed K edge absorption spectra of argon and Cl in CF_2Cl_2. However, there was insufficient time to obtain significant electron spectra.

Prior to the experiment it was determined that the photon flux at 3.2 keV could be maximized by operating the wiggler in a reduced field, undulator mode. Our observations of the performance of the insertion device as an undulator have been accepted for publication.

Activity at the NSLS has proceeded at an accelerated pace since April of this year. We have installed and operated all major beamline components. The UHV compatible crystal monochromator has been providing tuneable monochromatic x-rays since May. A focussed beam was obtained in June despite mechanical difficulties with the grazing incidence x-ray mirror mechanisms. Also in June, the first absorption edge scans were taken with the monochromator. By mid-August the performance testing of the beamline was largely completed. Due to the UHV compatible design, beamline X-24A delivers the highest intensity ($\sim 10^{11}$ photons/sec-mm^2) at 3.2 keV of any synchrotron beamline in the world. The energy resolving power of the monochromator is also higher than any previously reported. These results are in press.

A secondary x-ray spectrometer was constructed for high energy resolution measurements of x-ray scattering and fluorescence. The spectrometer is a tuneable curved crystal, Rowland circle instrument. A position sensitive detector permits simultaneous data collection at various wavelengths. A variable radius crystal bender was developed to permit the crystal to detector distance to remain fixed as the angle of the crystal is tuned.

Scientific research has begun at beamline X-24A. Both absorption spectra and fluorescence spectra have been obtained. At this writing it is expected that publishable results should be in hand by the time the Committee meets.

Particularly through experiments at HASYLAB and SSRL we became involved with x-ray surface diffraction. This is a recently emerged facet of x-ray diffraction which had already demonstrated utility in revealing ordered structure in overlayers but for which the diffraction process was not fully understood. Cowan formulated a dynamical model for the case of simultaneous total external reflection and Bragg diffraction from planes perpendicular to the surface. Interference between these processes permits manipulation of the fields and alteration of their spatial amplitude distributions.

We (Cowan, Brennan, Jach) obtained beam time last year at HASYLAB to test the prediction of Cowan's calculations. Analysis of the data during the present year showed good agreement with the theory but the surface conditions (Br passivated Ge operated in He) were far from rigorously established. To confirm that the observed effects were not due to contamination we were able to obtain both beam time and access to a specially built surface diffraction chamber at the Stanford Synchrotron Radiation Laboratory (SSRL) to study the predicted effects on a Ge(111) crystal. The advantages of using this chamber were that the surface could be prepared in the same ultra-high vacuum chamber that was used on a goniometer for the diffraction measurements. The data are still being analyzed but preliminary results indicate that the dynamical effects are present on the surface and are not merely an artifact of a dirty surface.

While at SSRL we collaborated with researchers from EXXON Research and Engineering Co. and from AT & T Bell Labs on a grazing incidence scattering study of clean and oxygen covered Cu(110). One of the novel effects that has been observed under grazing incidence diffraction conditions is the presence of "forbidden reflections," i.e. those which would not occur from bulk diffraction due to destructive interference from subsequent planes. Two that have been recorded are the Cu(110) and the Cu(100) reflections from planes perpendicular to the (110) surface. What is not yet settled is whether these reflections are due to surface defects or due to the exponentially decaying evanescent wave in the bulk, causing incomplete cancellation of reflected waves. The strength of the copper reflections seem to be dependent on the angle of miscut of the copper planes from the surface. No intensity was observed from the Ge(110) and (330) reflections; however the Ge crystal was very well oriented, such that the surface normal was aligned with the (111) zone axis to better than 30 arc seconds. Work is continuing in this area at all three institutions.

Advanced experimental development

Objectives and program:

Partly to clarify our own thinking, several less structured efforts are grouped here. Three areas are conspicuous at present: advanced optical physics, fundamental physics of and using cold neutrons and advanced x-ray optical technology. The first represents what has emerged from J. Snyder's long involvement with laser wavelength problems. The second is the beginning of a new long-term effort, principally by G. Greene and R. Deslattes, to exploit the new NBS cold neutron guide hall in the context of a national consortium. The third simply recognizes that detector development and x-ray optical design have become a big effort with ties to astronomy, and laser produced plasmas, as well as to our own interests.

Activities and accomplishments:

Optical Physics

A new project has been started by J. Snyder and R. Bonanno in collaboration with the Center for Radiation Research (Lucatorto and Debenham) to develop a novel, ultra-sensitive instrument for isotopic abundance analysis. This instrument will use a small racetrack storage ring to multi-pass sample ions through an isotopically selective process of charge neutralization, laser ionization and magnetic mass analysis. We (Snyder and Bonanno) have begun a preliminary experiment to measure some relevant cross sections of krypton, which has rare isotopes useful for geophysical dating and for environmental monitoring. We hope to complete the preliminary experiment and begin design and construction of a prototype isotope analyzer within the next year.

The collaboration with the Physikalisch-Technische Bundesanstalt (the West German national standards laboratory) continued with a five week visit by J. Snyder to Braunschweig last spring. The experiment is investigating the potential of calcium as possible future optical frequency standard. We have made substantial technical progress, but have not yet seen a signal from the transversely excited calcium beam.

An acousto-optic/fiber-optic multiplexing system for the Mössbauer-drive Lambda Meter has been developed and tested.

X-ray Optics

After the extended period of beamline optics development, we have focussed in the past year on spectrometers for registration of fluorescent spectra. Actually these systems have a strong overlap with those needed for (and already used in) accelerator experiments on one- and two- electron ions, laser produced plasmas and X-ray astronomy. Generically these instruments combine focussing crystal optics with position sensitive-detectors. Development work has included new work on both the crystal optics and on detectors with an emphasis on the latter.

Crystal optics are all of the Rowland circle Johann type with a total of six "fixed function" instruments now available in several laboratories. Realization of a wide-range general purpose instrument is a formidable and awkward engineering development when it is noted that 2 meter diameter Rowland circles are required to operate under high- or ultra-high vacuum conditions. One solution implemented this year for the NSLS work is to use variable crystal curvature to permit a fixed crystal to detector distance. The required variable radius design was accomplished by Henins and seems to warrant further development and application.

Most work concentrated on detectors, which so-far all employ cathode induction charge division ("Backgammon" detectors). Main emphasis has been on "second-coordinate" encoding with two avenues pursued. The first, which has already seen use in the July Heidelberg experiment, uses charge division of the end signals of a resistive wire "meander" pattern anode. This leads to coarse resolution in one-dimension (binning by wires with 1-2 mm spacing) while fine resolution (0.1 mm) is maintained in the other. A second approach, devised by Cowan using a complex (graded density x backgammon) cathode pattern to obtain both coordinates, is still in a preliminary phase. Production of reliable anode frames has been a difficult technical problem largely engaged by Luther(1/3) whose experience with fine fibers in gravitational experiments has been of great value to this work.

Neutron Physics

There are a variety of investigations involving measurements on low energy (cold neutrons) which can be fruitfully attacked using tools and techniques developed by members of the Quantum Metrology Group. The prospect of an in-house, cold neutron facility which is proposed to follow the NBS reactor upgrade has turned our attention (Greene 1/3) to this area of research. This work includes measurements which have implications in particle physics, nuclear physics, astrophysics and tests of fundamental symmetries and invariance laws.

These opportunities have been pursued in a variety of ways. Two of us (R.D. Deslattes and G.L. Greene) participated in a workshop on "Scientific Opportunities with Advanced Facilities for Neutron Scattering" at Shelter Island and one of us (G. L. Greene) has begun preparing (with the encouragement of the editors of RMP) a major review article on the properties of the neutron. In order to determine an optimal program for fundamental physics with cold neutrons, we have organized (with the Department of Energy and National Measurement Laboratory support) an International workshop on 14-15 November 1985.

In addition, work on an experiment has begun in collaboration with Los Alamos National Laboratory to measure the neutron lifetime, a fundamental quantity of considerable importance in nuclear, particle and astrophysics at the NBS reactor.

FUTURE OUTLOOK

For the most part the near future can be surmised from the activity summaries given above. In a few cases however, plans are either very well-developed or a new direction is involved. These are summarized below. An exception is made in the case of the synchrotron radiation work at NSLS since at the time of preparing this document we do not yet know how closely the experimental performance will approach our design goals. This should be clear by the time of the Committee meeting and results will be given then on specific plans.

Precision Spectroscopy

Following reinstallation of the precision spectrometer at ILL, the 2.2 MeV gamma-ray from H(n,γ)D will be remeasured. Because of the new source tube and better positioning of the spectrometer in the gamma-ray beam, count rates should improve by a factor of 10. The improved statistics and the improved angle measuring capability, suggest that a deuteron binding energy measurement near 0.1 ppm should be possible. Measurement of high energy capture gamma-rays from the reactions ^{14}N(n,γ) and/or ^{12}C(n,γ) are planned for the spring of 1986. Precision measurement of the intense lines from these reactions [4508, 5270, 5299, 5532, 5561, 6323 keV from ^{14}N(n,γ) and 1262, 3684, and 4946 keV from ^{12}C(n,γ)] will establish precision standards in a still higher energy region. The gamma-ray measurements when combined with the mass differences $^{15}N^1H_3$ - $^{14}N^1H_2{}^2H$ (0.87 ppm) or $^{12}C^2H^1H_3$ - $^{13}C^1H_4$ will permit a determination of the combination of constants $N_A h/c$ and will provide a new value of the fine structure constant α which is independent of Q.E.D. and solid state theory.

The group has had a long standing interest in precision x-ray wavelength measurements particularly in the high Z region. E.G Kessler has been invited to participate in "Precision Measurements of K Series X-ray Energies, Natural Widths, and Intensities in the Actinide

Region" at the ILL. An ILL curved crystal spectrometer will be used for these measurements. Because experiment-theory differences are large in this region, these measurements have the potential of a significant influence on theoretical understanding of many electron atoms.

The long term future of high-Z one- and two-electron ion spectroscopy clearly lies with the coming generation of heavy ion cooler rings. Ultimately all Z < 100 will become accessible but not for several years during which there is much that can be learned even within the limitations of current sources. We plan work at two facilities in the interim: the French nuclear center in Grenoble, CENG, and the GSI in Darmstadt. At CENG, Geller and collaborators have established a high performance ECR ion source; we expect to work in collaborations with J.P. Briand's group (U. Pierre et Marie Curie, Paris) on He-like spectra from Ne to A. The high beam currents and low velocities available in this facility are not (to our knowledge) equalled elsewhere. To move upward in Z so as to improve sensitivity in regard to QED tests in H-like ions, we propose an acel-strip-decel experiment for the UNILAC at GSI using naked Ni. This ion has been handled efficiently by the UNILAC accelerator and is near the upper Z limit for which there are sufficient radio frequency accelerator sections beyond those needed for attaining stripping energies to provide for adequate deceleration. The 1.5 Å spectral region is also favorable in that we can realistically hope for 0.1 ppm spectroscopy. Since the total radiative correction is 600 ppm in this case, there is an obvious potential for a sensitive measurement of the 1s Lamb shift.

<u>X-Ray Spectroscopy</u>

As this report is being prepared in September, it is difficult to give a precise listing of the coming year's research program at NSLS. While a more precise picture should be available by the time the Committee meets, it is likely that the upcoming work will include: Threshold excitation of x-ray fluorescence of argon and molecular gases containing chlorine and sulfur; threshold excitation of electron spectra from gases (following the winter shutdown of NSLS); resonant Raman and Rayleigh scattering of x-rays near threshold; and x-ray excited fluorescence and electron emission of solids and surfaces. In addition, the beamline monochromator will be tested with large d-spacing crystals to permit operations at lower energies while other beamline up-grades will include crystal cooling and pre-monochromator energy filtering in anticipation of increased power from the source. A proposal to study the structure of reconstructed Sn layers on Ge (111) has been submitted to SSRL while diffraction of fluorescence radiation at glancing take-off angles will be studied, likely at NSLS and an attempt made to observe x-ray standing waves produced during total reflection.

Neutron Physics

We intend to continue a vigorous program of activities in the area of the investigation of fundamental interactions with neutrons. This work will include further measurements of the neutron lifetime (proposal is currently under consideration by funding agencies), design work on the NBS cold neutron facility, feasibility studies for long (1 m) baseline neutron interferometry, and experiments to study nucleon-nucleon weak interaction through the investigation of parity violating effects with polarized neutrons.

Gravitation

After the final adjustments on the new fiber and the apparatus, we hope to complete the measurements on Al_2O_3 and SiO_2 so as to unequivocally decide either in favor of or against Stacey and so as to obtain the precision needed to answer the conjecture of T. Jacobsen. We hope to obtain sufficient data to shed light on the derivation of E. Sternglass.

An improved method for measuring the equivalence or nonequivalence of the active and passive mass has been devised, the feasibility of which will be analyzed in detail.

INVITED TALKS

Quantum Metrology Group (520.06)

Sean M. Brennan, "Two Dimensional X-ray Scattering," New Directions in X-ray Scattering Workshop, Asilomar, CA, April 1-5, 1985.

Sean M. Brennan, "Optical and Spectral Characterisitics of an Insertion Device Used Both as a Wiggler and an Undulator," International Synchrotron Radiation & Instrumentation Conference, Stanford University, Stanford, CA, July 1985.

Paul L. Cowan, "Dynamical Diffraction of Glancing Incidence Diffraction," Universit´e P. et M. Curie, Paris, France, October 8, 1984.

Paul L. Cowan, "Recent Theoretical and Experimental Work on Diffraction of Evanescent X-rays," Lawrence Berkeley Laboratory, Berkeley, CA, February 12, 1985.

Paul L. Cowan, "Recent Work on Diffraction of Evanescent X-rays," Lawrence Livermore Laboratory, Livermore, CA, February 21, 1985.

Paul L. Cowan, "A High Resolution X-ray Spectroscopy Synchrotron Radiation Beamline for the Energy Range 800 eV," International Synchrotron Radiation & Instrumentation Conference, Stanford University, Stanford, CA, July 1985.

Richard D. Deslattes, "New Tales of Lamb's Shift; How and Why to Dress a Naked Ion," State University of New York, Stoney Brook, NY; The University of Connecticut, Storrs, Connecticut, February 13-15, 1985.

Richard D. Deslattes, "Precision Measurements of ls Lamb Shifts in Hydrogen-like Ions", American Physical Society Meeting, Crystal City, Va, April 24-27, 1985.

Richard D. Deslattes, "Accurate Spectroscopy of Single-electron and Single-vacancy Ions," Atomic Theory Workshop, NBS, Gaithersburg, MD, May 23-24, 1985.

Geoffrey L. Greene, "The Silicon Lattice Spacing, The Neutron Mass and the Fine Structure Constant," University of Virginia, Charlottesville, VA, November 30, 1984.

Geoffrey L. Greene, "The Fundamental Properties of the Neutron," International Conference on Neutron Scattering, Santa Fe, NM, August 19, 1985.

James J. Snyder, "Ultrasensitive Laser Isotope Analysis of Krypton in an Ion Storage Ring," Argonne National Laboratory, Argonne, IL, March 1985.

James J. Snyder, "Resonance Ionization Mass Spectrometry: Applications in Atomic Physics and Analytical Chemistry," William Paterson College, Department of Chemistry, April 22, 1985.

James J. Snyder, "Ultrasensitive Laser Isotope Analysis of Krypton in an Ion Storage Ring," Univeristy of Bonn, Physics Department; University of Hamburg, Physics Department; Max-Planck Institut, Garching, W. Germany, April-May, 1985.

James J. Snyder, "Ultrasensitive Laser Isotope Analysis of Krypton in an Ion Storage Ring," VII International Conference on Laser Spectroscopy, Hawaii, June 24, 1985.

PUBLICATIONS

Quantum Metrology Group (520.06)

IN PRINT:

R.D. Deslattes, "Applications of X-Ray Interferometry," Precision Measurement and Fundamental Constants II, 303 (1984).

R.D. Deslattes, "Precision X-Ray Wavelength Measurements in Helium-like Argon Recoil Ions," J. Phys. B.: At. Mol. Phys. 17 L689 (1984).

B.P. Duval, J. Barth, R.D. Deslattes, A. Henins and G.G. Luther, "Position-Sensitive X-Ray Detector," Nucl. Inst. & Meth. in Phy. Res. 222 274 (1984).

P.L. Cowan, "Photon Energy Analysis by Reflectivity Modulation," Nucl. Instr. & Meth. 222 46 (1984).

G.L. Greene, "Trapping of Low Energy Neutrons," Progress in Quantum Electronics 8, 257 (1984).

B. Heckel, M. Forte, O. Schaepf, K. Green, G.L. Greene, N.F. Ramsey, J. Byrne, J.M. Pendlebury, "A Measurement of Parity Non-Conserving Neutron Spin Rotation in Lanthanum," Phys. Rev. C 29 2389 (1984).

G.G Luther and W.R. Towler, "Redetermination of the Newtonian Gravitational Constant "G", Precision Measurement and Fundamental Constants II, 573 (1984).

R.C.C. Perera and R.E. LaVilla, "Molecular X-ray Spectra: S-Kβ Emission and K Absorption Spectra of SCO and CS_2," J. Chem. Phys. 81 3375 (1984).

M.B. Morris, T.J. McIlrath and J.J. Snyder, "Fizeau Wavemeter for Pulsed Laser Wavelength Measurement," Applied Optics 23 3862 (1984).

H.F. Beyer, R.D. Deslattes, F. Folkmann and R.E. LaVilla, "Determination of the 1s Lamb Shift in One-Electron Argon Recoil Ions," J. Phys. B Atom. Mol. Phys. 18 207 (1985).

R. Bonanno, J.D. Fassett, T.B. Lucatorto, J.J. Snyder, and C.W. Clark, "Multiphoton Excitation of Autoionizing States of Mg," Bulletin of Am. Phys. Soc. 30 851 (1985).

R. Bonanno, J.D. Fassett, T.B. Lucatorto, J.J. Snyder, and C.W. Clark, "Stepwise Multiphoton Excitation of Autoionizing Rydberg Series in Mg," in Electronic and Atomic Collisions abstracts of Contributed Papers of the 14th International Conference on the Physics of Electronic and Atomic Collisions, Palo Alto, Ca, M.D. Coggiola, et al., (eds) p.69 (1985).

S. Brennan, "Two Dimensional X-ray Scattering," Surf. Sci. 52 1153 (1985).

P.L. Cowan, "Dynamical Theory of Evanescent X-ray Diffraction Stimulated by Glancing Incidence X-rays," Bull. Am. Phys. Soc. 30 310 (1985).

R.D. Deslattes, "Fundamental and Incidental Limits on the Spectroscopy of Single Electron Ions", Nucl. Instr. & Meth. in Phy. Res. 9 668 (1985).

R.D. Deslattes, R. Schuch, E. Justiniano, "Application of Decelerated Bare Nuclei to Precision Spectroscopy of One-Electron Ions," Phy. Rev. A, Rapid Communication 32 1911 (1985).

G.L. Greene, E.G. Kessler, R.D. Deslattes, H. Börner, "Accurate Determination of Gamma-Ray Energies for $E \leqq 2$ MeV," in Capture Gamma-Ray Spectroscopy and Related Topics ed. S. Raman, A.I.P. Conference Series (1985).

T. Jach, S. Brennan, P.L. Cowan, "Observation of Dynamical X-ray Diffraction from A Crystal Surface a Glancing Incidence," Bull. Am. Phys. Soc. 30 311 (1985).

E.G. Kessler, Jr., G.L. Greene, and R.D. Deslattes, "Gamma-ray Energies from the Reaction $^{35}Cl(N,\gamma)$," Phy. Rev. C 32 374 (1985).

R.C.C. Perera, J. Barth, R.E. LaVilla, R.D. Deslattes, A. Henins, "Multivacancy Effects in the X-ray Spectra of CH_3Cl," Phys. Rev. A 32 1489 (1985).

J.J. Snyder, T.B. Lucatorto, P.H. Debenham, R.E. Bonanno, and C.W. Clark "Ultrasensitive Laser Isotope Analysis of Krypton in an Ion Storage Ring," in Laser Spectroscopy VII, Proceedings of the Seventh International Conference (Springer-Verlag, 1985).

IN PRESS, IN REVIEW, OR NEARING COMPLETION:

S. Brennan, P.L. Cowan, T. Jach, R. Lavilla, R. Perera and H. Winick, "Optical and Spectral Characteristics of an Insertion Device Used as Both a Wiggler and an Undulator," Nucl. Instrum. and Meth. (in press).

S. Brennan, P.H. Fuoss and P. Eisenberger, "X-ray Crystallographic Studies of Pb Monolayers on Cu (110) Surfaces," Phys. Rev. B., (in press).

S. Brennan, P.H. Fuoss and P. Eisenberger, "X-ray Scattering Studies: The Structure and Melting of Pb on Cu (110) Surfaces," Proceedings of the First International Conference on the Structure of Surfaces, (in press).

P.L. Cowan, "A New Two-Dimensional Position Sensitive Proportional Counter," Nucl. Instrum. and Meth. (in press).

P.L. Cowan, "Diffraction of Evanescent X-rays: Results from a Dynamical Theory," Phys. Rev. B 32 (in press).

P.L. Cowan, S. Brennan, R.D. Deslattes, A. Henins, T. Jach and E.G. Kessler, "A High Energy Resolution X-ray Spectroscopy Synchrotron Radiation Beamline for the Energy Range 800 eV to 5000 eV," Nucl. Instrum. and Meth. (in press).

P.L. Cowan, S. Brennan, T. Jach, M. Bedzyk and G. Materlik, "Observation of the Diffraction of Evanescent X-ray at a Crystal Surface," Phys. Rev. Lett. (in preparation).

R.D. Deslattes, "Accurate Spectroscopy of Single-electron and Single-vacancy Ions," Proceedings of Atomic Theory Workshop, Am. Inst. Phy. (in press).

R.D. Deslattes, E.G. Kessler, Jr., "Experimental Evaluation of Inner-Vacancy Level Energies and Comparison with Theory," in Atomic Inner-Shell Physics Crasemann (ed.) (in press).

P.H. Fuoss, S. Brennan and P. Eisenberger, "Melting of Pb on Cu (110) Studied with Grazing Incidence X-ray Scattering," Submitted to Phys. Rev.

G.L. Greene "The Fundamental Properties of the Neutron," Physica B (in press).

G.L. Greene, R.D. Deslattes, E.G. Kessler, Jr., and H. Börner, "A New Determination of the Deuteron Binding Energy and the Neutron Mass," (in preparation).

G.G Luther, P.L. Cowan, A. Henins and S. Brennan, "New Two Dimensional Position Sensitive Proportional Detectors Using Charge Division," Nuclear Instrum. and Meth. (in press).

E.S. Marmar, J.E. Rice, E. Källne, J. Källne and R.E. LaVilla, "Precision Measurement of the 1s Lamb Shift in Hydrogen-like Argon," Phys. Rev. A (in press).

J. Snyder, T.B. Lucatorto, P.H. Debenham, S. Geltman, "Ultra-Sensitive Isotope Analysis by Laser Selective Multi-Stage Ion Acceleration," J. Opt. Soc. Am. B (in press).

TECHNICAL AND PROFESSIONAL COMMITTEE PARTICIPATION AND LEADERSHIP

Quantum Metrology Group (520.06)

S. Brennan, 6-GeV Ring Planning Group.

P.L. Cowan, European Synchrotron Radiation Project Beamline Instrumentation Study Group; Executive Committee, National synchrotron Light Source Association of Users; National synchrotron Light Source Instrumentation committee; Organizing Committee, Advanced Light source workshop.

R.D. Deslattes, Vice Chairman, The American Physical Society, Division of Electron and Atomic Physics.

J. J. Snyder, Co-editor of feature issue of the Journal of Optical Society B, on the subject "Ultra-Sensitive Laser Spectroscopy."

J. J. Snyder, Editor of Academic Press book on the subject of "Laser Characterization and Control."

TRIPS SPONSORED BY OTHERS
Quantum Metrology Group (520.06)

Sean Brennan; Was invited by the Tokyo Institute of Technology in Tokyo, Japan during the month of October 1985 to discuss and lecture on the subject of the NBS beamline at the National Synchrotron Light Source with researchers at the Photon Factory.

Paul Cowan; Was invited by the European Synchrotron Radiation Facility (ESRF) of Ispra, Italy (October 3-5, 1984) to be a member of the European Synchrotron Research Project (ESRP) Beamline Study Group, which has proposed a number of beamlines for the ESRF facility.

TECHNICAL ACTIVITIES
ELECTRICITY DIVISION
FISCAL YEAR 1985

Overview

The Electricity Division (ED) concerns itself with the fundamental electrical quantities such as current, voltage, and impedance at dc and low frequencies (to roughly 100 kHz) over many orders of magnitude and at the highest possible levels of accuracy. Its primary mission is to provide the central basis for a reliable and consistent system of electrical measurement throughout the U.S., including the Nation's scientific and defense communities as well as industry and commerce; and to ensure that the U.S. system is consistent with those of other countries and the internationally accepted system (i.e., the International System of Units or SI).

The justification for all of the ED's work comes directly from the Bureau's Organic Act, as amended, and is in its prime mission areas, that is, the areas of responsibility for which the Bureau was originally founded in 1901. The major technical problems which benefit from the ED's work include fundamental physical theory; high technology-based R&D; electrical power revenue metering, transmission, and distribution; industrial process control; quality control in the manufacture of electronic components and products; testing and maintenance of electronic systems, which includes the civilian side of defense and aerospace; and national defense requirements directly under the Department of Defense. End user groups include scientists in universities; electric power utilities, both public and private; electric equipment manufacturers; process engineers who design, build, and use industrial process control systems; manufacturers of electronic components and consumer products; high technology civilian companies and government agencies involved with communications, computers, aerospace, transportation, health, and defense; and finally the armed services.

It is probably not an overstatement to say that the Nation's electric power system, the cost-effective manufacture of reliable consumer goods, the economic production of industrial materials, a viable national defense, and R&D at the cutting edge of science and technology, would not be possible without adequate electrical measurements; and that the basis for all such measurements within the U.S. is the fundamental electrical units the ED maintains and disseminates through its various services; the measurement methods and instrumentation it develops; and the tests and calibrations of standards and instruments it performs. For example, each year well over one thousand calibrations are carried out on primary electrical standards of voltage, resistance, capacitance, inductance, and ac-dc difference (i.e., thermal ac/dc voltage and current converters) that belong to some of the Nation's most important corporations, utilities, universities and government organizations, including Hewlett-Packard, General Motors, IBM, General Electric, Pacific Gas and Electric, American Electric Power, Boeing, TRW, the TVA, the FAA, and the DoD. These standards are used in turn to calibrate and otherwise support a wide range of work-horse electrical measuring instruments and systems numbering literally in the tens of thousands, such as digital voltmeters (DVMs), programmable voltage and current sources, analog-to-digital and digital-to-analog converters, resistance/inductance/capacitance (RLC) meters, impedance bridges, electrometers, oscilloscopes, data recorders, component and printed circuit board testers, automatic test equipment (ATE), including ATE for weapons systems, etc. Without reliable measurement results from such equipment, a technologically sophisticated society like that of the U.S. could not even exist, let alone advance.

To fulfill its main responsibility of providing the central basis for the U.S. electrical measurement system, the ED carries out work in eight distinct but related areas with the following objectives:

1. Realize the SI definitions of basic electrical measurement units such as the ampere, volt, ohm, and farad, thereby ensuring that the U.S. legal electrical units are consistent with the internationally accepted system.

2. Develop and maintain U.S. Legal or National Reference Standards for the basic electrical units and related quantities, thus providing a central basis for the U.S. system of electrical measurement.

3. Disseminate the basic electrical measurements units to users within the U.S. via a variety of measurement and calibration services, and develop new means for doing so, thereby ensuring the traceability of electrical measurements made throughout the country to National Reference Standards.

4. Develop new methodologies and the required instrumentation and standards which will lead to advances in the state-of-the-art of electrical measurement, thus ensuring the availability to the technical community of adequate measurement techniques.

5. Determine fundamental physical constants closely related to the electrical units in order to provide the scientific community the means to test basic physical theory.

6. Initiate and participate in international comparisons of the basic electrical units, thus ensuring that the U.S. system of electrical measurement is consistent with those of other countries.

7. Participate in voluntary national and international standardizing activities related to the electrical units, and the fundamental physical constants, in order to foster international compatibility of electrical measurements, eliminate and prevent non-tariff barriers to trade, and contribute to internationally acceptable data compilations.

8. Provide training for personnel active in the field of electrical measurements and standards, including the presentation of seminars and workshops, and the generation of tutorial written material, thereby elevating the overall level of competence in the field.

The objectives, current activities, FY 85 accomplishments, and future plans of the various projects underway within the ED which contribute to these principal areas are described in detail in the following Project Reports. Highlights, categorized according to these eight principal areas of work, include:

1. Realize SI Units. Work actively continued to determine the ratio of the NBS as-maintained ampere to the SI ampere (or equivalently, the value of the Josephson frequency-voltage ratio 2e/h in SI units) to an eventual accuracy of 0.1 ppm by equating electrical to mechanical work. Extensive measurements with the new NBS room-temperature ampere balance revealed a number of problems, most of which have been solved. A value for the ratio accurate to 1 ppm or better should be obtained in FY 86. The redetermination of the NBS as-maintained farad and ohm in terms of their respective SI units via the NBS calculable cross capacitor also progressed well during the year and a tie between the NBS bank of 10 pF capacitors and 1 Ω resistors used to define and maintain the NBS farad and ohm, respectively, was completed with an accuracy of 0.05 ppm. The interferometry required to use the calculable capacitor to measure the 10 pF bank itself was essentially completed and a sub-0.1 ppm determination should be available by the end of FY 86.

2. Develop and Maintain U.S. Reference Standards. Monitoring of the U.S. legal unit of resistance using the quantized Hall resistance (QHR) continued and for the first time the decrease of the unit with time (~0.05 ppm/year) was directly measured. Additionally, a new QHR laboratory was designed, all the necessary equipment ordered (e.g., a new 15 T magnet), and its construction initiated. When completed, it will give NBS a truly unique QHR research and measurement capability. The collaborative effort with NBS/Boulder on the development of a Josephson array voltage standard at the 1 V level was initiated and excellent progress was made. Equipment is now being set up at NBS/Gaithersburg to compare an array voltage standard with the Josephson apparatus currently used to maintain the U.S. Legal Volt and to replace the latter with an array.

3. Dissemination. Although the workload this year was unusally heavy, electrical calibration services including MAPs were generally provided in a timely way and without serious problems. Nearly 1400 calibrations of basic standards were performed along with 24 MAP transfers. The turnaround time decreased slightly or remained stable in most areas but plummeted in the ac-dc difference area due to improved operating procedures and increased use of a new automated system. The automation of the Volt Facility moved rapidly ahead and all measurements are now being done automatically. A new calibration services computer (VAX 750) was ordered, received, and installed. Most of the existing software has been converted to run on the machine and all will be so converted by the end of FY 86. A new calibration service for conductivity standards used in eddy current non-destructive evaluation was formally initiated during the year.

4. New Methods, Instruments, and Standards. The dual-channel automated electronic comparator developed for determining the ac-dc differences of thermal converters by simultaneously measuring the difference in converter output when nearly equal ac and dc voltages are applied to both test and standard converters was completed and incorporated into the converter calibration service for routine use. A second system is under construction. The fully automated, high accuracy (0.01 ppm) resistance bridge for measuring quantized Hall resistances was put into routine operation. Two cryogenic current comparator resistance bridges for scaling between different resistance levels with accuracies approaching 0.01 ppm were constructed and initially tested. Some operational experience was obtained with commercial 10 V solid-state standards as MAP transfer standards. Their promise is considerable and based on this work one can expect a 10 V MAP in the not too distant future and the eventual replacement of saturated standard cells by solid-state standards, both at the 1 and 10 V levels and for both laboratory and transport standards.

5. Fundamental Constants. Since the quantum Hall effect can also be used to determine the fine-structure constant α, the work described above under 1. and 2. relating to the realization of the SI ohm and determining the quantized Hall resistance directly impacts the determination of α via the Hall effect. Also as noted above, determining the ratio of the NBS ampere to the SI ampere is equivalent to measuring 2e/h in SI units. An extensive analysis of previously reported NBS fundamental constant experiments was completed and accurate values in SI units for N_A, R_H, 2e/h, α, and F derived. Two new Precision Measurement Grants were awarded, one to handle, cool, and store antiprotons, the other to search for the electric dipole moment of the electron. The project to laser-cool and store neutral atoms made excellent progress during the year. A beam of Na atoms was stopped and trapped in a magnetic trap, and the results reported in two Physical Review Letters.

6. International Comparisons. An international comparison of conductivity standards for eddy current non-destructive evaluation was carried out with the National Physical Laboratory, U.K. Upon completion of the data analysis, a joint NBS-NPL report will be issued. A comparison of the U.S. and U.K. as-maintained unit of resistance using a NPL 1 Ω resistance transfer standard was also carried out. An international comparison of the as-maintained unit of capacitance of East Germany, West Germany, England, France, The Netherlands, and the International Bureau of Weights and Measures (BIPM) was completed under the auspices of BIPM using the three NBS traveling fused silica 10 pF capacitors.

7. Standardization. In September 1986 the Consultative Committee on Electricity (CCE) plans to meet to consider the international adoption of (1) a new value of 2e/h consistent with the SI for volt maintenance purposes via the Josephson effect, and (2) a value of the quantized Hall resistance consistent with the SI for ohm maintenance purposes via the quantum Hall effect. In preparation for the CCE meeting, extensive information was gathered within the U.S. on the potential impact a change in the U.S. Legal Volt of 9 ppm and a change in the U.S. Legal Ohm of 1.5 ppm would have on government and industry operations. (Such changes in the U.S. legal units would occur if the CCE adopted values consistent with the SI.) The consensus seems to be that the international uniformity of the national practical electrical units and having them consistent with the SI is a worthy goal and worth the cost of implementing the changes. Draft statements of the equivalency of the U.S. and Italian, and U.S. and Australian, practical or as-maintained units for voltage, resistance, and capacitance were prepared and should be formally adopted in FY 86.

8. Training. In collaboration with the National Conference of Standards Laboratories, two very well attended and received one week courses entitled "Workshop on Electrical Measurement Assurance Programs" were given, one in Seattle WA and the other in Williamsburg VA. During the year, a number of foreign Guest Workers were trained in various aspects of electrical metrology, as were a number of students including three from the metrology program at Butler Community College outside Pittsburgh PA. There were many shorter visits (i.e., one day to one week) by metrologists from U.S. and foreign government and industrial standards laboratories. The Division staff published over 25 scientific papers during the year and gave numerous presentations.

In summary, the Electricity Division has once again met its principal electrical unit maintenance and dissemination responsibilities and at the same time made good progress on a number of important research projects. This should continue in FY 86.

DISSEMINATION SERVICES: SUPPORT AND OPERATION

(N. B. Belecki, P. A. Boynton, C. B. Childers, R. F. Dziuba, B. F. Field, G. M. Free, R. C. Fronk, J. R. Hastings, F. L. Hermach (GW), G. R. Jones, Jr., T. E. Kiess, J. R. Kinard, L. H. Lee, C. R. Levy, T. E. Lipe, Jr., R. E. Long, T. P. Moore, A. Muciek (GW), E. S. Nowicki, D. D. Prather, J. E. Sims, S. B. Tillet, A. R. Wise, E. Zdral (PSC))

Objectives

The overall objective of this project is to enable all measurements of electrical quantities performed in the United States to be made in terms of the U.S. legal electrical units at the required levels of accuracy. The legal units are provided to the user community via reimbursable calibration and MAP (measurement assurance program) services listed in NBS Special Publication 250 and its appendices. The timeliness and adequacy of these services must be ensured by research and development work on new measurement techniques, standards, and apparatus, since the quality of both MAP and calibration services ultimately depends on the basic metrology competence of the NBS.

The outputs of this project are used directly by the metrology community - the major standards laboratories of industry, government, and the academic community - and indirectly through them by industry for the quality control and maintenance of electronic products, for the control of manufacturing processes in basic industry, for the support of research and development aimed at the improvement of instrumentation and in response to Federal and state regulatory requirements, such as those for traceability of voltage measurements used for the establishment of local power and energy standards and watt-hour meter testing by power companies. In large measure, the pre-eminence of the U.S. in high-technology areas, such as electronics, avionics, communications, aircraft, and space vehicles, has been made possible by our country's sophisticated measurement capability, reflected in automatic test equipment (ATE) systems and high-quality electronic instrumentation. Likewise, advances and progress in these areas have been rapid because they have not been limited by measurement constraints, such as the nonavailability of electrical instruments of adequate accuracy. This condition can only occur if NBS maintains a strong R&D program to ensure the availability of adequate electrical standards for the instrumentation industry.

Current Activities

The measurement services offered by NBS in the electrical area include the calibration of primary standards of alternating current and voltage, impedance at audio frequencies, direct (dc) voltage, and dc resistance, as well as MAP services for capacitance, dc voltage, and dc resistance. Some measurements are also done on ac ratio standards of the highest accuracy. In FY 85, 24 MAP transfers and approximately

1398 calibrations of basic standards were performed, as detailed at the end of this project description, for a total income of about $750 k for the year.

During the past year the turnaround time has decreased slightly or remained stable in most areas. A noteworthy exception is the ac-dc difference area, where the turnaround time plummeted to an average of 38 days in the second half of the FY from an average running well over 100 days in the first half. While scheduling and the queue awaiting calibrations have not yet been eliminated, the waiting time for individual calibrations has been shortened considerably. The improvement was caused by changes in operating procedures and increased use of the automated system for calibration work. Elimination of the queue is a goal for the next two years.

The majority of NBS calibration clientele is represented by the National Conference of Standards Laboratories (NCSL), which is a major source of information for planning future calibration activities, as well as a mechanism (through its technical committees) for disseminating NBS electrical metrology information. This past year saw extensive interaction between the Division management and the NCSL through its Measurement Requirements Committee and interactions at regional meetings. The military and its defense systems contractors and the instrumentation community are the heaviest users of electrical calibration services and it is from them that the most stringent measurement requirements arise. We continue to maintain close ties with the DoD via the Calibration Coordination Group (CCG) technical subcommittees and much of the work to be described below was partially funded by them.

Measurement services support activities fall into three broad categories: (1) the documentation of measurement services, (2) the development of improved measurement methods and standards, and (3) the automation of the measurement systems used to perform both regular and MAP calibrations.

A Division-wide effort to document all of the calibration services according to guidelines promulgated by the NBS Calibration Advisory Group is well under way. The guidelines require a description of the services offered, an exposition of the theory and rationale behind the measurement systems used, a complete analysis of the measurement uncertainties, and detailed, written operating procedures. Despite major changes in measurement systems in the impedance, resistance, and ac and dc voltage areas (requiring completely new procedures and error analyses), this work will be completed by the middle of FY 86, well in time for meeting NBS deadlines.

Work in the second category is directed toward improvement of the processes by which the electrical units are maintained, scaled, and disseminated. In the ac-dc difference area, which supports ac current and voltage measurements, the thrust of the work is to enhance the accuracy available by investigating new and adding improved standards to the set which now provides the basis for all calibrations. In the impedance area, aged bridges are being replaced with new bridges that take advantage of modern electronics. The thrust in the resistance area is to improve scaling from the national standards at 1 Ω, to 1 kΩ and 6453.2 Ω for the absolute ohm and quantized Hall effect experiments respectively, in time for NBS to contribute to a possible international adjustment of the ohm in late 1986. Both cryogenic current-comparators and Hamon devices are being employed in this effort. In the voltage area, emphasis is being placed on improved dissemination, mainly through the use of solid-state standards based on Zener diodes.

In the automation or third category, several of the hardware systems have been completed; future activities are aimed at the construction of complex software systems to collect and analyze calibration data. Such activities are particularly heavy in the ac-dc difference and voltage areas. The resistance automation activity has been reduced in priority this year to increase the effort devoted to scaling work in preparation for the change in the ohm mentioned above.

ACCOMPLISHMENTS

AC Current and Voltage
(J. R. Kinard, C. B. Childers, J. R. Hastings, F. L. Hermach (GW), T. E. Lipe, Jr.)

Construction of the second automated system (System II) for ac-dc difference calibrations has been completed. A block diagram of the system is given in Fig. 1. Its voltage and frequency ranges are indicated in Fig. 2 with the corresponding ranges of the manual system given for comparison. Preliminary testing has begun using software derived from System I, the existing system. System I is described in an article published in the June, 1985 issue of the IEEE Transactions on Instrumentation and Measurement.

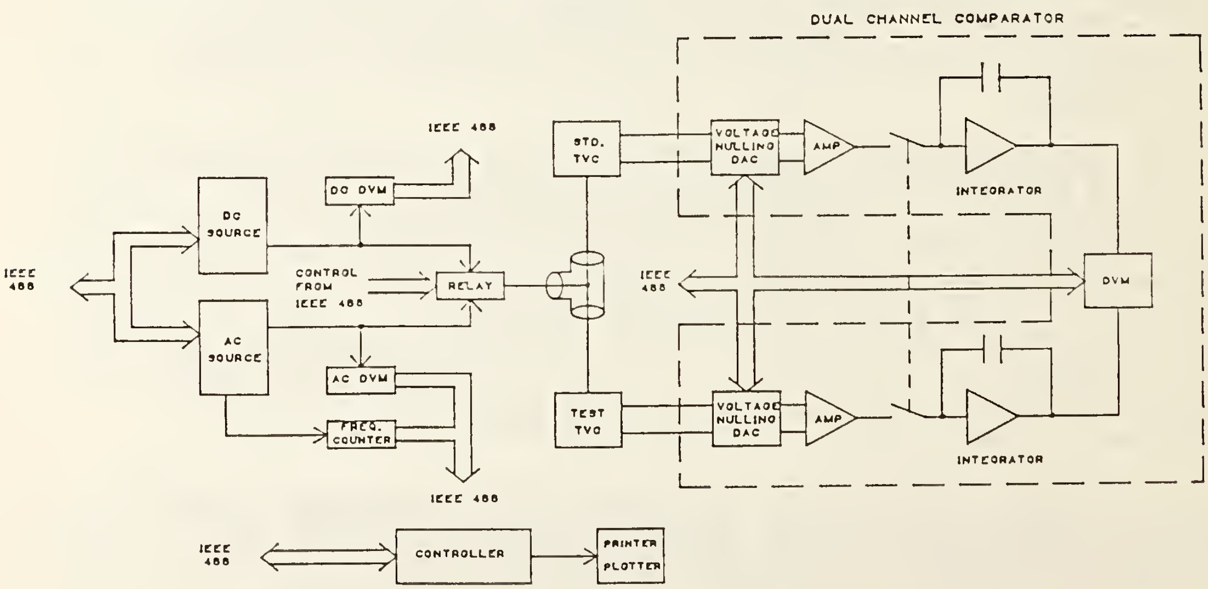

Figure 1.

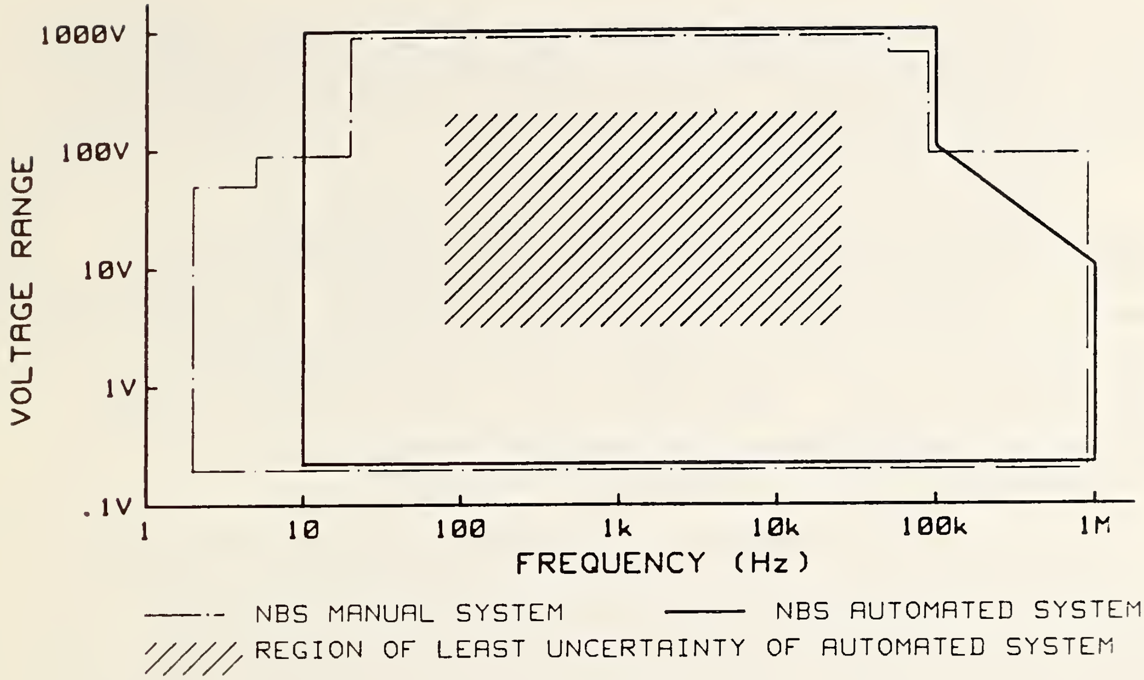

FIGURE 2.

In a further effort to facilitate ac-dc difference calibrations, an additional commercially-manufactured, coaxial, single-range, thermal voltage converter set has been obtained and delivery of a second new set is expected shortly. When they are fully characterized, the new converter sets will give us the capability for independent, parallel operation of at least two, and perhaps three, calibration consoles.

A bilateral, international intercomparison of single junction thermoelements at 100 Hz, 320 Hz, and 1 kHz for 5 mA has been initiated with the National Measurement Laboratory (NML) of Australia. Stimulated by work done at the NML by Dr. B. L. Inglis to determine ac-dc differences at very low to zero current levels, the interchange of thermoelements is expected to resolve differences between measurements based on multijunction and single junction thermoelement standards.

In a related area, specially-constructed thermoelements of NBS design intended to minimize thermoelectric errors have been ordered. The new thermoelements will be studied to determine if their construction pattern - using thermal shunts or bridges at the heater support junctions, Evanohm supports and heaters, and platinum leads - will produce nearly zero ac-dc differences.

Two additional multijunction thermal converters (MJTC's) were obtained to be incorporated into the group making up the NBS primary standards for ac-dc difference. Intercomparisons between one of the new MJTC's, the existing NBS primary group, and the NBS reference set indicate agreement to within 1 ppm from 20 Hz to 100 kHz. The agreement is particularly gratifying because the new MJTC's came from a source of manufacture not previously represented in the NBS primary group. This work has been heavily augmented through the efforts of F. L. Hermach (retired) who made many of the intercomparison measurements and provided technical guidance.

Two examples of an entirely new multirange instrument incorporating solid-state thermoelements were extensively tested. Generally encouraging results were obtained from these prototype commercial instruments in the range from less than 1 V to 1 kV and from 100 Hz to 1 MHz. The new instruments contain improvements over previous solid-state converter systems, but also have certain problems requiring further study. The results have been conveyed to the Navy Metrology Engineering Center, who sponsored the work, and to the manufacturer, with whom liaison is being maintained.

By special prior arrangement, the reduced uncertainty of 10 ppm for calibrations in the range of 5 to 100 V from 100 Hz to 20 kHz is being offered to Department of Defense primary laboratories and manufacturers of thermal transfer standards. A further special service, offered to DoD primary laboratories only, features 5 ppm uncertainties for measurements at 5 and 10 V over the above frequency range. The new service involves direct comparisons with a member of the NBS primary multijunction converter group. Calibration uncertainties at these low values require evaluation of the stability of the converters being calibrated over several months, with a considerably extended set of measurements being made.

Direct (DC) Voltage
(B. F. Field, T. E. Kiess, R. L. Long, J. E. Sims)

Automation of the Volt Facility is nearly complete. Two new automated systems for the intercomparison of standard cells have been completed and their control software written and tested. One of the two is in regular use making the measurements required for the operation of the Volt Transfer Program, the Division's MAP service for dc voltage. The other, a replacement for the manual system used to measure customers' standard cell enclosures sent to NBS for calibration, is currently under test. A system of data file formats, management and backup procedures, and computer programs to implement necessary data-base management functions for both technical and administrative data has been developed and is nearly fully written. New quality control procedures for ensuring the integrity of the measurements in the Volt Facility have been developed and implemented. Included are both hardware and software to permit the evaluation of both the measurement instrumentation and the working reference standards on a daily, automatic basis. A new automated crossbar controller has been designed and built to permit the automatic intercomparison of primary, secondary, and working standards to increase and enhance the information available on the performance of these standards. The above developments have been fully documented.

Three commercially-available, 10 V, Zener-based voltage standards were tested for the effects of temperature shock and power cycling on their transportability. Two of the units exhibited excellent reproducibility when subjected to a power outage and subsequent 30 $^{\circ}$C temperature change. They typically returned to their original values to within 0.02 ppm and 0.06 ppm respectively (see Fig. 1). The other, however, was not reproducible when power was interrupted for two days, a common duration for shipment even by air freight. This unit also jumped unpredictably by as much as 2 ppm when subjected to a rapid temperature change from 23 $^{\circ}$C to 10 $^{\circ}$C.

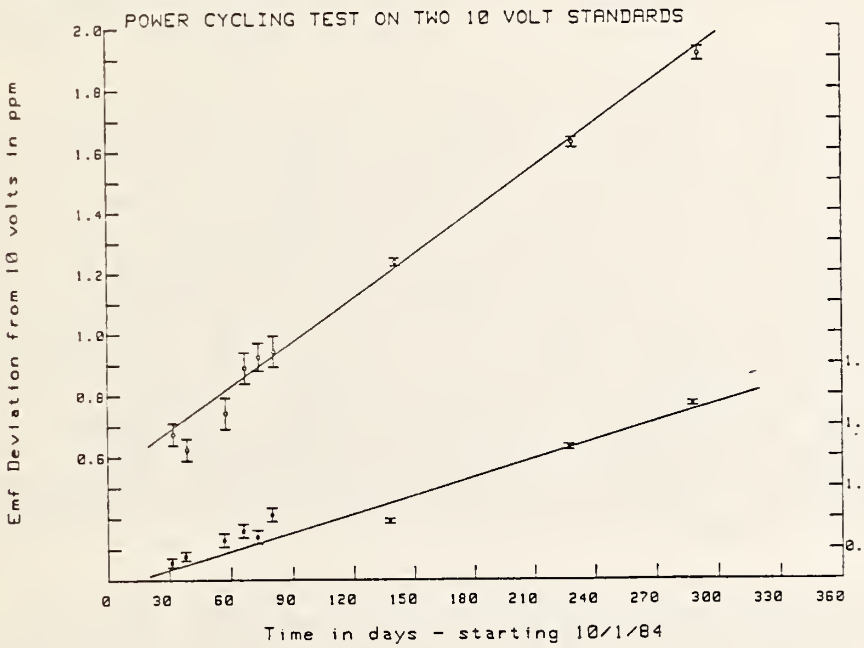

Fig. 1 Plot of the voltage of two solid-state standards. The standards were turned off between each of the points. Each plotted point is the mean of from 4 to 64 measurements. The error bars represent a 1 σ estimate of the random uncertainty of the plotted point.

A 10 V experimental MAP transfer to the Navy Primary Standards Laboratory in San Diego was completed. The two reproducible standards mentioned above were shipped off power to the laboratory in two separate experiments, one in April 1985 and the other in June. The NBS units were compared to two commercial Navy 10 V standards using a switch box constructed by NBS. The difference between the NBS volt and the Navy volt at 10 V as defined by their two standards was found to be 0.65 ppm and 0.84 ppm in April and June respectively. This is consistent with the drift of about 1 ppm/year observed in a number of other commercial units of the type used by the Navy as calibrated by NBS. The two NBS standards maintained good agreement for both transfers. The difference between the Navy volt and NBS volt determined from each of the two NBS standards agreed to within 0.02 ppm for the first transfer and 0.07 ppm for the second.

As a follow up to the Navy MAP transfer, a 10 V round-robin transfer involving all of the DoD primary standards laboratories has been started. The two NBS standards and one similar Army standard are being sent as a group to each of the DoD primary laboratories in turn, with NBS calibrations at the beginning and end of the transfer. The two NBS units are being shipped off power and the Army unit is being shipped under battery power. The experiment has been designed to determine the ability of each of the laboratories to make accurate 10 V measurements as well as to evaluate the transport characteristics of the Zener-based standards.

Precision component Zener diodes are continuously being evaluated for suitability to be incorporated in an NBS 10 V transport standard. A total of 200 devices have been obtained from five manufacturers and a station has been designed and built to permit the rapid testing of devices for temperature coefficient and sensitivity to temperature shock and power cycling. Computer programs to collect and analyze the data automatically have been written. Eleven devices have been tested to date for their dependence on current, temperature, and power cycling. Based on the data, a model has been developed which partially predicts their behavior. All necessary components (transformers, resistors, dividers, etc.) required for building several prototype 10 V transport standards have been ordered and it remains only to identify suitable references for incorporation before they can be built. Several commercial resistive dividers have also been ordered. They are intended to be used in conjunction with 10 V standards to produce 1.018 V as a possible replacement for standard cells as transport standards. Upon their arrival, they will be tested for stability and their sensitivity to temperature changes.

The fourth and fifth in a series of seminars on MAP's for electrical quantities were held in Seattle, Washington during the week of October 20, 1984 and in Williamsburg, Virginia, during the week of March 23, 1985. The forty attendees in each workshop participated in five days of lectures and workshops covering statistics, voltage metrology, quality-control techniques, and NBS MAP procedures. The instructors for the seminars were W. G. Eicke (now retired), M. C. Croarkin (CAM), D. Vecchia (CAM), N. B. Belecki, and A. O. McCoubrey (CBS), who also was responsible for logistics and administrative support.

Impedance

(G. M. Free, R. C. Fronk, G. R. Jones, Jr., L. Lee, C. R. Levy, S. B. Tillet, E. Zdral (PSC))

The automatic capacitance bridges being built following a design by R. D. Cutkosky are well underway. These bridges make three-terminal measurements comparing each of up to sixteen standard capacitors in the range from 12 pF to 1200 pF with an internal 10 pF fused-silica dielectric capacitor at selectable audio frequencies. They are intended as research tools and to replace the Division's Type 2 bridge, dating from the 1950's, used for the calibration of fused-silica and gas dielectric standards. The bridges are controlled internally by a model 8085 microprocessor and can be commanded from software in a desktop computer or calculator via the IEEE 488 Standard Instrumentation Interface. Good progress in the construction of four bridges was made under contract, and circuit boards and transformers for additional bridges were built by two summer Butler Community College students. Electronics modules that can be tested outside of a completed bridge were examined to ensure that they were in good working order and functional checks were made on transformers. The final assembly of the first bridge has begun and will be completed in early FY 86. Technical guidance and assistance is being provided by L. Lee who was instrumental in the development, construction, and testing of the original prototype bridge.

The new inductance bridge designed to replace the Maxwell-Wien bridge (circa 1955) currently used to calibrate standard inductors has been completed and is being calibrated. The ground circuit of the bridge has been redesigned so that all adjustments to parameters can be made using on-off switches to program DAC's (digital-to-analog-converter) so that eventual automation of the bridge will be relatively simple. A binary inductive voltage divider (IVD), whose design permits self-calibration (with the use of an external pair of matched capacitors), has been designed by N. M. Oldham of the Electrosystems Division and constructed for incorporation in this bridge circuit to facilitate automation of the balancing procedure. Initial comparisons of the binary divider with the three-winding, two-stage transformer used for inductive voltage divider calibrations indicate ratio errors as small or smaller than those commonly seen in commercial IVD's and quadrature errors an order of magnitude smaller.

A new calibration service for eddy-current conductivity standards was announced in the April 1985 issue of the SP 250 Appendix. Two sets have been calibrated to date and the actual operating procedures for making these calibrations a routine service are being worked out. The measurements required for issuing SRM 2408 (a pure copper eddy-current conductivity standard) were nearly completed by the end of FY 85.

An international comparison of eddy current conductivity standards was carried out with the National Physical Laboratory (NPL) of the U. K. ending in February 1985. At that time a set of NPL standards, hand-carried to NBS by A. E. Drake of NPL, was compared to a similar set using NBS apparatus. The NBS standards ranged from 29% to 61% IACS (International Annealed Copper Standard).

An investigation of the temperature-cycling properties of gas dielectric standard capacitors has been nearly finished. The results indicate that the instability problems with the capacitance MAP standard that led to the curtailment of the service were due to a combination of exposure of the standard to extremes of temperature and mechanical stress on the capacitors themselves. An experiment to determine the feasibility of using temperature controlled fused-silica capacitors at 10 pF and 100 pF for a MAP service at 1000 pF is nearly complete. At issue here is the capability of existing customer instrumentation to make the required ten-to-one ratio measurements with sufficient accuracy to be useful; the capacitors have been long known to be excellent transport standards. In the experiment, a commercial bridge of the type used by typical MAP customers is being used to calibrate 1000 pF NBS standards in terms of a pair of fused silica standards. The two standards are first used to establish an accurate 10/1 ratio and then the 100 pF standard is used to calibrate the 1000 pF units. A potential problem with the quadrature balance in the commercial bridge may force the use of auxillary balancing networks which NBS would have to supply for the transfer. Final results of the investigation are expected by the end of 1985.

DC Resistance
(R. F. Dziuba, P. A. Boynton, T. P. Moore, E. S. Nowicki)

An automated, self-balancing cryogenic current comparator resistance bridge was designed and constructed with the help of Joji Kinoshita, a guest worker from the Electro Technical Laboratory, the national electrical metrology laboratory of Japan. Preliminary resistance ratio measurements of 100 Ω/100 Ω, 10000 Ω/100 Ω, and 6453.2 Ω/100 Ω have been completed. The random uncertainty of the measurements is on the order of 0.02 ppm.

Two special resistance boxes were constructed in support of the NBS absolute ampere experiment (see Realization of the SI Ampere). These provide a highly accurate resistance ratio that will be used to determine the ratio of two currents in the experiment. The resistance boxes were calibrated against the NBS 1 Ω reference bank via a 100:1 Hamon standard.

Two special in-house resistance transfers were completed. One transfer involved the scaling down in resistance from the 1000-ohm transport standard used in the absolute ohm experiment (see Realization of the SI Farad and Ohm) to the NBS 1 Ω reference bank. The other transfer involved measuring a 6453.2 Ω transport standard used in the quantized Hall resistance experiment (see Quantized Hall Resistance) against the 1 Ω reference bank. Both methods utilized specially-built Hamon standards. The uncertainty was estimated to be 0.044 ppm, one standard deviation.

A new dc current-comparator potentiometer was modified and put into operation as the basis of the 100 Ω automated measurement system. This system is now operating on a routine basis for the calibration of customer's 100 Ω standards.

The high accuracy system used for the calibration of the best 10 kΩ standard resistors was relocated and improvements made in the system. A temperature lagging box was constructed to minimize the effects of temperature on air-type standard and control resistors. A connector panel was constructed to provide more ready connection of test resistors to the measurement circuit.

Major accomplishments in the project to automate the calibration of standard resistors in the range from 100 Ω to 1 MΩ included the modification of a guarded mercury stand to hold the resistors being calibrated, and the construction of a prototype circuit to determine the optimum detector system.

Overall Support for Calibration Services
(N. B. Belecki, R. C. Fronk, D. D. Prather, A. R. Wise)

A new Digital Equipment Corp. VAX 11/750 minicomputer, intended to replace the Division's aging Interdata 7/32 computers, was installed in mid-March. Software conversion was done rapidly and the VAX now supports resistance and impedance calibrations and the administrative functions associated with the calibration services. The Interdata on the first floor which previously provided this capability is now only used for ac-dc difference calibrations. The degree to which the VAX will be used to support dc voltage calibrations is not yet clear; the Hewlett-Packard microcomputer system used to control the measurements in the voltage laboratory may have sufficient capacity to handle data analyses and display without resorting to use of the VAX.

A complete revision of NBS Special Publication 250, Calibration and Related Measurement Services of the National Bureau of Standards, has been undertaken by the Office of Measurement Services. The descriptions of the services have been updated, reordered, and renumbered. The management information system used in the Division to monitor the calibration process has been modified to accomodate the new numbering system, which is expected to go into effect in April, 1986.

FUTURE PLANS

AC Current and Voltage

--Reduce the queue for calibration customers by at least fifty per cent.

--Establish measurement controls and procedures to enable DoD primary standards laboratories and those of instrumentation manufacturers to obtain reduced uncertainties for special tests of thermal voltage converters.

--With partial OA support, study the suitability of commercial instruments for use as transport standards for ac current and voltage measurements as a basis for providing improved support for industrial and DoD standards laboratories.

--Complete the study of new multirange solid-state converter systems, especially investigating the effects of stray impedance loading on the output.

--Make appropriate measurements to verify NBS measurement capability at frequencies above 100 kHz and voltages above 400 V, and adjust uncertainties appropriately (it is expected that uncertainties will be reduced in the former instance and increased somewhat in the latter.)

--Complete the documentation of the calibration services.

Direct (DC) Voltage

--Complete implementation of the new automated system for the calibration of standard cells, including software and operational systems.

--Continue software development in order to move data handling and calibration report production from the old Interdata minicomputer to the Hewlett-Packard data system and the VAX.

--Complete an analysis of the uncertainties of the measurements taken by the new automated systems for both the calibration and MAP services.

--Begin to upgrade the primary, secondary, and working groups of standard cells by replacing bad cells in a number of enclosures as soon as practical, consistent with maintaining laboratory operations.

--Begin to investigate the use of a Zener-based transport standard at the 1.018 V level as a replacement for the standard cell enclosures used for the Volt Transfer Program.

--Construct, test, and implement a second automated calibration system for solid-state voltage standards with outputs up to 10 V to facilitate development of improved standards.

--Complete the documentation of the standard cell and solid-state standards calibration and MAP services.

--Complete an evaluation of the measurement capability of the DoD primary laboratories at the 10 V level.

Impedance

--Complete the calibration of 100 copper eddy-current SRM's, No. 2408, 101% IACS, and deliver to the Office of Standard Reference Materials (OSRM).

--Calibrate and deliver to OSRM 100 titanium SRM's, one to two percent IACS.

--Complete the investigation of an alternate approach to the recently curtailed 1000 pF capacitance MAP, based on the use of 10 and 100 pF fused silica capacitors in order to improve the transfer of the farad to industry. The investigation will culminate in an interlaboratory transfer with one or more commercial concerns.

--Complete the construction of four automated capacitance bridges and begin their testing. A microcomputer to drive them via the IEEE 488 bus will be purchased and the calibration and testing software developed by Cutkosky will be used to perform the testing.

--Complete the necessary hardware and software, including optimized balancing algorithms and special logic for controlling the grounding circuits, for automating the new inductance bridge.

--Continue development work on binary inductive voltage dividers for automation of the main ratio balances for the new inductance bridge. Optimum core materials and winding schemes will be determined, a final divider constructed, and its input and output loading characteristics determined.

--Complete the documentation of all measurement systems in the impedance and eddy current conductivity area.

DC Resistance

--Complete the documentation of all eight resistance areas, including error analyses, descriptions of services, and references.

--Continue development work on Hamon devices and the cryogenic direct current comparator for scaling in the resistance area with the goals of determining the uncertainties associated with present scaling measurements, particularly those in support of the absolute ohm and quantized Hall effect projects, and improving these measurements to the greatest extent feasible.

Overall Support for Calibration Services

--Complete the conversion of the software used to support ac-dc difference calibrations to the VAX and retire the Interdata 7/32.

--Cooperate with the NCSL to find legitimate ways to ship standard cells. It was discovered late in FY 85 that standard cells can only be shipped legally if they are conspicuously labelled as containing a corrosive substance (mercury) and a Class B poison (mercurous sulphate). Industrial experience has shown that packages so labelled are routinely refused or delayed by the airlines and air freight companies, thus making shipment under power difficult or impossible. This has a deleterious effect on the NBS Volt Transfer Program, as well as on customers' standard cell calibrations.

--Explore the possibility of the use of Dataplot, an NBS statistics/graphics program written by J. J. Filliben in the Statistical Engineering Division, for general control charting as a quality control measure in the resistance and capacitance areas.

--Seek, test, and purchase a data-base management system to be used to store and analyze historical data on customers' standards in order to improve calibration reports and provide information on their long-term accuracy.

Estimated Calibration Workload -- FY 85

SP-250 #3.1 Resistance Measurements

662 Standard Resistors and Shunts
10 MAP Transfers

#3.2 Precision Apparatus

37 Inductive Voltage Dividers

#3.3 Impedance Measurements

173 Standard Inductors
260 Standard Capacitors
13 Eddy-current Conductivity Standards (2 sets)

#3.4 DC Voltage Measurements

140 Standard Cell Enclosures
(582 cells)
14 MAP Transfers
(24 companies)
30 Unsaturated Cells
32 Zener-diode Based Standards

#3.5 Electrical Instruments (AC-DC)

55 Standard Thermal Converter Instruments
(1241 points)

Estimated FY 85 Billing $750,000

JOSEPHSON VOLTAGE STANDARDS

(R. L. Steiner, R. F. Dziuba, B. F. Field, J. Toots)

Objectives

The objectives of this project are to maintain the NBS or U.S. Legal Volt via the ac Josephson effect in superconductors to an accuracy of a few parts per 100 million, and to improve the maintenance and dissemination of the unit of dc voltage for the U.S. through the development of voltage standards based on the ac Josephson effect.

More specifically, the objectives are to (i) periodically maintain the U.S. Legal Volt using the assigned value 2e/h = 483593.420 GHz/V_{NBS} for the Josephson frequency-voltage ratio. (ii) Construct, evaluate, and calibrate a new volt maintenance system based on the zero-crossing step Josephson junction array. This array operates at a microwave frequency of 70 - 95 GHz and generates voltage steps exceeding 1 volt, allowing a one-to-one ratio calibration of standard cells at an accuracy of a few parts in 10^9. (iii) Collaborate with the Electromagnetic Technology Division's Cryoelectronics Group, NEL-Boulder, Co. on the design, fabrication, and characterization of these voltage standard arrays. Also included in this collaboration is cooperation with the Physikalisch-Technische Bundesanstalt (PTB) in West Germany on the design and characterization of similar arrays. (iv) Upgrade the capabilities of the Electricity Division's thin film facilities to enable local fabrication of arrays and other high quality Josephson junctions for the existing Josephson junctions for the existing Josephson voltage standards. (v) Use the improved thin film facilities to investigate arrays made with NbN films. (vi) Finish supplying Josephson junctions and system hardware for the commercial 1 ppm voltage standard developed for the Calibration Coordination Group (CCG) of the DoD and the Korean Standards Research Institute (KSRI).

Current Activities

Objective (i) is presently the most critical. One calibration measurement per month of the primary standard cells is necessary to keep a close check on the drift rates of the cells. Maintenance and repair of the cryogenic and electronic components continues, along with new Josephson junction fabrication and testing, as necessary.

Objectives (ii) and (iii) are aimed at replacing this complex, 100:1 voltage ratio system at 8.5 GHz with a simpler, more accurate one based on the recently developed Josephson series array. Several operational array IC chips have been tested at NBS-Boulder and the appropriate microwave, cryogenic, and measurement equipment have been ordered for constructing and testing the new system. Collaboration with the Boulder Cryoelectronics Group and PTB is continuing, especially concerning fabrication processes, design, material composition, and characterization of these arrays.

The initial improvement of the Division's thin-film fabrication facilities [objective (iv)], has begun with repairs to the rf sputtering and electron beam evaporation machine, which has been returned to regular use after two idle years. The vacuum pumps are being repaired and the different deposition processes are being standardized and recorded. These activities also anticipate objective (v), the sputtering of NbN films for the arrays.

Work on the final objective (vi) is still continuing, with the testing and calibration of several Josephson junctions for the commercial voltage standards.

Accomplishments

In FY 85 there were eight comparisons of the Josephson voltage standard against NBS reference groups of Weston cells. The results of these measurements indicate that the mean of the standard cells of the primary reference group NBS-13 is drifting at the rate of -0.055 μV/month.

A new Josephson researcher (R. L. Steiner) arrived this year and worked at NBS-Boulder for two weeks in December 1984 and over the three month period in February-April 1985. While in Boulder, a comparison was made at one volt between an operational Nb/Nb_2O_5/Pb-alloy array and a calibrated Zener diode voltage reference source. The results showed an accuracy of 0.5 ppm, limited by the transport stability of the Zener source, and a precision of 2.5 parts in 10^8, limited by null detector drift. The array voltage was stable under test for tens of minutes, and the array had not changed characteristics over eight months and many thermal cycles.

The month of June 1985 was also spent at PTB participating in an experiment using Pb-alloy series arrays to demonstrate that the current dependence of the voltage steps is less than 7 parts in 10^{12}.

At both NBS-Boulder and PTB, much information was obtained from participation in the fabrication processes for both kinds of arrays, microwave circuit design, photo-lithographic mask preparation, and testing of the arrays. This information is essential for the Division's future Josephson junction and array fabrication objectives.

Objective (vi) has nearly reached completion with the successful testing and delivery of the KSRI commercial 1 ppm voltage reference. A Guest Worker from KSRI arrived in January 1985 for a three month stay to receive training in how to use the system and to assist in its calibration. Presently the electronics for the Navy Western Standards Laboratory system are operational, but are being kept to test junctions for this system and replacements for the other delivered systems.

Future Plans

Maintenance of the U.S. Legal Volt will continue, with construction, testing, and changeover to the one volt array system as the primary calibration standard at the earliest possible time. The accuracy of this new system should be a few parts in 10^9. Initially it will be compared against the present system for calibration at the few parts in 10^8 level.

Collaboration with Boulder and PTB will continue. The goals are the optimization of the array design with respect to low microwave power input and to step stability. NbN thin films used in the array could provide even better thermal cyclability, higher operating temperatures (e.g., with cryorefrigerator cooling), and generation of higher voltages.

The thin film facilities will be gradually upgraded to enable fabrication of arrays locally. Necessary for this is the cleanup and repair of existing vacuum systems, additional equipment for the complex photo-lithographic techniques associated with the series arrays and for NbN thin-film production, and the standardization of fabrication processes for both future and present junction requirements.

Concerning the commercial reference standards, several working junctions are nearly calibrated. Once replacements for the existing systems and a reserve supply of backup junctions are obtained, the WSL system can be delivered and objective (vi) completed.

REALIZATION OF THE SI AMPERE

(P. T. Olsen, W. D. Phillips, E. R. Williams,)

Objectives

The objective of this research is to measure directly the NBS as-maintained ampere in terms of the SI units of mass, length, and time to an accuracy of at least one or two parts in ten million, or nearly two orders of magnitude better than has ever been previously achieved. A realization of the SI ampere with a given uncertainty is equivalent to determining the Josephson frequency-voltage ratio 2e/h in SI units to essentially the same uncertainty.

While the accuracy (now about 5-10 ppm) of such measurements has not changed significantly since the turn of the century, a new technique promises dramatic improvement. This is particularly important because measurements of other fundamental constants now indicate serious inconsistencies between direct realizations of the ampere and indirect determinations based on other constants. A new measurement will help resolve these discrepancies, provide a solid contact between SI and as-maintained electrical units, and could even lead to artifact-independent definitions of the kilogram and mole.

Current Activities

Traditional absolute ampere experiments have measured the force between current-carrying coils whose dimensions were carefully determined. Dimensional uncertainties have been the major limitation in accuracy. The new approach avoids dimensional measurement by comparing the mechanical and electrical work done as one coil is moved in the field produced by another coil. The experiment is performed in two parts. First, we measure the voltage induced in one coil while it moves in the magnetic field of the other, current-carrying, coil. Second, we measure the force exerted on the movable coil by the other when both carry current and the movable coil traverses the same path as in the first part of the experiment. From the measured voltage and force, along with the current, times, and displacements involved, quantities equivalent to electrical and mechanical work are calculated and their comparison results in an absolute ampere determination. The difficult dimensional measurement is thus replaced with a straightforward displacement measurement.

Our plan for determining the NBS ampere in terms of the SI ampere has three phases. The first phase, completed in early FY 82, involved assembling and making measurements with a relatively small scale working model to evaluate the general method described above. It was surprisingly successful considering the primitive nature of the apparatus, yielding a statistical measurement uncertainty of about 2 ppm. The sytematic uncertainties were not seriously evaluated, however, because of the unfavorable Pellat balance (rotational) geometry used.

Phase II involves more sophisticated apparatus in a highly favorable linear geometry. Construction of this apparatus and its assembly and partial testing was completed in FY 83; evaluation of the complete system began in early FY 84. Figure 1 schematically represents the essential components.

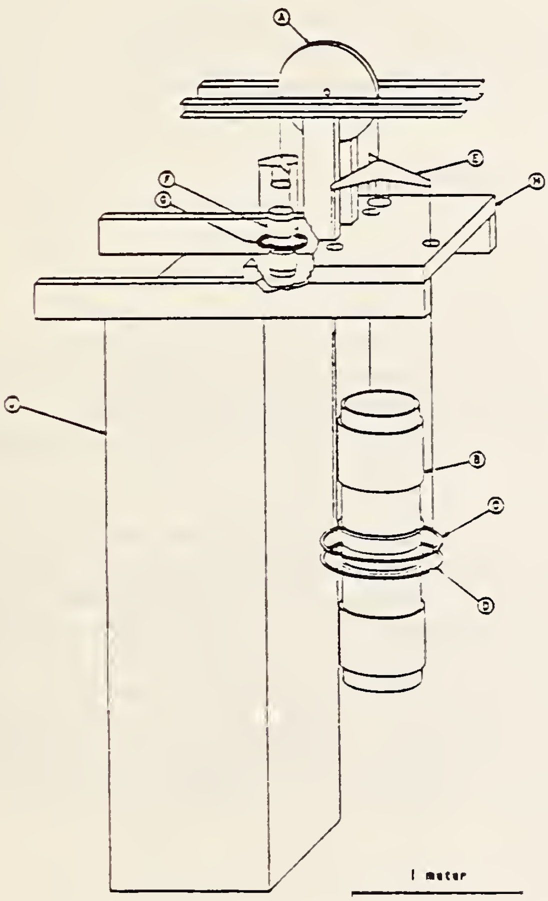

Fig. 1. A: Balance wheel; B: main magnetic field generating coil; C: movable coil; D: reference coil; E: balance support spider; F: servo magnetic field generating coil; G: servo movable coil; H: marble slab; J: stone pier.

The heart of the apparatus is the system comprising coils B and C, the fixed and moving coils respectively. Coils B , placed symetrically above and below C, provide the radial magnetic field in which C moves. The voltage induced in C and the force exerted on it are measured in the two parts of the experiment. The balance wheel A allows C to move vertically with negligible horizontal motion. This wheel, which pivots on a knife edge at its center, allows force determinations with a sensitivity equivalent to about 10 μg.

The reference coil D allows us to correct for changes in the field at C due to ambient field shifts or motion of the coils B. Coils F and G provide the force needed to move the balance and translate C during the voltage measurement phase of the experiment.

The displacement of coil C is measured interferometrically using a HeNe laser. Forces are measured in terms of calibrated masses and the measured local acceleration of gravity, while voltages and currents are measured in terms of the NBS standards of voltage and resistance.

Two versions of coil system B are available. During Phase II, we are using a room-temperature version which provides a force of 20 g on C and induces a voltage of 20 mV. In phase III, we will use superconducting coils which will provide a force equivalent to 1 kg and an induced voltage of 1 V.

Accomplishments

Ampere measurements made during the first half of FY 85 revealed several sources of error and noise as well as the fact that a significant measurement of the ampere can be made using the room temperature magnet. We have now corrected most of the noise and error sources. This was accomplished in part by improved electrical measurement and isolation and shielding of the instrument, which reduced pick-up from various sources and improved the noise performance of the experiment.

Other sources of error and noise were drift and noise in the balance zero, drift in the standard resistors, drifts and shifts in the current source used to establish standard voltages, and excessive noise in the voltage-velocity part of the measurement. The balance drift and a good deal of the balance noise during the weighing part of the experiment has been corrected by better thermal control of the balance enclosure. This helps to eliminate changes in temperature differences throughout the balance enclosure, which cause drifts mainly due to air bouyancy changes. Thermal control also helps to eliminate convection currents which cause force fluctuations. The effect of these can be further reduced by increasing the force to be measured. We are building a new suspended coil which can carry more current and thus increase this force by at least a factor of five.

Better thermal control of the resistor oil bath has also eliminated drift in those standards, while a redesign of the current source has virtually eliminated drift and shifts in the voltage references.

A particularly difficult source of error was related to the peculiar type of balance which we use and was the source of considerable noise in the velocity-voltage phase of the experiment.

Surface finish imperfections in the balance wheel and in the bands which roll off the wheel were responsible for the effect. Surface variations on the order of 0.3 micrometers produce a 1 ppm change in the balance arm length. Because of the large dead weight carried by the balance, this resulted in a large, fluctuating force when the balance wheel was moved.

When the balance wheel perimeter was polished and the solid brass band was replaced with a row of about 60 platinum-tungsten filaments, the noise in the velocity data was reduced by about a factor of fifty.

Our progress this year was considerably aided by an exchange of workers between our laboratory and the National Physical Laboratory of Great Britain. NPL is engaged in a conceptually similar, but physically quite different ampere experiment. P. T. Olsen of our laboratory spent a month at NPL, and B. P. Kibble of NPL later spent a month in our laboratory. The exchange of ideas about experimental technique and treatment of systematic error has been quite helpful to both efforts.

Future Plans

Originally, the absolute ampere apparatus was designed to be used with the superconducting magnet. The improvements which we have made to the room temperature version, however, indicate that with the new suspended coil to provide a larger force, and possibly a faster coil velocity to generate more voltage, we can achieve a significant measurement of the ampere, at the 1 ppm level or better, sooner than originally anticipated. Indeed, we expect to submit a value for 2e/h in SI units with an uncertainty of 1 ppm or less, as obtained with the room temperature version of the experiment, to the Consultative Committee on Electricity of the CIPM in time for its September 1986 meeting at which it plans to consider adopting a new value for 2e/h to be used by all national standardizing laboratories which use the Josephson effect to define and maintain their unit of voltage. Ultimately, and with little additional delay, the use of the superconducting magnet should allow a 0.2 ppm measurement or better.

REALIZATION OF THE SI VOLT
(F. K. Harris, L. H. Lee)

Objectives

The objective of this project is to realize the SI volt directly by force measurements in terms of the base SI mechanical units of length, mass, and time interval, and the assigned SI magnetic constant.

The present volt assignment is derived from absolute ohm and ampere determinations and is uncertain to the same extent as the latter (5 ppm or more). However, a direct volt determination should be free from some of the systematic errors of past ampere determinations. Furthermore, there is no conversion of electrical energy to heat, which may have affected dimensional results and balance operation in past ampere determinations. Thus it is hoped that a direct determination of the volt may reduce the uncertainty in its assigned value.

Current Activities

Our volt balance consists of a vertically aligned coaxial-cylinder electrode system with the low-voltage electrode in the annular space between an inner and outer high-voltage electrode, and suspended from the balance beam. The vertical electrical force on this suspended electrode is compared by substitution to the mechanical force produced by a known mass. The relation between electrical and mechanical forces,

$$E^2\frac{\partial C}{\partial z} = 2mg,$$

requires that capacitance be measured against vertical electrode displacement; and the high-voltage electrode system is mounted on a carriage which can be moved vertically on three guide rails, position being determined using a laser interferometer.

It has been shown that horizontal electrical forces which are present if the system is not truly symmetrical about a vertical axis may translate into a quasi-vertical force if the knife-edges of the balance beam are not in a horizontal plane. Thus it is extremely important that the electrode system be accurately symmetrical (within a few micrometers) about an axis that is vertical (within a few seconds of arc); the carriage movement of the high-voltage electrode system must also be vertical within the same constraint.

A mechanical disturbance to the central system can cause the suspended electrode to oscillate as a pendulum about its central position. When voltage is impressed on the electrometer, there is a lateral electrical force acting on the displaced suspended electrode tending to increase its displacement during pendulous motion. This is opposed by the centering force of gravity. If operational stability is to be retained, the value of impressed voltage is limited, but can be increased by lowering the center of gravity of the suspended electrode. At the present time our system is stable for a 1 g force, but not for voltages corresponding to 2-5 g forces which we would like also to employ. Francis Hermach recently suggested the possibility of axial stabilization of the suspended electrode by using the repulsive force between like poles of permanent magnet pairs, one magnet fixed to the upper rim of the suspended electrode, and its companion to the fixed shielding ring that surrounds the upper end of the electrode. If such a magnetic stabilization scheme can be realized, it will remove the need to lower the center of gravity of the suspended system for force measurements above the 1 g level. A model of the suspended electrode system is being constructed so that we may study the possibilities of magnetic stabilization.

Accomplishments

The grounding and shielding of the electrometer structure and the capacitance measuring bridge have been improved in order to reduce interference from external sources. Isolation has increased, but some intermittent disturbance of unknown origin is still present from time to time. Determinations of $\partial C/\partial z$ have been made using varying ∂z intervals. The results tend to confirm the need to lap the suspended electrode.

The model to permit the study of additional means to stabilize the suspended electrode has been built. It contains a duplicate of the electrometer electrode suspended from crossed knife-edges.

Future Plans

The suspended electrode will be removed and lapped in order to reduce the variations in $\partial C/\partial z$. The recently constructed model will be used to study possible mechanisms to provide additional restoring torque.

REALIZATION OF THE SI FARAD AND OHM
(J. Q. Shields, L. H. Lee, G. R. Jones, Jr.)

Objectives

The objectives of this project are to build, maintain, and operate equipment for calibrating the NBS standards of capacitance and resistance in terms of their SI definitions to an accuracy of 1 or 2 parts in 100 million, and to assure the compatibility of these standards with those of other countries.

Accurate realizations of the farad and ohm are required to assure the compatibility of instruments (via resistance, inductance, and capacitance calibrations) that are manufactured within the U.S. and for the determination of certain fundamental constants. The NBS absolute farad and ohm measurements make use of a calculable cross capacitor and a series of bridges for comparing capacitors and resistors. The result of the measurement sequence is an absolute calibration of the NBS reference standards of capacitance and resistance that is accurate to a few parts in 10^8. These measurements can also be considered as fundamental constant determinations, with applications to questions concerning the adequacy of quantum electrodynamic theory and to the determination of more exotic constants. For example, a reliable value of the ratio of the NBS ohm to the SI ohm is required in order to obtain a value for the fine-structure constant from a measurement of the proton gyromagnetic ratio and 2e/h as measured via the Josephson effect; and from a measurement of the quantized Hall resistance in a two dimensional electron gas. It is also necessary for the new NBS absolute ampere experiment.

Current Activities

The equipment was completed a number of years ago and is among the best in the world; a value for the NBS farad and ohm in terms of the SI farad and ohm accurate to a few parts in 10^8 was obtained in 1974. Work is presently concentrated on the preparation of this equipment for a new determination of the absolute farad and ohm with slightly improved accuracy. Other current activities include maintenance of the NBS unit of capacitance at the 10 pF level, and participation in international comparisons of capacitance and resistance standards.

Accomplishments

A comparison of the NBS bank of 10 pF capacitors with the NBS bank of 1 Ω resistors was completed in FY 85 with an estimated uncertainty of $\pm 5 \times 10^{-8}$ or 0.05 ppm. The basic steps in the comparison are as follows: (1) a 10:1 ac bridge is used in two stages to compare the NBS bank of 10 pF capacitors with a 100 pF capacitor which is in turn compared with two 1000 pF capacitors; (2) the 1000 pF capacitors are used as two arms of a special frequency-dependent bridge which measures the ac resistances of two 10^5 ohm resistors in terms of capacitance and frequency; (3) a 100:1 ac bridge is used to measure the ac resistance of a 1000 Ω transportable resistor in terms of the 10^5 Ω resistors; (4) the difference between the ac resistance and the dc resistance of the 1000 Ω transportable resistor is determined from ac and dc bridge comparisons with a special resistor designed to have a negligible ac-dc difference; and (5) the 1000 Ω transportable resistor is carried to the dc resistance laboratory where it is measured in terms of the NBS bank of 1 ohm resistors which comprise the NBS ohm using Hamon dividers and other dc techniques. In addition to the basic steps described, there are numerous calibrations and other measurements, some very time-consuming, which are required to assure the accuracy of the comparisons.

Results of the comparison show that the NBS unit of resistance has changed with respect to the NBS unit of capacitance by 0.48 ppm ± 0.05 ppm during the eleven year period between 1974 and 1985. If it is assumed that the NBS unit of capacitance has remained constant since 1974, then the NBS ohm has changed from Ω_{NBS} = 1 Ω - 0.82 μΩ in 1974 to Ω_{NBS} = 1 Ω - 1.30 μΩ in 1985. This is in good agreement with the results of recent international comparisons of capacitance and resistance, taking into account the additional uncertainties associated with international comparisons.

The primary vehicle for international capacitance comparisons continues to be a set of three 10 pF capacitors of NBS design and construction which have been circulating for many years among the major national laboratories. The capacitors were recently returned to NBS following measurements in East Germany, West Germany, England, France, and the Netherlands. They continue to exhibit excellent stability while being shipped via commercial carrier. They have just recently been sent to Australia.

Work on the computable cross capacitor itself is now underway. All of the critical mechanical dimensions have now been measured. The results show that no mechanical adjustments are necessary at the present time.

The cross capacitor's built-in Fabry-Perot interferometer with associated laser and other equipment is now producing fringes which appear very good to the human eye and are easily detected with a phototransistor. This is due in large part to the help provided by Dr. Howard P. Layer of the Length and Mass Division, CBS.

Future Plans

We intend to continue work on the computable cross capacitor with the expectation of obtaining an SI farad with an uncertainty of ±0.1 ppm or less by early 1986. A comparison of the NBS units of capacitance and resistance will then be repeated while keeping the cross capacitor in operation. This should hopefully yield an SI ohm by the middle of 1986. Subsequent work will concentrate on reducing the uncertainties in the measurements. A comparison of the NBS unit of capacitance with that of the Netherlands using the three 10 pF travelling standards is also planned.

QUANTIZED HALL RESISTANCE

(M. E. Cage, C. T. Van Degrift, R. F. Dziuba, B. F. Field, T. E. Kiess, W. J. Bowers)

Objectives

To develop techniques used to observe the quantum Hall effect in semiconductors to the point where it can be used (1) to determine the fine-structure constant α with the unprecedented accuracy of a few parts in 100 million, thereby allowing the unequivocal testing of quantum electrodynamic (QED) theory; and (2) to establish a reproducible resistance standard of the same accuracy.

The quantum Hall effect has the potential of providing the most accurate QED-independent value of the fine-structure constant as well as an SI or absolute resistance standard based on fundamental constants of nature rather than the present resistance artifacts. It would thus permit definitive tests of QED as well as allow NBS to maintain the U.S. unit of resistance continually to very high accuracy in SI units, rather than at multi-year intervals via the very difficult calculable cross-capacitor experiment.

Current Activities

The method for achieving these goals involves measurements of the Hall resistance, R_H, of metal-oxide-semiconductor field effect transistors (MOSFETs) and of GaAs-AlGaAs heterojunctions at liquid helium temperatures in large magnetic fields. The Hall resistance $R_H(i)$ [the ratio between the Hall voltage $V_H(i)$ and sample current I] is given by

$$R_H = \frac{V_H(i)}{I} = \frac{\mu_o c}{2\alpha i} \cong \frac{25,812.8}{i}\ \Omega \qquad (1)$$

where μ_o is the permeability of vacuum (defined to be $4\pi \times 10^{-7}$ H/m), c is the speed of light in vacuum, and i is an exact quantum integer.

Currently we are: (1) performing quantum Hall effect experiments on GaAs heterojunction samples using an 8 T magnet installed in a shielded room at NBS; (2) using the quantum Hall effect to monitor the national unit of resistance; (3) constructing a new laboratory which will allow us to continue maintaining the national unit of resistance in one magnet system while enabling us to expand our basic research using a second system capable of attaining magnetic fields of 15 T and temperatures down to 30 mK.

Accomplishments

The United States unit of resistance is now being unofficially maintained via the quantized Hall resistance R_H.

In order to use the quantum Hall effect to maintain the national resistance standard (the "NBS Ohm" or "U.S. Legal Ohm"), four operations must be performed. First, each device is thoroughly studied for magnetic field, temperature, and current dependence. Second, the 6453.2 ohm quantum Hall resistance [Eq. (1) with i=4] is transferred to a room temperature resistor of nearly the same value. Third, a Hamon series/parallel resistance network is used to transfer that value to a 100 ohm standard. Finally, another Hamon device is used to complete the transfer to the set of five NBS one-ohm resistors which comprise the NBS ohm.

Figure 1 (see next page) displays the latest results of these relative comparisons between the quantum Hall resistance $R_H(4)$ and the resistance of a 6453.2 ohm wire-wound reference resistor. These measurements have typical one standard deviation total uncertainties of ± 0.02 ppm. The figure also shows that the value of this resistor is increasing at a rate of (0.052 ± 0.005) ppm/year relative to the quantum Hall resistance. This increase occurs even though the resistor is hermetically sealed, is continuously temperature-controlled to within ± 0.002 celsius, and has not been moved.

A second 6453.2 ohm reference resistor was also calibrated in terms of $R_H(4)$ and then hand-carried to a basement laboratory and calibrated in terms of the set of five one-ohm resistors which comprise the NBS ohm (operations 3 and 4, above). The uncertainty of this transfer is estimated to be ± 0.044 ppm -- giving a total one standard deviation uncertainty of ± 0.05 ppm for the step-down from the quantized Hall resistance to the NBS ohm. Figure 2 (see next page) shows this result. These data provide the first direct evidence that the national unit of resistance is drifting; its value is apparently decreasing at the rate of (0.052 ± 0.021) ppm/year. The uncertainty in this drift rate is quite large, but should be further reduced as a result of our continued measurements using the quantum Hall effect.

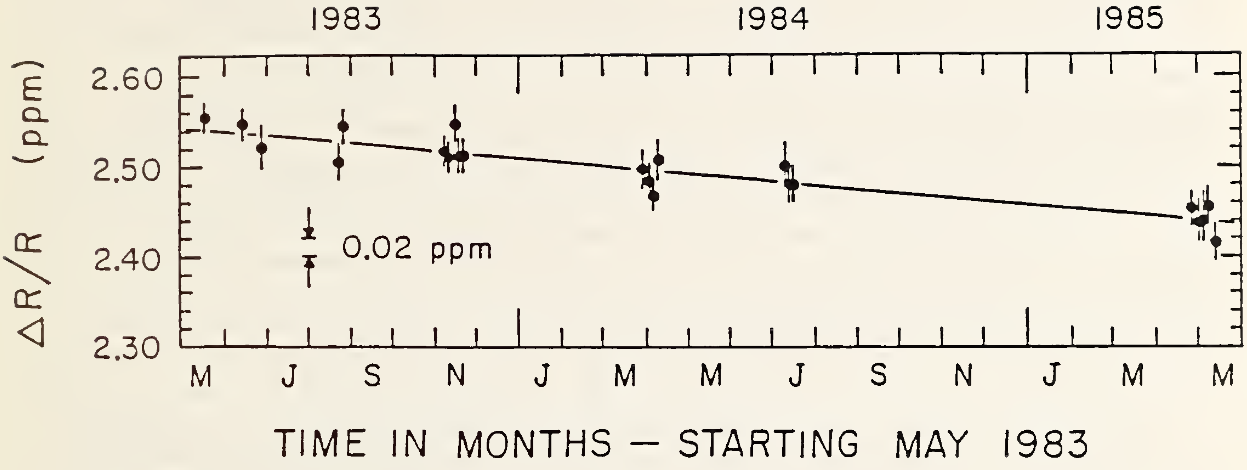

Fig. 1. Relative comparisons as a function of time of the quantum Hall resistance with a room temperature reference resistor of 6,453.2 ohm nominal value. $\Delta R/R = (R_H - R_R)/R_R$.

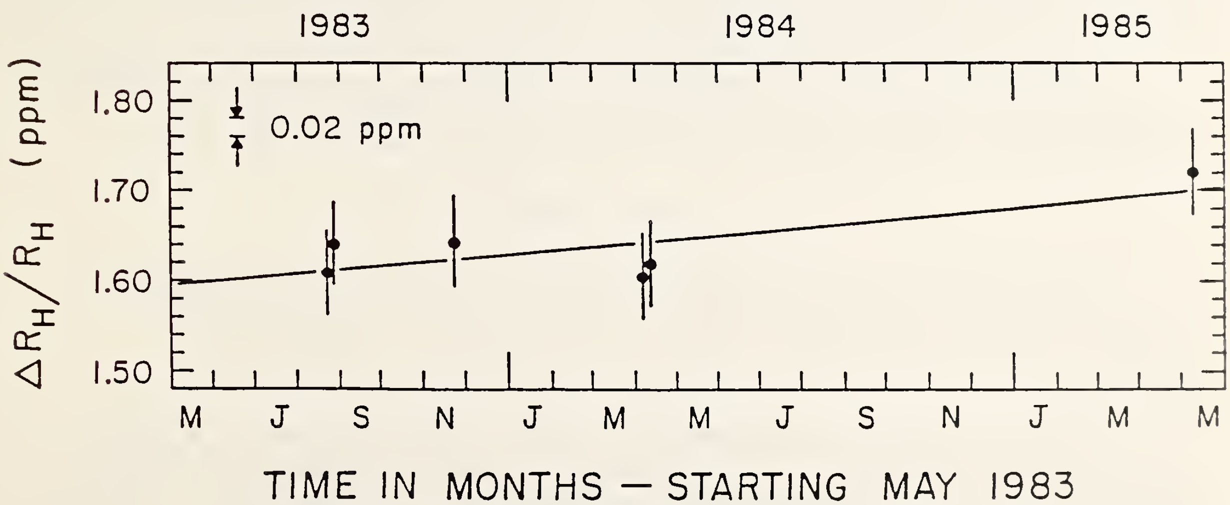

Fig. 2. Monitoring as a function of time the value of R_H expressed as a difference in ppm from a nominal value of 6,453.2 ohm NBS.

Much effort was expended this past year on performing extensive testing of the manual and automated resistance measurement systems. The manual system utilizes a potentiometric comparison between the quantum Hall voltage and that developed across a room temperature four-terminal reference resistor, whereas the fully-automated system is a modified Wheatstone bridge. Most of the work was devoted to calibrating the amplification factors (the gains) of the low-level dc detectors used in both systems. In order to achieve an uncertainty contribution of less than 0.01 ppm in the resistance comparisons, the detector gains must be calibrated to better than 0.1%. With considerable difficulty, we were ultimately able to calibrate each detector sufficiently well that, for one hour of measurement, the manual system had a precision of 0.01 ppm and an accuracy of 0.02 ppm while the automatic system had a precision of 0.007 ppm and an accuracy of 0.02 ppm.

During the past year R. F. Dziuba and Guest Scientist J. Kinoshita from the Electro-Technical Laboratory (ETL), Tsukuba, Japan, designed and assembled a cryogenic current comparator bridge to improve the resistance scaling accuracy between resistance values of 6453.2 and 100 ohms, and between 100 and 1 ohm. Two comparators of different design have been constructed with sufficient redundancy of discrete ratios to provide confidence in the scaling process. A superconducting quantum interference device (SQUID) is used to detect the bridge balance. Initial testing of this bridge at the sub-ppm level, which is currently underway, indicates that the basic design is sound. We expect that work during the next year will refine this bridge to the point where we will be able to use it to reduce the resistance scaling uncertainty by a factor of two to about 0.02 ppm. (See also the DC Resistance portion of the Dissemination Services project description.)

Much effort was also expended this past year on designing a new quantum Hall effect research laboratory and initiating its construction. It is described in some detail under Future Plans.

Future Plans

The new quantum Hall effect research laboratory will allow us to expand the scope of the NBS QHE research effort to higher magnetic fields, lower temperatures, and higher accuracy in temperature measurement.

Accurate temperature measurement of a sample located in a high magnetic field can only be made by placing the thermometer outside of the field and by providing a good thermal like to the sample. This requires a considerable vertical extent for the apparatus. In addition, the attainment of temperatures well below 1 K requires a dilution refrigerator and still more vertical height. The new laboratory will be located in a 13-foot-high basement room with a

14-foot-deep work area cut into the floor to accommodate a new 15 T, persistent-current superconducting magnet. This will allow ample room for a dilution refrigerator capable of cooling the samples to 30 mK and having the means to measure the sample temperature within 0.5 mK of true thermodynamic temperature.

An important feature of this system will be a vacuum interlock arrangement which will permit the samples to be easily changed without warming the magnet or dilution refrigerator. Because of the ease with which we will be able to change samples, we will be able to study a large number of devices prepared by different laboratories using different semiconductor compositions and different geometries.

In addition to this 15 T system, we will also operate in the same laboratory the present 8 T magnet system. This will allow us to dedicate the 8 T magnet system to the monitoring of the National unit of resistance while permitting complete freedom in the use of the 15 T research system. Furthermore, we will be able to simultaneously compare the quantized Hall resistances of different devices to within 0.02 ppm even though their steps might occur at different magnetic fields.

The new laboratory is expected to be in operation by the spring of 1986. The initial experiments planned include a precision measurement of $R_H(2)$ at 12906.4 Ω in GaAs heterostructures and a comparison of $R_H(4)$ as optained from Si MOSFETs and GaAs heterosturctures. We also expect to submit a value for R_H in SI units with an uncertainty of 0.1 ppm or less to the Consultative Committee on Electricity of the CIPM in time for its September 1986 meeting at which it plans to consider adopting a universal value for R_H to be used by all national standardizing laboratories to define and maintain their unit of resistance.

GAMMA-P AND THE FINE-STRUCTURE CONSTANT

(E. R. Williams, G. R. Jones, Jr., P. T. Olsen, W. D. Phillips)

Objectives

To carry out an improved determination of the gyromagnetic ratio of the proton in H_2O, γ_p', to an accuracy of a few parts in 100 million, thereby obtaining a value of the fine structure constant α to an accuracy of 0.02 - 0.03 ppm. This will extend the precision with which quantum electrodynamics (QED), the Josephson effect, and the quantum Hall effect, can be tested. It will also provide an alternate means for monitoring and maintaining the NBS units of voltage and current.

The present approach to redetermining α is based on improving the inductive dimensional measurement method developed in our laboratory for determining the pitch and diameter variations of a precision solenoid and used to carry out a 0.2 ppm determination of γ_p' reported in 1979. The NPL in England and the VNIIM in the USSR have reported values of γ_p' that are in complete disagreement with our 1979 result (10-15 standard deviation discrepancies). The Chinese value obtained at NIM, Beijing, agrees with our value. We expect a new determination of γ_p' will resolve this major disagreement.

Current Activities

The gyromagnetic ratio of the proton is defined as the ratio of the angular precession frequency ω_p', of a proton in a magnetic field B to the magnitude of the field, $\gamma_p' = \omega_p'/B$ (the prime indicates the proton is in a spherical, pure, H_2O sample at 25 °C). The precession frequency is measured by standard nuclear magnetic resonance methods. The magnetic field is calculated from the measured physical dimensions of a single-layer solenoid, wound on a precision-ground quartz form, with a known (in terms of NBS standards) electric current in the turns of wire. The location of each turn of the solenoid is found by an inductive pick-up probe and a laser interferometer which locates the position of the probe. We are constructing a new solenoid and measuring apparatus that will reduce the sources of error in the previous experiment. This new experiment will have the following improvements: (i) a reduced sensitivity to the diameter of the solenoid; (ii) improved axial symmetry of the inductive pick-up probe; (iii) an improved straightedge used to guide the probe; (iv) an improved laser measuring system that will allow measurement of all six degrees of freedom; (v) increased S/N ratio for the NMR signal; (vi) improved temperature control; (vii) improved calibrations for the length and electrical standards; and (viii) capability for a direct measurement of all susceptibility corrections. These advances should produce nearly an order of magnitude improvement in our previous determination. The quantum Hall effect, which provides an independent value of α, provides additional incentive for completing the γ_p' measurement in the near future.

Accomplishments

This past year began with a great deal of turmoil. One night while the solenoid was being measured the refrigerator used to cool the solenoid cooling fluid failed and the temperature of the fluid rose to 40 °C. The copper windings on the solenoid expanded and went slack. Upon cooling the distribution of tension in the wire was no longer uniform and several turns remained slack. Rewinding the solenoid was the only solution. The entire system was therefore disassembled and the solenoid taken to the shop. The wire tension was increased so that the temperature at which the solenoid goes slack is now much higher. This extra tension squeezed the solenoid form and made it 3 ppm longer. Safety circuits have been installed and a new chiller system is being installed to prevent a similar accident.

One positive result has come from the rewinding. A few gold flakes from the gold-plated wire formerly circulated in the cooling fluid and occassionally short-circuited a winding. We carefully washed the wire and the solenoid while rewinding it and painted between the turns with shellac to make shorts less likely. We have not had a shorted turn since rewinding.

Computer failures have also plagued the experiment this year. We have had four failures each requiring a delay while factory repairs were made. A backup for one unit that failed three times has been ordered to reduce further delays.

In spite of these difficulties, we have improved the dimensional measurements and tested for most systematics. Most of the improvements have been in the control program and related servo systems. We also reduced a major noise source when we mechanically constrained the straightedge so that it moves ten times less when the probe is pushed along the solenoid axis. A lower-noise amplifier improved the diameter variation data. There still exists one unexplained shift of 0.5 ppm in the apparent length of the solenoid between February and July. Some further tests will be required to sort this out.

In evaluating potential systematic errors, we measured the magnetic susceptibility of the soil in the vicinity of the nonmagnetic building and were surprised at how large it was. Because of the unexpectedly high iron content of the soil, the susceptibility is between 3×10^{-3} and 10^{-2}. A susceptibility this large implies a systematic shift of the measured value of γ_p' of about 0.1 ppm. We have developed a new method to measure susceptibility using an inductive technique similar to that used for measuring the solenoid dimensions which we will use to evaluate this correction directly.

Future Plans

Our goal for this year is very straightforward: We want to have a publishable value for γ_p by the time of the Conference on Precision Electromagnetic Measurements (CPEM 86) to be held at NBS in June 1986. This result will be very important in determining the absolute or SI value of the NBS ohm and thereby the value in SI units of the quantized Hall resistance R_H which will be used to define and maintain laboratory units of resistance throughout the world. The Consultative Committee on Electricity (CCE) of the CIPM will be meeting in September 1986 to adopt a specific value for R_H and we are in a very competitive position to influence this value. We expect to have a value of γ_p' with an accuracy of about 0.1 ppm, which will lead to values of R_H and alpha accurate to 0.04 ppm.

LASER COOLING AND TRAPPING OF NEUTRAL ATOMS
(W. D. Phillips, A. L. Migdall, H. J. Metcalf (GW))

Objectives

The fundamental objectives of this project are to decelerate and cool a neutral atomic beam, and to confine and further cool neutral atoms in electromagnetic traps.

The motivation for this work is that cooling and trapping provide solutions to the problems of 2nd order Doppler effect, residual 1st order Doppler, transit time, and other motional effects which limit the performance of ultra-high resolution spectroscopy. This work is complementary to the trapped/ion cooling ion work in the Time and Frequency Division. Both projects are directed to improved spectroscopic resolution, but neutral atoms present different opportunities, such as studies of atoms in electric fields. These could test theories of the Stark effect or provide a new determination of the fine-structure constant from Stark splittings. Spectroscopy of very cold neutral atoms also has possible applications to frequency standards, fundamental constants, and fundamental physics such as electric dipole moment searches. Dense, cold, trapped neutral atoms offer the possibility of studying quantum collective effects such as Bose-Einstein condensation. Slow, cold atomic beams could be used in collision experiments or in sensitive deflection experiments to test statistics of photon absorption or charge neutrality of matter.

Current Activities

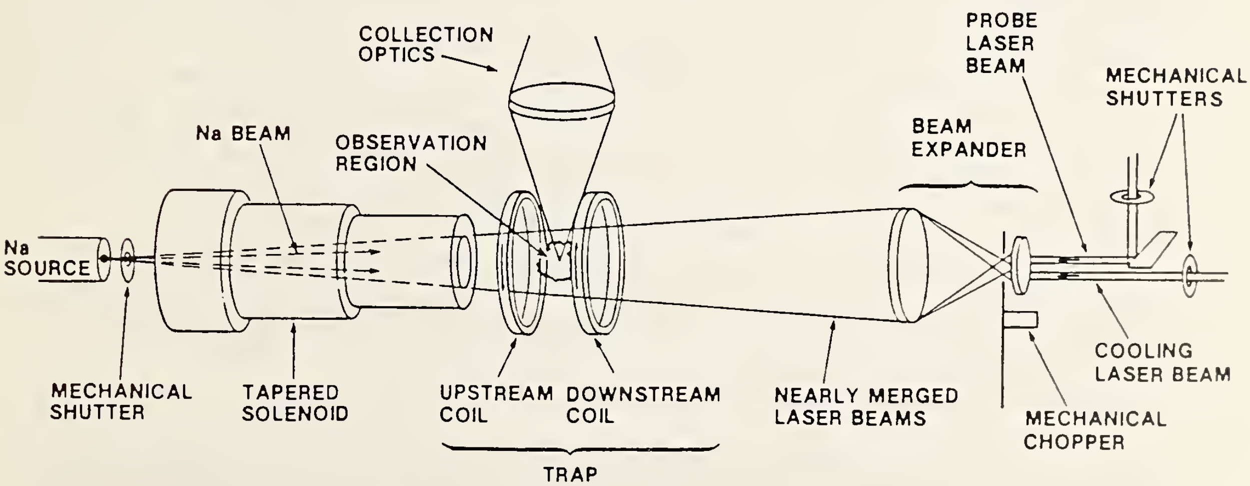

Figure 1 shows the apparatus used for laser cooling and magnetic trapping of neutral atoms. Sodium atoms from the oven are collimated to form a beam which travels along the axis of a varying-field solenoid. The atomic beam is opposed by a laser beam which is resonantly tuned to the yellow optical transition in sodium. As the atoms absorb and re-radiate the laser photons, the resulting momentum transfer slows the atoms down. The changing Doppler shift of the decelerating atoms would soon take them out of resonance with the laser were it not for the varying-field solenoid which provides a compensating changing Zeeman shift. This Zeeman compensation of the Doppler shift allows a continuous atomic beam with a thermal spread of velocities to be brought to rest near the exit end of the solenoid.

Accomplishments

During the past year we have succeeded in demonstrating for the first time electromagnetic trapping of neutral atoms. The trap is a magnetic quadrupole and takes advantage of the force exerted by an inhomogeneous magnetic field on the magnetic dipole moment of the sodium atom. Trapping is accomplished as follows: Once an equilibrium situation is established, with the atomic beam stopped near the end of the solenoid, the laser is abruptly shut off. Now all the atomic velocities are frozen, and atoms which have not yet come to rest (those closer to the oven than the stopped atoms) proceed out of the solenoid and into the trapping region. After an appropriate delay, atoms of a specific velocity (typically 100 m/s) are in the center of the trap region. Here, the laser is pulsed on briefly, bringing the atoms to rest. With the atoms at rest, the opposing coils of the quadrupole trap are energized with electric current and the atoms are trapped.

We have achieved central densities of trapped atoms greater than $10^3/cm^3$ in a trap whose total volume is 20 cm^3. The density decays with a time constant of about 0.8 s, a rate which is determined mainly by scattering of trapped atoms by background gas atoms. The maximum energy of the trapped atoms is 17 mK, corresponding to a velocity of about 3 m/s.

Future Plans

During the coming year we intend to improve the vacuum in the trapping region so as to increase the trapping time. Ultimately the trapping time should be limited by Majorana transitions which can change the orientation of the magnetic moments so atoms will be expelled from the trap. Trapping times as long as a thousand seconds may be possible. With longer trapping times it should be possible to further reduce the energy of the trapped atoms by various cooling techniques and to increase the density by repeated or continuous loading of atoms into the trap.

The procedure we have developed for stopping atoms should also allow us to load atoms into laser traps. Here, atoms are confined by virtue of dipole or radiation pressure forces from near-resonant light beams. We are also investigating the possibility of concentrating slow atoms in a gas cell by three dimensional laser cooling of the gas.

FUNDAMENTAL CONSTANTS DATA CENTER
(B. N. Taylor)

Objectives

The principal objectives of this project are to provide an international information center within the U.S. for work in the general area of precision measurement and fundamental constants, to analyze the consistency of measured values of the fundamental constants that are obtained from different experiments, and to obtain sets of recommended values of these constants for international use.

The close relationships that exist between the fundamental constants and precision measurements, basic measurement units such as the ampere, volt, and ohm, fundamental physics, and state-of-the-art measurement technology, makes the subject a natural one for NBS involvement. One of the purposes of this project is to provide assistance and guidance in the general area of precision measurement and fundamental constants to both NBS staff and university scientists, in particular, to advise them on the potential impact of the various experiments they are considering carrying out and to keep them informed of related work currently underway in various laboratories throughout the world.

Self-consistent sets of "best values" of the fundamental constants, obtained by means of least-squares adjustments, are required for a variety of purposes in science and technology, for example, in accurate calculations of the energy levels of atoms that are of importance in nuclear fusion, or for critical comparison of theoretical calculations with experiment. Furthermore, as the basic invariants of nature, they can be expected to form the basis of a system of reproducible, artifact-independent measurement units. Such a system is the ultimate long-range goal of metrology.

Current Activites

Current activities in the precision measurement-fundamental constants (PMFC) field include (1) keeping apprised of and maintaining a complete reprint collection of the latest accomplishments throughout the world in PMFC; (2) carrying out new least-squares adjustments of the fundamental constants to obtain sets of recommended values; (3) participating in the work of national and international groups (for example, the CODATA Task Group on Fundamental Constants and the NAS/NRC Advisory Committee on Fundamental Constants); (4) publishing the quarterly "Preprints on Precision Measurement and Fundamental Constants" (PPMFC) for the Office of Standard Reference Data (this publication lists preprints as well as reprints of PMFC papers); (5) attending and organizing national and international conferences on PMFC, visiting laboratories carrying out work in this field, and giving talks and preparing papers on the present status of the fundamental constants; and (6) answering inquiries from both within and without NBS relating to the PMFC field.

Accomplishments

The four issues of PPMFC were published on schedule and the maintenance of the data Center's extensive PMFC file was continued.

In collaboration with W. D. Phillips of the Electricity Division, oversight of the Proceedings of the Second International Conference on Precision Measurement and Fundamental Constants (PMFC-II) was continued. The volume appeared in November 1984 and has been viewed as a significant contribution to the PMFC field.

Work was begun to ensure that PMFC papers would be strongly represented at the forthcoming 1986 Conference on Precision Electromagnetic Measurements to be held 23-27 June 1986 at NBS.

As part of the effort to complete the 1985 Least Squares Adjustment of the Fundamental Constants (LSAFC 85) being carried under the guidance of the CODATA Task Group on Fundamental Constants and in collaboration with its chairman, E. R. Cohen of Rockwell International, three relevant papers were prepared and published. Of special interest is "New Results From Previously Reported NBS Fundamental Constants Determinations," J. Res. Natl. Bur. Stand. 90, 91 (1985). This paper reports a new treatment of the previously reported results of three electric-unit-dependent fundamental constant experiments carried out at NBS over the last decade or so which yields accurate, indirect values in SI units for a number of important quantities. These include the fine-structure constant α, the Avogadro constant N_A, the Josephson frequency-voltage ratio $2e/h$, and the quantized Hall resistance $R_H \equiv h/e^2$.

It should be noted that originally, LSAFC 85 was to be completed in 1984 and to be known as the 1983 Least-Squares Adjustment of the Fundamental Constants (LSAFC 83). It was to include all the relevant data available through 31 December 1983. However, because of delays in finishing LSAFC 83 by the end of 1984 which was the original goal and the completion of new, relevant work during 1984, it was decided to extend the cut-off date for new results to early 1985 and to call the new adjustment LSAFC 85. Work aimed at finishing LSAFC 85 by the end of 1985 is currently underway.

Future Plans

There are three major goals for FY 85: (1) Complete the data analysis portion of LSAFC 85, prepare a summary in draft form suitable for publication as a CODATA Bulletin, circulate it to the CODATA Task Group on Fundamental Constants, incorporate their comments as appropriate into a final version, and submit it for publication to CODATA by the end of December 1985. (2) Review and analyze all the available data relevant to the Consultative Committee on Electricity (CCE) September 1986 meeting at which the CCE hopes to adopt (a) a new value, consistent with the SI, for the Josephson frequency-voltage ratio 2e/h to be used by every national standards laboratory which employs the Josephson effect to define and maintain its laboratory unit of voltage, and (b) a value of the quantized Hall resistance R_H, consistent with the SI, to be used by every national standards laboratory which employs the quantum Hall effect to define and maintain its laboratory unit of resistance. (3) On the basis of the review and analysis of (2), actively participate in the meeting.

PRECISION MEASUREMENT GRANTS
(NBS Precision Measurement Grants Committee; B. N. Taylor, Chairman)

Objectives

The annual objectives are to award two new Precision Measurement Grants of $30 k (renewable for two additional years at the option of NBS), and to renew four existing grants. The grants are awarded to scientists in academic institutions in order to (i) promote and encourage fundamental research in the field of measurement science in colleges and universities and train future measurement-oriented scientists, and (ii) foster contacts between NBS scientists and those researchers in the academic community who are actively engaged in such work.

The importance of research in the precision measurement-fundamental constants field has been covered in the project report entitled FUNDAMENTAL CONSTANTS DATA CENTER. While NBS has a strong interest in this area and much experimental work underway, it cannot do it all - there is much expertise and relevant work in the colleges and universities. It is the purpose of this project to tap this reservoir and to foster the training of students who might eventually become NBS staff by awarding grants to a selected number of outstandingly qualified, academic researchers. Only those individuals working in areas of immediate or potential future benefit to ongoing NBS programs are chosen to receive awards. Thus, the work carried out by the grant recipients serves to compliment the efforts of the Bureau's own staff in closely related areas. Selection is based primarily upon the originality of the work proposed as described in formally submitted proposals.

Current Activities

The research supported under the PMG program includes experimental and theoretical studies of fundamental physical phenomena which may lead to improved or new measurement methods and standards; the determination of important fundamental physical constants; and general research and development on basic measurement techniques and instrumentation. To simplify the selection process, candidates are first requested to submit a biographical sketch and preproposal summary outlining the objective of their proposed research, why they believe it to be important, and the general approach to be used, including some indication of what they expect to accomplish in the three year time period covered by the grant. On the basis of this material, four to eight candidates are selected by the NBS Precision Measurement Grants Committee (consisting of four senior NBS staff) and the Outside Advisory Committee (consisting of four senior university professors) to submit more detailed proposals. The same committees evaluate these, and on the basis of this evaluation, the recipients are finally selected. The criteria used in evaluating the preproposals and full proposals include the importance of the proposed research to science, the feasibility of the research, and the past accomplishments of the applicant.

Accomplishments

The procedures outlined above for selecting candidates, which were first instituted in FY 77, were again used successfully in FY 85. Proposals were openly solicited via an advertisement in Physics Today, announcements in appropriate trade journals and newsletters, and the mailing of a brochure to the physics departments of all of the colleges and universities in the U.S. which grant bachelor's degrees in physics (about 850). Excellent proposals were received from 29 candidates, five of whom were chosen to submit final, full proposals. The following are the two recipients selected, their institutions, and project titles:

Gerald Gabrielse, University of Washington
Injection of Protons, Antiprotons, and Heavy Ions into a Penning Trap for Precision Mass Measurements

Larry R. Hunter, Amherst College
A New Method to Search for the Electric Dipole Moment of the Electron

The aim of Gabrielse's research is to develop techniques to handle, cool, and indefinitely store antiprotons in thermal equilibrium at 4 K in a Penning trap in order to test the CPT theorem (charge conjugation, parity and time reversal transformations) by comparing the mass of the antiproton and proton to one part in 10^9, an improvement of 10^4. The same techniques will be applied to heavy ions as a step towards high precision heavy-ion mass spectroscopy in a Penning trap. The aim of Hunter's research is to put an upper limit on the electric dipole moment (edm) of the electron which is 1000 times smaller than the current limit, thereby testing time reversal invariance (the T transformation in CPT) and certain classes of gauge theories. The basic principle of the experiment is to spin polarize the ground state of the cesium atom and to search for a precession of that polarization in an applied electric field. A limit on the edm of the cesium atom results in a limit on the electron's edm approximately 100 times smaller.

For FY 85, the NBS Precision Measurement Grants Committee consisted of Drs. Deslattes, Hall, Taylor, and Wineland; the Outside Advisory Committee of Professors Metcalf, Ritter, Robinson, and Williams.

The following grants were renewed in FY 85: C. M. Caves, California Institute of Technology, Quantum-Mechanical Analysis of High-Precision Measurements on Harmonic Oscillators; W. N. Hardy and A. J. Berlinsky, U. British Columbia, Development of a Cryogenic Hydrogen

Maser; T. E. Chupp, Harvard U., A Test of Local Lorentz Invariance Using Polarized ^{21}Ne Nuclei; M. J. Levine, Carnegie-Mellon U., Precision Calculation of the Anomalous Magnetic Moment of the Electron Using a Specialized Computational Engine.

Future Plans

FY 86 plans naturally focus on renewing the four eligible current grants and awarding two new grants. Current and past recipients will be invited to visit NBS and to present talks as appropriate, and visits to current and past recipients will be made by NBS staff in conjunction with other travel.

Electricity Division Sponsored Seminars/Workshops

A Seminar on Electrical Measurement Assurance Programs, held October 20-24 1984, Marriot Sea-Tac Motel, Seattle, WA.

A Seminar on Electrical Measurement Assurance Programs, held March 25-29, 1985, Holiday Inn 1776, Williamsburg, VA.

Invited Talks

N. B. Belecki, "Automated Voltage Converter Calibrations at NBS," Precision Measurements Association San Diego Chapter, San Diego, CA, January 1985.

N. B. Belecki, Chairman of "Ask the Experts - NBS," session at the 1985 Measurement Science Conference, Santa Clara, CA, January 1985.

N. B. Belecki, "Quality Control of Voltage Measurements at NBS," Rochester American Society for Quality Control Annual Conference on Quality Control, Rochester, NY, March 1985.

N. B. Belecki, "Automated Resistance Calibration at NBS," NCSL Region Three Meeting, Gaithersburg, MD, June 1985.

N. B. Belecki, invited participant in "DC-Low Frequency Requirements Workshop," National Conference of Standards Laboratories (NCSL) Annual Workshop and Symposium, Boulder CO, July 1985.

M. E. Cage, "Quantized Hall Effect and the Realization of a Unit of Electrical Resistance," Instrument Society of America Symposium for Innovation in Measurement Science, Geneva, NY, August 1985.

M. E. Cage, "Experimental Aspects and Metrological Applications of the Integer Quantum Hall Effect," Special Course on the Quantum Hall Effect, University of Maryland, College Park, MD, September 1985.

R. F. Dziuba, "Resistance Calibrations in the NBS Electricity Division," 1985 Measurement Science Conference, Santa Clara, CA, January 1985.

B. F. Field, "Review of dc Voltage Calibration Services of the Electricity Division," 1985 Measurement Science Conference, Santa Clara, CA, January 1985.

B. F. Field, "New Atomic Ohm Standard and Zener Reference Monitoring System," Precision Measurement Association San Diego Chapter, San Diego, CA, January 1985.

B. F. Field, "The Impact of Physics on Electrical Metrology: Instrinsic Standards," American Physical Society 1985 March Meeting, Baltimore, MD, March 1985.

B. F. Field, "Atomic Physics Based Electrical Standards," Government-Industry Data Exchange Program Metrology Meeting, Gaithersburg, MD, April 1985.

B. F. Field, "Automated Voltage Calibrations," NCSL Region Three Meeting, Gaithereburg, MD, June 1985.

G. M. Free, "Low Frequency Impedance Measurements at NBS," 1985 Measurement Science Conference, Santa Clara, CA, January 1985.

G. M. Free, "Recent Developments in the National Bureau of Standards Eddy Current Calibration Program," American Society for Nondestructive Testing, Spring Conference, Washington, DC, March 1985.

G. M. Free, "Conductivity Measurements for Material Sorting," ASTM Symposium on Methods for the Identification and Sorting of Metal and Metal Alloys, Los Angeles, CA, June 1985

J. R. Kinard, "Recent Developments and Future Plans for the AC-DC Difference Calibration Service at NBS," 1985 Measurement Science Conference, Santa Clara, CA, January 1985.

J. R. Kinard, "NBS Automated AC-DC Difference Calibration System," NCSL Region Three Meeting, Gaithersburg, MD, June 1985.

A. L. Migdall, "Magnetic Trapping of Atoms," Center for Basic Standards Colloquium, NBS, Gaithersburg, MD, May 1985.

A. L. Migdall, "Laser-cooling, Stopping and Trapping Atoms," Seventh International Conference on Laser Spectroscopy Maui, Hawaii, June 1985.

W. D. Phillips, "Laser-Cooling and Trapping Neutral Atoms," Alfred Kastler Memorial Symposium, Paris, France, January 1985.

W. D. Phillips, "Laser Cooling and Trapping of Neutral Atoms," Spring Meeting of the American Physical Society, Crystal City, VA, April 1985.

W. D. Phillips, "Cooling, Stopping and Trapping Neutral Atoms," Physics Department Colloquium, Yale University, New Haven, CT, September 1985.

B. N. Taylor, "Possible Changes in the U.S. Legal Units of Voltage and Resistance," NCSL Annual Workshop and Symposium, Boulder, CO, July 1985.

Publications FY 85

1. In Print.

M. E. Cage, R. F. Dziuba, and B. F. Field, "A Test of the Quantum Hall Effect as a Resistance Standard," IEEE Trans. Instrum. Meas. IM-34, 301 (1985).

M. E. Cage, R. F. Dziuba, B. F. Field, C. F. Lavine, and R. J. Wagner, "Status of the NBS-NRL Determination of the Fine-Structure Constant Using the Quantized Hall Resistance Effect," in Precision Measurement and Fundamental Constants II, Ed. by B. N. Taylor and W. D. Phillips, Natl. Bur. Stand. (U.S.), Spec. Publ. 617 (USGPO, Washington, DC, 1984), p. 539.

B. F. Field, "A High-Accuracy Resistance Bridge for Measuring Quantum Hall Devices," IEEE Trans. Instrum. Meas. IM-34, 320 (1985).

B. F. Field, "A Sub-ppm Automated 1-10 Volt DC Measuring System," IEEE Trans. Instrum. Meas. IM-34, 327 (1985).

F. L. Hermach, "An Investigation of the Uncertainties of the NBS Thermal Voltage and Current Converters," NBSIR 84-2903, April 1985.

L. B. Holdeman and J. T. Holdeman, Jr., "Support Electrode Torque on a Spherical Superconducting Gyroscope," IEEE Trans. Magn. Mag-20, 2042 (1984).

L. B. Holdeman, "Josephson Effect," in McGraw-Hill Encyclopedia of Science and Technology, Fifth Edition, Vol. 7 (McGraw-Hill, New York, 1982), p. 438.

M. J. Littman and W. D. Phillips, "A New Method of Measuring the Fine-Structure Constant Using Stark Spectroscopy," in Precision Measurement and Fundamental Constants II, Ed. by B. N. Taylor and W. D. Phillips, Natl. Bur. Stand. (U.S.), Spec. Publ. 617 (USGPO, Washington, DC, 1984), p. 173.

H. J. Metcalf and W. D. Phillips, "Laser Cooling of Atomic Beams," Comments At. Mol. Phys. 16, 79 (1985).

H. J. Metcalf, "Magnetic Trapping of Decelerated Neutral Atoms," Prog. Quant. Electr. 8, 169 (1984).

A. L. Migdall, J. V. Prodan, W. D. Phillips, T. H. Bergeman, and H. J. Metcalf, "First Observation of Magnetically Trapped Neutral Atoms," Phys. Rev. Lett. 54, 2596 (1985).

P. T. Olsen, V. E. Bower, W. D. Phillips, E. R. Williams, and G. R. Jones, "The NBS Absolute Ampere Experiment," IEEE Trans. Instrum. Meas. IM-34, 175 (1985).

P. T. Olsen, W. D. Phillips, and E. R. Williams, "Status of the Measurement of the NBS Ampere in SI Units," in Precision Measurement and Fundamental Constants II, Ed. by B. N. Taylor and W. D. Phillips, Natl. Bur. Stand. (U.S.), Spec. Publ. 617 (USGPO, Washington, DC, 1984), p. 475.

W. D. Phillips and H. J. Metcalf, "Time Resolved Sub-Natural Width Spectroscopy," in Precision Measurement and Fundamental Constants II, Ed. by B. N. Taylor and W. D. Phillips, Natl. Bur. Stand. (U.S.), Spec. Publ. 617 (USGPO, Washington, DC, 1984), p. 177.

W. D. Phillips, J. V. Prodan, and H. J. Metcalf, "Laser-Cooled Atomic Beams," in Atomic Physics 9, Ed. by R. S. Van Dyck, Jr., and E. N. Fortson (World Scientific, Singapore, 1984), p. 338.

W. D. Phillips, J. V. Prodan, and H. J. Metcalf, "Neutral Atomic Beam Cooling Experiments at NBS," Prog. Quant. Electr. 8, 119 (1984).

W. D. Phillips, "Laser Cooling of Atomic Beams," in Physics News in 1983, Ed. by P. F. Schewe (American Institute of Physics, New York, 1983), p. 73.

J. Prodan, A. Migdall, W. D. Phillips, I. So, H. Metcalf, and J. Dalibard, "Stopping Atoms with Laser Light," Phys. Rev. Lett. 54, 992 (1985).

J. V. Prodan and W. D. Phillips, "Chirping the Light-Fantastic? Recent NBS Atom Cooling Experiments," Prog. Quant. Electr. 8, 231 (1984).

B. N. Taylor, "Electrical Units, Fundamental Constants, and the 1983 Least-Squares Adjustment," IEEE Trans. Instrum. Meas. IM-34, 155 (1985).

B. N. Taylor, "New Results From Previously Reported NBS Fundamental Constant Determinations," J. Res. Natl. Bur. Stand. 90, 91 (1985).

B. N. Taylor, "Impact of Quantized Hall Resistance on SI Electrical Units and Fundamental Constants," Metrologia 21, 37 (1985).

B. N. Taylor and W. D. Phillips, Precision Measurement and Fundamental Constants II, Natl. Bur. Stand. (U.S.), Spec. Publ. 617 (USGPO, Washington, DC, 1984).

E. R. Williams, G. R. Jones, J. S. Song, W. D. Phillips, and P. T. Olsen, "Report on the New NBS Determination of the Proton Gyromagnetic Ratio," IEEE Trans. Instrum. Meas. IM-34, 163 (1985).

E. R. Williams, P. T. Olsen, and W. D. Phillips, "The Proton Gyromagnetic Ratio in H_2O - A Problem in Dimensional Metrology," in Precision Measurement and Fundamental Constants II, Ed. by B. N. Taylor and W. D. Phillips, Natl. Bur. Stand. (U.S.), Spec. Publ. 617 (USGPO, Washington, DC, 1984), p. 497.

E. S. Williams and J. R. Kinard, "A Dual-Channel Automated Comparator for AC-DC Difference Measurements," IEEE Trans. Instrum. Meas. IM-34, 290 (1985).

2. In Press, In Review, or Nearing Completion

B. F. Field, "Metrology of Intrinsic Standards," to be submitted to Rev. Sci. Instrum.

C. A. Hamilton, R. L. Kautz, R. L. Steiner, and F. L. Loyd, "A Practical Josephson Voltage Standard at One Volt," submitted to IEEE Trans. Electron. Device Lett.

J. R. Kinard, E. S. Williams, and T. E. Lipe, Jr., "Automated Thermal Voltage Converter Intercomparison," submitted to Proc. IEEE.

H. J. Metcalf and W. D. Phillips, "Laser Cooling and Magnetic Trapping of Atoms," submitted to McGraw-Hill Yearbook of Science and Technology.

H. J. Metcalf and W. D. Phillips, "Electromagnetic Trapping of Neutral Atoms," submitted to Metrologia.

A. Migdall, T. Bergeman, J. Dalibard, H. Metcalf, W. Phillips, J. Prodan, and I. So, "Cooling, Stopping, and Trapping Atoms," to appear in Laser Spectroscopy VI, Ed. by T. Hänsch and Y. Shen, (Springer, Berlin).

J. Niemeyer, L. Grimm, C. A. Hamilton, and R. L. Steiner, "High Precision Measurement of the Resistive Slope of Josephson Array Voltage Standards," submitted to IEEE Trans. Electron Device Lett.

W. D. Phillips, "Laser Cooling and Trapping Neutral Atoms," submitted to the Proceedings of the Alfred Kastler Memorial Symposium, Paris, January 1985.

W. D. Phillips, "Laser Cooling, Stopping, and Trapping of Neutral Atoms," submitted to Physics News in 1985, Physics Today.

W. D. Phillips, H. J. Metcalf, and J. V. Prodan, "Laser-Cooling and Electromagnetic Trapping of Neutral Atoms," submitted to J. Opt. Soc. Am. B.

N. N. Tadros and L. B. Holdeman, "Thin Film Cryogenic Resistors from Aluminum Alloys," submitted to Cryogenics

B. N. Taylor, "Possible Changes in the U.S. Legal Units of Voltage and Resistance," submitted to NCSL Newsletter.

Technical and Professional Committee Participation and Leadership

N. B. Belecki, member, ANSI S82, American National Standards Institute Committee on Electrical Standards, Instrumentation, and Devices.

N. B. Belecki, member, National Conference of Standards Laboratories Measurement Assurance Committee.

N. B. Belecki, member, National Working Group, OIML (International Organization of Legal Metrology) Pilot Sectetariat 13, Measurement of Electrical and Magnetic Quantities; and Co-chairman, U.S. National Working Group, OIML (International Organization of Legal Metrology) Reporting Secretariat 13.1, International Compatibility of National Primary Standards Used for Instrument Verification.

N. B. Belecki, member, TC-2, DC and LF Standards, Instrumentation and Measurements Committee of the Instrumentation and Measurement Society, Institute of Electrical and Electronics Engineers (IEEE).

N. B. Belecki, member, National Conference of Standards Laboratories Measurement Requirements Committee

N. B. Belecki, member, National Conference of Standards Laboratories Education Liaison Committee

G. M. Free, member, ASTM E7, American Society for Testing and Materials, Nondestructive Testing; ASTM E7, SC.7, Electrical and Magnetic Methods (vice chairman); E7, SC.9, Materials Inspection and Testing Laboratories; E7, SC.9, Editorial Review; E7, SC7.02, Glossary (chairman); E7, SC7.01, Nonmagnetic Applications (chairman).

G. M. Free, secretary, American Society for Nondestructive Testing, C1, Research Promotion Committee.

G. M. Free, member, American Society for Nondestructive Testing, C2, Electrical and Magnetic Methods Committee.

W. D. Phillips, member, NBS Research Advisory Committee

W. D. Phillips, member, Steering Committee for the NBS Discussion Group on Atomic Physics

W. D. Phillips, member, Editorial Board of Progress in Quantum Electronics

B. N. Taylor, member, Advisory Committee on Fundamental Constants of the Division of Chemistry and Chemical Technology, Numerical Data Advisory Board, National Academy of Sciences/National Research Council/National Academy of Engineering.

B. N. Taylor, Chairman, NBS Precision Measurement Grants Committee.

B. N. Taylor, NBS representative, Consultative Committee on Electricity (CCE), International Committee on Weights and Measures.

B. N. Taylor, member, ANSI C-42, American National Standards Institute Committee on Definitions of Electrical Terms.

B. N. Taylor, member CODATA (Committee on Data for Science and Technology Task Group on Fundamental Constants.

B. N. Taylor, Technical Advisor (Chairman, U.S. National Working Group) OIML (International Organization of Legal Metrology) Pilot Secretariat 13, Measurement of Electrical and Magnetic Quantities; and Co-chairman, U.S. National Working Group, Reporting Secretariat 13.1, International Compatibility of National Primary Standards Used for Instrument Verification.

B. N. Taylor, NBS representative to Conference on Precision Electromagnetic Measurements (CPEM) Executive Committee and Comptroller, CPEM.

Collaborations, Consulting, Miscellaneous Activities

N. B. Belecki and R. F. Dziuba are collaborating with metrologists from six Southern California Companies (Beckman Instruments, Electrical Standards Repair Service, Ford Aerospace & Communications, Lockheed of California, Rockwell International Anaheim, and TRW) in a pilot experiment to develop methodology for a "self-help" group MAP in resistance. The goal is a procedure by which companies could set up and run their own MAP, including data reduction and error analysis, using NBS's calibration services and their own transport standards. Some of the equipment is being furnished by the NCSL Measurement Assurance Committee.

N. B. Belecki and B. F. Field provided technical guidance on voltage standards and voltage, resistance, and temperature measurements to engineers at the Charles Stark Draper Laboratories, Cambridge, MA, in support of a program to evaluate inertial guidance units under intense radiation conditions.

M. E. Cage, R. F. Dziuba, and B. F. Field are collaborating with S. M. Girvin of the Surface Science Division (541) on the theoretical aspects of the quantized Hall resistance experiment.

M. E. Cage, R. F. Dziuba, and B. F. Field are collaborating with D. C. Tsui of Princeton University, and A. C. Gossard and H. L. Stormer of Bell Laboratories, on quantized Hall resistance measurements of GaAs-AlGaAs heterojunctions.

M. E. Cage, R. F. Dziuba, and B. F. Field are collaborating with M. Razeghi of Thomson-CSF, France, on quantized Hall resistance measurements of GaInAs-InP heterojunctions.

M. E. Cage, R. F. Dziuba, and B. F. Field are collaborating with E. Mendez of IBM on quantized Hall resistance measurements of GaSb-InAs heterojunctions.

M. E. Cage, R. F. Dziuba, and B. F. Field are collaborating with J. Gulerno, E. Sichel, and H. Sample of GTE Laboratories on quantized Hall resistance measurements of GaAs-AlGaAs heterojunctions.

B. F. Field is collaborating with a number of companies (John Fluke Mfg. Co., National Semiconductor, Standard Reference Labs) on the evaluation of improved solid-state voltage standards.

B. F. Field and T. E. Kiess are collaborating with personnel from the DoD Primary Standards Laboratories (Redstone Arsenal, North Island Naval Air Station, Washington DC Navy Yard, Newark Air Force Station) on the use of commercial 10 V solid-state voltage standards as MAP transfer devices.

G. M. Free is collaborating with M. Oldham of the Electrosystems Division, CEEE, NEL, on the design, construction, and testing of binary inductive voltage dividers.

J. R. Kinard is collaborating with personnel from the Navy Metrology Engineering Center, Pomona, CA, and the John Fluke Mfg. Co. on the evaluation of solid-state thermal converters.

J. R. Kinard is collaborating with personnel from the Navy Metrology Engineering Center, Pomona, CA, and Ballantine Laboratories on the evaluation of automatic programmable ac to dc converter instruments.

J. R. Kinard and T. E. Lipe, Jr., are collaborating with personnel from the Air Force Primary Standards Laboratory, Newark, Ohio, on the development of a turnkey ac-dc difference calibration system.

P. T. Olsen is collaborating with personnel of the Navy's Primary Standards Laboratory, East (Washington Navy Yard) on the calibration of magnetometers.

W. D. Phillips is collaborating with M. G. Littman of Princeton University on the spectroscopy of Rydberg atoms in electric fields and applications to the measurement of the fine-structure constant.

W. D. Phillips is collaborating with J. Dalibard and C. Cohen-Tannoudji of Ecole Normale Superieur, Paris, on the laser trapping of neutral atoms.

W. D. Phillips is collaborating with H. J. Metcalf, I. So and T. Bergeman of S.U.N.Y at Stony Brook on laser deceleration (cooling) and magnetic trapping of sodium atoms.

R. L. Steiner and J. Toots are collaborating with C. A. Hamilton, R. L. Kautz, and F. L. Loyd of the Cryoelectronics Group of the Electromagnetic Technology Division, CEEE, NEL, NBS/Boulder, and J. Niemeyer of the Physikalisch-Technische Bundesanstalt, West Germany, on the development of 1 V Josephson array voltage standards.

B. N. Taylor is collaborating with E. R. Cohen, Rockwell International, and the CODATA Task Group on Fundamental Constants, on a new least-squares adjustment of the fundamental physical constants to be completed in early 1986 for international adoption by CODATA.

B. N. Taylor serves as Editor with D. R. Lide of NBS' quarterly Preprints on Precision Measurement and Fundamental Constants.

J. Toots is collaborating with D. W. Braudaway, Sandia Laboratories; and K. Jaeger, Lockheed Missiles & Space Co., on the implementation of a Josephson voltage standard at their respective laboratories by fabricating Josephson tunnel junctions.

TEMPERATURE AND PRESSURE DIVISION

SUMMARY OF ACTIVITIES

FISCAL YEAR 1985

DIVISION CHIEF'S OVERVIEW

This past fiscal year has seen significant adjustments in two Division resources: personnel and finances. As to the former, two professionals were retired; two professionals were hired; one postdoctoral fellow was retained under contract and new assignments were made for five professionals and one technician. As to the latter, the Division is achieving a firmer financial basis through a significant increase in other agency funding.

Changes as large as the ones referred to above called upon the resourcefulness, flexibility and cooperation of all the Division staff. They came through with a maturity that will stand them in good stead in years to come.

For the past two years I have classified the Division projects into eight categories. I will use the same system in detailing the resource changes for the remainder of this section, leaving the technical accomplishments for discussion in subsequent sections.

I. HIGH TEMPERATURE SCALE RESEARCH
900 K $<$ T $<$ 200 K

Two of the subprograms (Optical Fiber Thermometry and Gas Thermometry) suffered no personnel changes. The major change was in the third component - High Temperature Platinum Resistance Thermometry. John Evans retired, but still performs services under contract. Thus, this subprogram has not completely collapsed It proceeds, however, under a no-frills, bare-bones mode in which absolute essentials needed for Division health (maintenance of Al, Ag, and Au fixed points; calibration of several Division platinum resistance thermometers at these fixed points; characterization of special platinum resistance thermometers) are maintained.

II. INTERNATIONAL PRACTICAL TEMPERATURE SCALE (IPTS-68)
13 K $<$ T $<$ 1500 K

II.A. THERMOCOUPLES

The thermocouple group assumed an extra responsibility: an other agency contract to assist the military in improving jet engine temperature measurements (JETCAL). M. Reilly made major contributions to JETCAL this past fiscal year, preparing to turn the program over to the thermocouple group (G. Burns and M. Scroger) in FY 86.

II.B. PLATINUM RESISTANCE THERMOMETERS

The changes in the program are profound. G. Furukawa retired and makes contributions to the Division under contract. B. Mangum has assumed technical management responsibility for the program. The Division is undertaking a two-year modernization of the Platinum Resistance Thermometry Laboratory. Thus, R. Kaeser has joined the effort as an expert in automation; G. Evans provides technician support part time; and E. Pfeiffer has joined to help in several areas. H. Marshak is also assisting in design and testing of a cryogenic triple-point (Ar) apparatus. Finally, the program has attracted some other agency funding (CCG).

II.C. LABORATORY THERMOMETRY

J. Wise continues to run this program. It is supported entirely from calibration fees.

II.D. SMALL TUNNEL DIODE OSCILLATOR PRESSURE SENSOR/GAS THERMOMETER

C. Van Degrift is winding down the project on Tunnel Diode Metrology and has effectively joined Division 521 to participate in a collaboration on the Quantum Hall Effect experiment.

III. LOW-TEMPERATURE SCALE

0.001 K < T < 30 K

E. Pfeiffer has completed the establishment of a calibration service based on EPT-76. He will continue to offer the service on a part-time basis, as he now joins the platinum resistance calibration laboratory automation project, II.B.

A Postdoctoral Associate, W. Fogle, was retained on contract. Otherwise, there was no change in personnel or financing in this project.

IV. MEDICAL THERMOMETRY

0 °C < T < 200 °C

As was discussed in II.B., B. W. Mangum assumed charge of the Platinum Resistance Thermometry program. This has resulted in some deemphasis of the Medical Thermometry program (Dr. Mangum's original, sole responsibility). The Medical program is not finished, however, so Dr. Mangum will keep it going with Guest Scientists, etc. The program has attracted some other agency funding (NASA), and may attract more this FY (OSRM; NCI).

V. DYNAMIC PRESSURE AND TEMPERATURE

0.2 atm < P < 10 atm; 300 K < T < 2000 K

The stalwarts of the program (G. Rosasco, W. Hurst and R. Dove) will be joined this FY by two one-year visitors (Dr. L. Petway and Dr. K. Smyth). Other-agency support is pending.

VI. PRESSURE

10^5 Pa < P < 1.2 GPa

This program has had no change in permanent personnel, but it has attracted several Guest Scientists. An other agency contract for the Army has assisted them in their high-pressure needs. Additional other agency support is pending.

VII. VACUUM

10^{-6} Pa < P < 10^5 Pa

At the beginning of this FY, A. Filippelli joined this group. A new laboratory was established and is being improved. Other agency support is strong, including the Navy (new manometer); CCG (speed of sound in Hg); DOE (properties of vacuum gages); and NBS Initiative. R. Dove was reassigned part time to assist the group.

VIII. LEAK STANDARDS

C. Ehrlich joined the group at the beginning of the FY. This group works closely with VII, but enjoys separate funding (Sandia).

I. HIGH TEMPERATURE SCALE RESEARCH

(M. Reilly, J. Schooley, R. Edsinger, W. Bowers and J. Evans)

The temperature range covered here extends from 904 K (the upper limit of the platinum resistor scale) to approximately 2000 K (no particular reason for this cutoff). This temperature range is presently defined by standard thermocouples. For a variety of technical reasons, errors in temperature measurement using these devices can become unacceptably large (~0.5 K). Accordingly, the Division has initiated a program to address this problem. The goal is to develop a temperature scale accurate to 10 ppm based on a comparison of two instruments based on two physical laws: the ideal gas law and the Planck radiation law. A further consideration is to develop transfer standards based on special platinum resistance thermometers or on the optical fiber thermometer. Development of the optical fiber thermometer using the Planck radiation law is a relatively new task assumed by Division personnel with the direct support (financial and administrative) of the Director of NBS. It is coordinated with the other Division projects - gas thermometry and high-temperature PRT's - as will be explained below.

I.A. OPTICAL FIBER THERMOMETER

The principal goals of the Optical Fiber Thermometer (OFT) program are (1) to establish accurate values for the thermodynamic temperature of the freezing points of silver (962 ^{o}C) and gold (1064 ^{o}C) relative to that of aluminum (660 ^{o}C) and (2) to provide a means of interpolating temperature between these fixed points with an uncertainty that does not exceed 20 ppm. Through its development and use as a primary thermometer, we hope that the OFT can provide the basis for the formulation of a more accurate temperature scale over the interval 630 to 1064 ^{o}C. This program was initiated in 1983.

The OFT, as was originally conceived by R. Dils, is a self-contained measurement system with a high-temperature probe of single-crystal sapphire rod (nominally 1 mm diameter and 30 cm length) with a metallic blackbody cavity sputtered on its tip. The low-temperature end of the probe is coupled directly to a silicon photodiode detector via a compound narrow-band interference filter. When the cavity is heated, the radiant flux emitted in a narrow wavelength band can be used to determine its temperature. Because of a high index of refraction, the sapphire probe captures significantly more signal than does the optical system of conventional pyrometers and, as a consequence, it has greater sensitivity and can operate to lower temperatures than those instruments. If the cylindrical surface of the probe is perfectly smooth, radiant flux from the surroundings of the probe will not be transmitted to the detector.

In principle, once the OFT is calibrated at a single temperature within its range, it is capable of measuring thermodynamic temperatures over its entire range (600 to 1600 ^{o}C). In practice there are three major sources of error which limit the accuracy with which the OFT can measure thermodynamic temperature. These are: (1) uncertainties in the optical properties of the probe; (2) uncertainties in the spectral response characteristics of the optical system (particularly the interference filter and detector); and (3) uncertainties in the linearity of the detector and the electronic circuitry.

At present, the dominant source of error is that due to the attenuation of the transmitted radiant flux due to absorption in the probe plus the loss of the transmitted flux (and likely gain of unwanted background flux) due to scattering at the cylindrical surface of the probe. Sapphire rods tested to date all show much more absorption and scattering than can be tolerated for the OFT program. We have also found that the absorption and scattering tend to increase with prolonged exposure in air of an unprotected probe in a simple tube furnace maintained at 1000 °C.

Neutron activation analysis of samples taken from various sapphire rods indicate that the bulk impurity content of most of the material is quite low (less than 10 ppm). However, scanning electron microscopy has revealed clusters of patterned formations scattered over an otherwise featureless cylindrical surface and subsequent electron probe analysis indicates that these formations can have localized metallic ion impurity concentrations of up to 0.1 wt %! The formations on the surface cause absorption as well as scattering.

We believe that these localized concentrations of impurity develop when the rod is flame polished (the final step which fabricators use to produce a "smooth" finish once the sapphire, which is cut from a large boule, has been centerless ground to dimension). We are therefore studying a number of approaches toward improving the quality of the cylindrical surface of the probe among which are various etching, annealing, and polishing techniques. We are also working cooperatively with a manufacturer (who can grow sapphire rod of the required diameter and length directly from the melt) to assist through various analytical efforts, in upgrading the optical quality of the sapphire rod produced. The most recent rod tested shows significant improvement over earlier rods manufactured.

Rods of vitreous synthetic silica from several manufacturers show about an order of magnitude less absorption and scattering than do the best of the sapphire rods tested. Moreover, preliminary studies with the most promising of these, Suprasil, indicate that the absorption and scattering (near 800 °C) do not significantly increase after exposing the rod for 16 hours at 1000 °C provided it was first sealed within a silica tube containing dry argon gas.

Thus, several OFT probes of silica-sheathed, hermetically-sealed vitreous synthetic silica rod have been built. Also enclosed within the sheath is a small graphite blackbody cavity which surrounds the tip of the rod. The probes are of sufficient length (an advantage of silica) so that they can be used in the existing thermometric freezing-point cells as well as the NBS Gas Thermometer. Their performance is currently being tested over the range 660 to 960 °C.

In anticipation of a need to provide calibration services for OFT's, we are now prepared to provide "special" calibrations on IPTS-68, which will also include evaluation of the absorption and scattering characteristics of the probe. We expect to examine several commercial instruments in FY 86.

We expect to begin construction in January 1986 of a laboratory committed completely to the Optical Fiber Thermometer program.

I.B. HIGH-TEMPERATURE GAS THERMOMETRY

In the FY 84 Annual Report, we reported progress in determining the difference between the IPTS-68 and the Kelvin Thermodynamic Temperature Scale by gas thermometry in the range above 457 °C, the highest temperature for which results had been published by the NBS Gas Thermometry project staff. Our FY 84 results, obtained using a new, gas-filled furnace as a thermal environment for the Pt-Rh alloy gas bulb, had been marked by unsuccessful efforts to duplicate the earlier, published data. The major difficulty had appeared to be a strong time-dependent decrease in the gas-bulb pressure at all temperatures above 0 °C, with a rate corresponding to as much as 6 mK/day at 660 °C.

During FY 85, we eliminated several possible causes of this drift by checking the system for leaks and for impurities in the working gas, and by other methods that stopped short of dismantling the gas bulb. They were unsuccessful. Therefore, despite the substantial investment in time and effort involved, we removed the Inconel 600 protective case from the gas bulb and made several changes designed to eliminate the drift. These included:

- Enlargement of the inner diameter of the Inconel case, to reduce the likelihood of a touch between the case and the gas bulb, as had occurred in an earlier assembly;

- Removal of the oxide layer from the inside of the Inconel case, in the hope of retarding the transport of Ni and Cr impurity atoms that we detected on the outside of all the used Pt-Rh gas bulbs;

- Increasing the thickness of the flat bottom of the gas bulb by about a factor two, in the hope of retarding any tendency for it to "droop" at high temperatures and thus expand slightly the volume of the gas bulb; and

- Removal of impurity atoms from the outside of the gas bulb by careful polishing.

After re-assembly of the gas bulb onto its capillary and of the Inconel case onto the capillary cover-tube, we outgassed the apparatus at 700 °C for about two weeks, flushing several times with clean 4-He gas.

From the first set of measurements at 457 °C, it was clear that the pressure decrease that had spoiled so many earlier efforts was much reduced. While still present, the effect was now somewhat less than half as large as it had been. To ameliorate the effect of the drift, we instituted a modified procedure for evaluating the thermodynamic temperature associated with a given IPTS-68 temperature:

- Each high-temperature measurement must be immediately preceded or immediately followed by a reference measurement at the ice point; and

- After one series of measurements to evaluate the magnitude of the pressure drift was completed, no effort was made to extend the duration of high-temperature measurements. The gas-bulb assembly was maintained at the high temperature only long enough to minimize temperature gradients in the furnace volume surrounding the bulb. This procedure has the added benefit of reducing the time during which material transport between the Inconel case and the gas bulb can occur.

The measurements that we have obtained with the re-built gas bulb assembly, while limited in number, have shown improved precision over previous efforts. The agreement between the present results at 457 °C and the NBS results published earlier has improved considerably, although there remains a discrepancy of 10-20 mK as shown in Fig. 1.

During FY 85, Jung of the PTB in Berlin published preliminary results of spectral radiation thermometry in the range 457 °C to 660 °C that are based upon the NBS results at 457 °C. Accordingly, we have concentrated our own efforts on the same limited range. All of our results to date, as well as those of Jung, are shown in Fig. 1.

The major uncertainties in our determinations arise from uncertainties in the corrections for thermal expansion, for thermomolecular pressure in the capillary, for the non-ideality of 4-He gas, and for gradients in the furnace temperature. We estimate the overall level of uncertainty as ± 20 mK. Once sufficient measurements are complete so as to allow evaluation of our random measurement uncertainty, it is our intention to dismantle the gas bulb assembly in order to re-measure its thermal expansion throughout the range 0 - 660 °C, and to measure the capillary thermomolecular pressure effect in the same range. Given the improved precision to be expected from spectral radiation thermometry above 660 °C, it may not be necessary for us to continue measurements above that temperature.

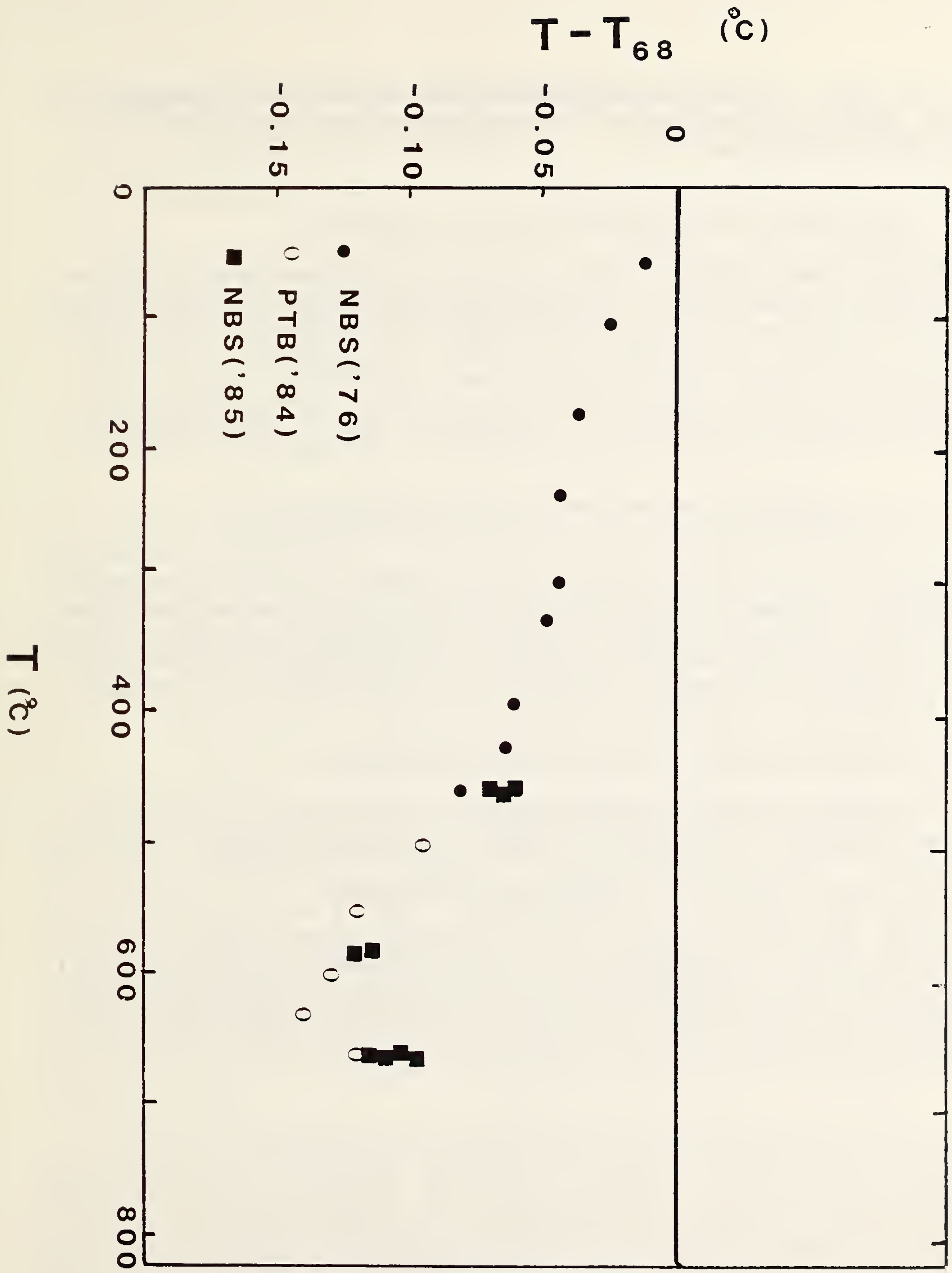

Fig. 1. IPTS-68 vs. Kelvin thermodynamic scale.

Our plans for the coming year also include completing publication of the thermal expansion measurements performed in conjunction with the earlier NBS gas thermometry.

I.C. HIGH-TEMPERATURE PLATINUM RESISTANCE THERMOMETRY

The purpose of this project is to develop high-temperature platinum resistance thermometry as a long needed and more precise replacement for thermocouple thermometry in defining a practical temperature scale. The program consists of the design and testing of thermometers, electrical measuring systems, thermometric fixed points, and interpolating formulations, with the goal of achieving 10 mK or less uncertainty over the full range 630 to 1064 °C. Progress in these areas is outlined below.

1. Testing new high-temperature platinum resistance thermometers.

The Chino Company (Japan) is a commercial source of these resistors. J. Evans (under contract) studied two of these resistors and found them to perform as well as other candidates (made by NBS, and in China). These results are providing an accumulating body of evidence which suggests that special, commercially available PRT's will supplant thermocouples for temperature scale realization.

2. NBS traceability to Ag and Au fixed points.

J. Evans calibrated several NBS PRT's at the Al, Ag and Au fixed points in support of the other two high-temperature projects.

3. Recertification of thermocouple calibration.

Many customer thermocouple calibrations are done at the Sb, Ag and Au fixed points. J. Evans compared his high quality fixed points with those used by Burns and Scroger for the thermocouple calibration service. Evans found that the calibration laboratory fixed points were incorrect and provided the data needed to correct them.

II. INTERNATIONAL PRACTICAL TEMPERATURE SCALE (IPTS-68)

(B. Mangum, G. Burns, M. Scroger, W. Bigge, J. Wise, G. Evans, C. Van Degrift and G. Furukawa)

II.A. THERMOCOUPLES

These cover the range from 273 K to 2400 K; the thermocouple laboratory is managed by G. W. Burns with the assistance of M. S. Scroger. The activities generally fall into two categories: routine calibrations and non-routine calibrations.

1. Routine calibrations.

Approximately 300 thermocouples were calibrated for 80 customers during FY 85 producing 105 k$ in test fees.

A new computer, having several times the memory of the previous computer, was procured and put into operation in the Thermocouple Calibration Laboratory. The new computer will greatly simplify the processing of calibration results and the production of emf-temperature calibration tables for our calibration customers. Since the operating systems and basic languages of the new and old computer differ, existing programs must be rewritten and this lengthy task was begun.

2. Non-routine tests.

a. IMGC - NBS Collaboration on Tungsten-Rhenium Thermocouples

As part of a scientific cooperative program between the NBS and the Istituto di Metrologia "G. Colonnetti" (IMGC) in Torino, Italy, Dr. Roberto Perissi spent eleven weeks at NBS working with G. Burns on the calibration of tungsten-rhenium type thermocouples. A group of sixteen W-3%Re versus W-25%Re thermocouples (thirteen NBS thermocouples and three IMGC thermocouples) were calibrated in the range 1000 to 2000 °C by direct comparison with a new transfer standard optical pyrometer developed and calibrated by Dr. R. Righini and others at the IMGC. The thermocouple calibrations were conducted in a UHV high temperature furnace where the measuring junctions of the thermocouples were located within a hollow, cylindrical blackbody cavity formed from tantalum tubing.

With the exception of one calibration run, the repeatability of the measurements was very good. However, a systematic difference, ranging from about 2 °C at 1000 °C to 3 °C at 1600 °C, was observed between calibration results obtained in this work and previous calibration results for similar thermocouples (taken from the same spools of wire) that were calibrated by comparison with Type S and Type B reference thermocouples. This difference was thought to have been caused by the lack of true blackbody conditions in the cavity. A calibration check of the IGMC pyrometer performed by the NBS Radiometric Physics Division at about 1064 °C agreed with the earlier calibration of the instrument made at the IGMC within 0.1 °C.

The joint IGMC-NBS program will be continued during FY 86. Another blackbody cavity of improved design will be fabricated for use in the NBS furnace. Dr. Righini will construct a transfer standard optical pyrometer at IMGC for the NBS Temperature and Pressure Division. G. Bussolino of IGMC will come to NBS to assist G. Burns with the initial setup and operation of the pyrometer. Additional calibrations of IGMC and NBS thermocouples will be carried out in the 1000 to 2100 °C range. This effort is aimed at achieving improved thermocouple standards in the 1600 to 2100 °C range to enable more accurate thermocouple calibrations to be provided for NBS calibration customers.

b. ASTM and ISA Committee Work

To assist ASTM Committee E20.04 with the preparation of a new document giving temperature-emf tables for some non-standard thermocouple systems, temperature-emf tables were computed using existing polynomials for the following thermocouples:

1) W versus W-26%Re
2) Platinel II
3) Type KP versus Au-0.07at.%Fe
4) Pt-5%Mo versus Pt-0.1%Mo
5) Pt-40%Rh versus Pt-20%Rh
6) Ir-40%Rh versus Ir

Tables (in both °C and °F) for the above thermocouples were provided to the Committee in the appropriate format for inclusion in the document, which is to be published in the ASTM Annual Book of Standards, Vol. 14.01.

Since the nicrosil versus nisil thermocouple was recently assigned a letter designation, Type N, by the SP-1 Committee of the Instument Society of America (ISA), emf-temperature tables for the thermocouple were prepared for inclusion in ISA standard MC96.1 and sent to the Chairman of the SP-1 Committee.

Temperature-emf tables for the Type N thermocouple (in both °F and °C) and for its thermoelements versus platinum (Pt-67) were also prepared in the appropriate format for inclusion in the next revision of ASTM Standard E-230 and sent to the Chairman of Committee E20.04.

c. Thermometry for Jet Engines (G. Burns and M. Reilly)

This project, initiated in May of 1984 with support from the U.S. Navy, is now sponsored by all members of the Armed Forces Combined Calibration Group (CCG). The overall objectives are to (1) investigate and evaluate present DOD calibration support of jet engine temperature measurements; (2) provide a comprehensive report that details the present system and demonstrates several alternative methods to provide the calibration support required; and (3) develop the support system that is mutually agreed upon to optimize performance by means of automation.

In each jet aircraft engine, groups of thermocouple sensors are located at various zones within the engine so that the junctions will accurately sense conditions which are critical to the safe and proper operation of the aircraft. The average dynamic state sensed by the thermocouple array is characterized as a temperature which, through experience obtained during the design and testing stages of engine development, can be related to engine performance. A primary zone of interest is that of the exhaust gas temperature (EGT) just downstream from the turbine. Readings above the normal limit for this zone indicate conditions which can cause significant reduction of engine life and make engine operation extremely hazardous. Readings below the normal limit indicate a condition of reduced engine efficiency with consequent loss of thrust.

For most types of jet engine thermocouples, the active element is Type K wire which meets ASTM/ISA special calibration tolerances. The thermocouple is usually enclosed within a specially designed metal housing (unique to each engine zone) which provides protection for the junction as well as correct aerodynamic flow of the hot gas stream in order to minimize the error in the reading. Each assembly is mounted on the outer surface of the engine wall with the junction penetrating into the engine to a fixed depth. The calibration of the engine thermocouple is known to degrade with use; the useful lifetime depends upon its particular thermal history and environment within the jet engine.

For many military aircraft, particularly those in the Navy, the performance of the EGT system is routinely tested in situ without running the engine by using instrumentation called a JETCAL Analyzer System. This is done by simulating a known engine operating temperature and verifying that the instrumentation of the aircraft indicates that temperature to within the specified tolerance. To achieve this, each thermocouple of the EGT array is simultaneously heated by a JETCAL heater probe (a small furnace of special design which is clamped onto the thermocouple housing). The JETCAL Analyzer controls the average temperature of the probes at the specified test temperature (usually near 600 °C) by matching the signal produced by the thermocouple embedded in each probe to a known voltage generated within the Analyzer. When the temperature of the EGT thermocouples has stabilized, the aircraft instrumentation should indicate the test temperature within a specified tolerance, generally ±10 °C.

The JETCAL Analyzer is also used "at the bench" to test all unmounted engine thermocouples during engine overhaul and as well as at the test stands where the performance of the overhauled engine is tested and "trimmed".

The JETCAL heater probes are electrically heated using an internal wire-wound resistance with power supplied by the Analyzer. A calibrated, special tolerance Type K thermocouple, embedded in the probe core, is used to sense its temperature. Each model of JETCAL probe is specially designed to test one particular type of engine thermocouple assembly. The heater probes are required to be calibrated to ± 4 °C or better.

Several studies by the Navy indicate that the present system used to provide calibration support for JETCAL/TEMPCAL heater probe has been inadequate for a number of years. The principal reason is because adequate standards have not been available to the calibration laboratories. (Because of their unusual geometry, most jet engine thermocouples cannot be reliably calibrated and therefore do not make suitable standards by themselves.) It was concluded in 1983 that, due to the limitations of the current procedures being used by the Navy for the calibration of the JETCAL probes, realistic calibration uncertainties were more likely to be ±8 °C.

At the request of the CCG, the Temperature and Pressure Division (TPD) has undertaken the task of assisting the DOD calibration laboratories to develop improved standards and procedures for the calibration of the JETCAL heater probes. In April 1985 we submitted an initial report in which we recommended both long- and short-range goals for upgrading procedures and improving the accuracy of the calibration of JETCAL heater probes.

The most important long-range goal is for Navy land-based standards laboratories responsible for the JETCAL heater probe calibration to use the tin, zinc and aluminum freezing-point cells for direct calibration of their working standards rather than the current method which is to compare the working standards with a calibrated Type S thermocouple in a horizontal tube furnace. In support of this goal, we propose to work together with the Naval Metrology Engineering Center to develop procurement specifications for the required freezing-point cells and associated furnaces, the Navy Primary Standards Laboratories to establish calibration protocols, and the Type II Standards Laboratories to help set up the calibration facilities and to train their personnel in the use of the freezing-point apparatus.

In support of the principal short-range goal, to resolve known problems associated with the calibration of specific JETCAL heater probes, we propose to develop several new working standards which will correctly simulate the thermal loading characteristics of the jet engine thermocouple when it is placed inside the heater probe during calibration. To do this we expect to devise suitable adapters (specific for each engine thermocouple) which can be attached to the standard thermocouple after its calibration. The standard thermocouples will be of sufficient length so that they can be calibrated in thermometric freezing-point cells (tin, zinc and aluminum) without immersion errors.

II.B. PLATINUM RESISTANCE THERMOMETERS (PRT's)

The objectives of this program are (1) to maintain the IPTS-68(75) in the range 13 K to 904 K (the region of the scale in which the standard instrument is the SPRT); (2) to make improvements in the realization of that scale; (3) to disseminate the scale (through calibrations, precision measurement seminars, MAP's, lectures, publications, interactions with standards-writing organizations, etc.); and (4) to prepare for a new IPTS.

The following table outlines the SPRT calibration procedure.

SPRT CALIBRATION PROCEDURE

13 K to 500 K	Capsule SPRT's	Calibrations by comparison against reference standards
78 K to 904 K	Long-stem SPRT's	Calibrations by comparison against reference standards at 90 K and by use of fixed points (TP H_2O, Sn, and Zn).

For the capsule PRT's we are re-evaluating the calibration procedure. The old system, although having a fast turnaround time, is largely manual. E. Pfeiffer has studied the feasibility of performing capsule PRT calibrations on his EPT-76 automated laboratory. That successful result is reported in III.A.

In the case of the long-stem PRT's, a new automated laboratory is under construction. Specific accomplishments this FY include:

(1) Dr. G. T. Furukawa has been analyzing data obtained on the triple point of oxygen and a paper on the results is in progress.

(2) A draft of the documentation of the platinum resistance thermometer calibration service was written and given to J. Simmons. This turned out to be a rather massive volume.

(3) A set of lecture notes on platinum resistance thermometry was prepared for the lectures to be presented at the Precision Thermometry Seminar in October 1985.

(4) A new set of posters detailing the SPRT calibration procedure and the IPTS-68(75) was prepared.

(5) Modernization and semi-automation of the SPRT Calibration Laboratory were planned with the help of Drs. R. Soulen and G. Furukawa and Messrs. R. Kaeser, E. Pfeiffer and W. Bigge.

(6) Apparatus and electronic equipment required for item (5) were ordered. Most, but not all, of these have been received.

(7) Tin and zinc fixed-point cells are used in the calibration of SPRT's and since there is a critical shortage of these in the PRT Laboratory, materials required for the preparation of several new cells of each were ordered. With the exception of some samples of pure tin and pure zinc, the materials (graphite crucibles, precision bore glass tubing, rubber stoppers, etc.) are now in hand and ready for use in the preparation of the new cells.

(8) Dr. G. Furukawa (under contract) is testing a new 3-zone furnace (to be used for the zinc point) that he designed. He supervised the construction of the various parts of the furnace by the NBS Instrument Shops, and when that was completed he assembled the furnace.

(9) Three new SPRT's suitable for use to the silver point were purchased from Chino Works America, Inc.

(10) Drs. G. Furukawa and H. Marshak, with some advice from Drs. B. Mangum and R. Soulen, designed an apparatus, incorporating an argon triple-point cell, to be used in the calibration of long-stem SPRT's. Dr. Furukawa provided the principal design information for the system. This apparatus will accommodate 7 long-stem SPRT's and 6 capsule SPRT's. Construction has begun on this apparatus and when it is complete, it will replace the comparison apparatus currently used at the oxygen point.

(11) We have a continuing MAP on calibration of SPRT's. The MAP with the U. S. Army Test, Measurement, and Diagnostic Support Group, Redstone, was completed and the MAP SPRT's are now at Boeing Aerospace Company.

(12) Since the zinc-point furnace was burned out last year, there is only one operating furnace left for both the tin and zinc cells. Nevertheless, during this past FY 62 SPRT's were calibrated. In addition, data have been taken but not analyzed and reports prepared for 8 additional SPRT's, giving a grand total of 70 SPRT's calibrated.

During the calibrations of these SPRT's, further comparisons were made between the manually operated Guildline dc current comparator bridge and the automatic Cutkosky dc-pulse bridge in preparation for automation of the measurement and analysis processes in the calibration of SPRT's.

(13) The SPRT Calibration Report has been revised significantly so that, when the automation is completed, the customer will get substantially more information about his thermometer and the calibration process and its attendant uncertainties. Also, the SPRT will be routinely calibrated at two currents, with tables provided for zero-power dissipation in the SPRT and for a continuous current of 1 mA flowing through the SPRT.

(14) The data and results maintained on computer cards for all of the SPRT's calibrated at the NBS on the IPTS-68 were transferred to files which can be read and manipulated by the new NBS computer.

(15) Planned organization of the PRT Laboratory for the new IPTS being proposed.

(16) We began a contract with CCG for the NBS to evaluate the "best" commercial IPRT's (i.e., non-SPRT) up to 650 °C. As part of this contract, we selected the "best", i.e., most stable, IPRTs commercially available and ordered 11 of them - 4 from Minco, 2 from Hy-Cal, 3 from RDF, and 2 from Burns Engineering.

We have located a furnace to use in this project but we must adapt it for testing the IPRT's at 650 °C. Following the preparation of the furnace and testing it, we will begin tests on the IPRT's.

II.C. LABORATORY THERMOMETERS

Approximately 520 liquid-in-glass thermometers and 10 thermocouples were calibrated by Ms. J. Wise. The number of additional thermometers calibrated as special tests, including thermistors, industrial platinum resistance thermometers and digital thermometers, remained at approximately 100, indicating that the public still has a need for these special calibrations.

R. Soulen and J. Wise completed a monograph entitled, Thermometer Calibration: A Model For the State Calibration Laboratory, that will be printed next month. With the help of this monograph, a state or industrial organization should be able to establish a laboratory to calibrate temperature measuring instruments in the range of 0 °C to +200 °C with an accuracy of 0.1 °C.

The computer has been put on the NBSNET, which saves a great deal of time in processing the data and producing reports of calibration. Generating reports of calibration in this way enables any errors to be corrected through the word processing program on the computer, and a new report generated immediately. Conversion of computer programs from the UNIVAC 1100 to the Cyber 205 has been completed.

J. Wise completed approximately one-half of the Documentation Project for laboratory thermometers.

J. Wise participated in the biannual Precision Thermometry Seminar and continued to work with ASTM as Secretary of E-20, Thermometry. She is also Secretary of Subcommittees E-20.90, Advisory, and E-20.05, Liquid-in-Glass Thermometers and Hydrometers. J. Wise serves as a member of ASTM Subcommittees E-20.91, Editorial and Nomenclature and E-20.08, Medical Thermometry.

II.D. SMALL TUNNEL DIODE OSCILLATOR PRESSURE SENSOR/GAS THERMOMETER

C. Van Degrift continued his transition to the Quantum Hall Effect project with 65% of his time spent helping M. Cage with proposal and report writing, major procurements, and the design of the new research laboratory. His experience with the low-temperature refrigeration and thermometry in high field solid helium-3 research is an excellent complement to the existing capabilities of the Electricity Division (521) in that project.

The remainder of Dr. Van Degrift's time was directed toward the completion of the Solid He-3 and the Tunnel Diode Oscillator Transducer projects. Calibrations of the two germanium resistance thermometers used in the solid helium-3 research against the melting curve, proceeded with difficulty. The lack of an <u>in situ</u> valve at the sample may prevent the calibration from being more accurate than ± 0.5 mK. Calibrations of the tunnel diode oscillator pressure sensor against a piston gage are nearly complete, although it was found necessary to spin the piston by hand since the drive motor introduced instabilities at the 10-ppm level.

An apparatus, constructed by visiting Italian scientist, Dr. F. Pavese of Istituto di Metrologia "G. Colonnetti", has been maintained to within 100 mK of 0 °C since January to study the reproducibility and long-term stability of the small tunnel diode pressure sensors. The results are not very encouraging, as we can easily see some relaxation processes which have a time scale of hundreds of hours. We will continue this study on a low priority basis in order to fully understand the fundamental physics of the relaxation. It tentatively appears that the diaphragm relaxation follows the non-exponential behavior proposed by P. W. Anderson, et al., for relaxation of "heirarchically constrained systems".

III. LOW TEMPERATURE SCALE

(E. Pfeiffer, J. Schooley, J. Colwell, H. Marshak, W. Bowers, W. Fogle)

This project is divided into two parts: (1) the temperature region covered by the EPT-76 (0.5 K - 30 K) and (2) the region below 0.5 K covered by the temperature scale NBS-CTS-1 (0.010 K - 0.5 K).

III.A. EPT-76: TEMPERATURE SCALE

Goal: The primary goal of the EPT-76 laboratory has been to establish at NBS the Provisional 0.5 K to 30 K Temperature Scale (EPT-76) and to provide a calibration service based on that scale. Secondary goals include a thermometric evaluation of the various resistance thermometers which presently serve, or may be candidates to serve in the future, as secondary reference standards in the EPT-76 region. Such evaluations would address such factors as sensivity, stability, durability, and smoothing or interpolation methods. Another secondary goal is the development of automated calibration procedures for transfer to other temperature calibration laboratories. An added goal in 1985 was evaluating the feasibility of performing automated calibrations of capsule platinum resistance thermometers (PRT's) on IPTS-68 between 13.81 K and 273.15 K in the EPT-76 comparison cryostat, with a view toward transferring such calibrations out of the PRT calibration lab.

Progress during FY 1985: A major accomplishment during FY 85 was the completion of a three month experimental run during which up to 19 resistance thermometers were variously compared at temperatures between 0.30 K and 295 K. Starting on May 2 and ending August 3, the experiment, for the most part, ran around-the-clock seven days a week, attended to by only one person. Some specific accomplishments from the run include:

a) Calibrated three germanium resistance thermometers (GRT's) and one rhodium-iron resistance thermometer (RIRT) over the range 0.5 K to 30 K against EPT-76 for outside customers. This reduced the EPT-76 customer backload to zero.

b) Calibrated three GRT's over the range 0.3 K to 100 K for another research project within the Division. An RIRT for the same project was found to be unsatisfactory for calibration due to excessive self-heating in vacuum, apparently as a result of leakage of the filling gas from the enclosing capsule. Also calibrated four additional GRT's from 1 K to above 90 K for general use at NBS.

c) Transferred EPT-76 from the two NPL-calibrated RIRT's which serve as main secondary reference thermometers for the scale at NBS to a third RIRT to serve as a backup reference thermometer. The backup RIRT was compared against both reference RIRT's at 43 temperatures over the range 0.45 K to 27.5 K. The resultant 86 calibration points were smoothed to a standard deviation of 0.12 mK by fitting the R values to a 12th order polynomial in T. This compares with a s.d. of about 0.15 mK for the smoothed NPL reference calibrations.

d) Measured the self-heating of four RIRT's (the three NBS 100-ohm RIRT's mentioned above plus a customer's 50-ohm device) over the range 0.5 K to 30 K. The results agree with earlier measurements done below 10 K.

e) Recalibrated a stable GRT which has been in continuous use at NBS for more than 20 years and which presently serves as a check thermometer for GRT calibrations in the range 1.5 K to 30 K. A preliminary analysis indicates that the latest calibration agrees with a 1983 calibration within 0.2 mK below 15 K and within 0.5 mK between 15 K and 30 K. This seems adequately within the claimed accuracy of ± 1 mK for NBS calibrations on EPT-76.

f) Realized the transitions of Superconductive Fixed Point Device SRM-767 (Delta). The transitions of this SRM constitute five of the 11 defining reference points of EPT-76. This particular device (Delta) is monitored during each EPT-76 calibration run as a check on the stability of the reference RIRT measurements for the range 0.52 K to 7.2 K. The results indicate a long-term stability and/or reproducibility of the combined SRM-767/RIRT measurement system of about ± 0.1 mK. This SRM-767 device also is periodically loaned to the SRM-767 production laboratory of J.F. Schooley to serve as an inter-laboratory check standard on EPT-76 temperatures disseminated by the EPT-76 calibration laboratory and by the SRM-767 production laboratory. A comparison of the two laboratories' results indicate an inter-laboratory agreement of ± 0.2 mK.

g) Compared three PRT's between 13.81 K and 181.7 K and at room temperature to assess the performance of the EPT-76 calibration cryostat above 30 K with respect to future automated PRT comparisons and to assess the non-uniqueness of present NBS IPTS-68 PRT calibrations in that region. Not suprisingly the largest disagreement of 1.2 mK occurred at 181.669 K, midway between the IPTS-68 calibration points of 90.188 K and 273.15 K. Between 100 K and 21 K the disagreement reduced to 0.3 mK or less, while between 21 K and 13.8 K it was as much as 0.7 mK.

h) Coincident with the PRT comparisons described above, the three RIRT's discussed in c) above were calibrated against IPTS-68 from the PRT's up to 94 K using the Cutkowsky automatic resistance bridge, and up to 181 K using the dc measurement system. Such calibrations should reveal any irregularities in the smooth merging of EPT-76 with NBS IPTS-68 at 30 K and, furthermore, might even reveal any "fine-structure" deviations of NBS IPTS-68 with respect to thermodynamic temperatures. A preliminary analysis of the data between 20 K and 94 K for one RIRT indicates that such merged calibrations are smooth to no better than about ± 0.6 mK.

Plans for FY 1985:

a) Although the final documentation of the EPT-76 research was not completed in FY 85 as previously planned, it is currently estimated to be 80 - 90 percent completed and the completed portion has undergone a preliminary division review. Selected results from the 1985 experimental run will be incorporated into the document, which is expected to be completed during the first quarter of FY-86. At that time the evolution of the EPT-76 laboratory will be considered complete and the calibration service completely documented. Thereafter, the calibrations based on EPT-76 will probably be conducted over a 3-month period once per year by E. Pfeiffer.

b) Limiting the EPT-76 calibration to a once per year event will free Pfeiffer to work on several projects in the new PRT laboratory.

III.B. EPT-76: SUPERCONDUCTING FIXED POINTS

SRM 767a contains six metallic samples (Nb, Pb, In, Zn and Cd) that are reproducible to within ± 0.3 mK. SRM 767a is in regular production (6 units supplied to the NBS Office of Standard Reference Materials this past fiscal year). The units are calibrated in a laboratory maintained by J. Schooley.

The major effort during FY 85 was given to evaluations of both the long-term and short-term temperature reproducibility attainable through the use of SRM 767a. Concerning the long-term drift, the first set of data comes from a study by E. Pfeiffer in his EPT-76 laboratory.

Pfeiffer re-measured the T_c values of the samples contained in the SRM 767a device, code-named "Delta". The data that he has obtained over a three-year period in this study are summarized in the following Table.

Evidence of an apparent long-term drift of 0.3 mK in Schooley's laboratory is under study. Evidence indicates that the observed "drift" in the T_c is not an actual variation in the superconductive transitions, but due to a measurement error induced by a change in laboratory procedure.

The short-term precision of a T_c measurement was studied in Schooley's laboratory. Experiments show that apparently it is possible to repeatedly measure temperatures that are uniform within ten microkelvins by the use of the SRM 767a devices.

During FY 86, Schooley plans a direct re-calibration of his RIRT against Pfeiffer's standards to test directly the possibility of thermometer drift. He also plans to complete measurements of the dependence of T_c upon magnetic field. A further experiment planned for the coming year involves evaluating the stability of paramagnetic thermometers by use of the SRM 767a device.

T_c VALUES OF SAMPLES IN THE SRM 767a DEVICE "Delta"

Element	T_c,K 1982	T_c,K 1983	T_c,K 1985
Pb	7.199 95 (dc) 7.199 90 (ac)	7.200 02 (ac)	7.200 05 (dc)
		Range = 0.000 15 K	
In	3.414 40 (dc)	3.414 46 (ac)	3.414 43 (dc)
		Range = 0.000 06 K	
Al	1.179 75 (dc)	1.179 75 (ac)	1.179 86 (dc)
		Range = 0.000 11 K	
Zn	0.850 35 (dc) 0.850 15 (ac)	0.850 20 (dc)	0.850 32 (dc)
		Range = 0.000 20 K	
Cd	0.519 95 (dc)	0.519 95 (dc)	0.519 93 (dc)
		Range = 0.000 02 K	

Note that the ranges of the measured temperature variations occurring in the T_c values listed in the table are no larger than 0.2 mK, and average about one-half that amount. Barring coincidental, simultaneous drifts of the reference thermometer calibrations and the sample transitions, these results place an upper limit of 0.1-0.2 mK on the long-term drift of T_c for the "Delta" samples.

III.C. NBS-CTS-1

This scale, developed at NBS and distributed wordwide via SRM 768, does not have international sanction. Research along parallel lines at other national standards laboratories (KOL; PTB-Berlin; Helsinki) should bring confirmation and the possibility of adoption of a provisional temperature scale from 1 mK to 500 mK by the CCT when the next scale is formulated.

The scale is based on a comparison of two absolute thermometers: noise and nuclear orientation. Research in both of these areas this past year has been directed at understanding all systematics so that ultimately a scale accurate to 0.1% will evolve. To these two primary thermometers are added two secondary thermometers: the melting curve of He-3 and the paramagnetism of cerium magnesium nitrate.

1. New apparatus

The keystone to the low-temperature scale is the establishment of a new apparatus which can be used to extend the measurements to temperatures as low as 1 mK. A new dilution refrigerator was installed this past FY. Leaks delayed the successful operation by 4 months. Retrofitting the apparatus with filtered, high-quality leads; upgrading the resistance bridge; improvements in the plumbing and numerous other upgrading projects took another 4 months. The apparatus has been successfully operated to temperatures as low as 4.5 mK three times and the performance of the system well documented. The thermometry experiments to be conducted on the new apparatus may now commence in FY 86.

2. Auxiliary thermometry

A SQUID system has been added to the cryostat and tested *in situ* in preparation for the paramagnetic measurements. A gas handling system has been built for the He-3 melting curve thermometer.

3. Noise thermometry

Improvements in noise thermometry have been made at the PTB-Berlin, which suggest that the performance of the NBS noise thermometer could by significantly improved by a radical redesign. Such are design was done and a new noise thermometer constructed. Tests will proceed in FY 86.

4. Nuclear Orientation Thermometry

The objectives of the nuclear orientation thermometry program are: a) Recompare the ^{60}Co*Co* (single crystal) γ-ray anisotropy thermometer and the Josephson junction noise thermometer to ~0.1%. b) Investigate rare earth systems for their possible use as γ-ray anisotropy thermometers in the temperature region above that defined by the ^{60}Co*Co* (single crystal) thermometer, namely above ~50 mK. c) Investigate the use of γ-ray anisotropy thermometers for absolute thermometry in magnetic fields.

a) The recomparison of the ^{60}Co^{59}*Co* (single crystal) γ-ray anisotropy thermometer and the Josephson junction noise thermometer is awaiting final test and modifications to the new ^{3}He/^{4}He dilution refreigerator in R. Soulen's lab. Preliminary data on the performance of ^{60}Co thermometer has been taken on the Marshak dilution refrigerator using both NaI(Tl) and Ge(Li) detectors. The agreement between the temperatures deduced using each detector is fairly good; however, since this refrigerator can only cool to ~15 mK, the results are not that conclusive (the peak of the ^{60}Co thermometer's sensitivity is at 6.9 mK).

New ^{59}Co single crystals have been prepared and are ready to be irradiated to produce the required ^{60}Co activity so that they can be used on the new dilution refrigerator discussed in item 1 above.

b) The collaborative (NBS-Freie Universitat-Bonn Universitat) research work on the low-temperature magnetic properties of the rare earth system $^{160}Tb^{159}\underline{Tb}$ (single crystal) is proceeding very nicely. Here at NBS we have measured the anisotropies of some of the more intense γ-rays as a function of magnetic field and temperature. These measurements were done on a bulk $^{160}Tb^{159}\underline{Tb}$ (single crystal) sample; i.e., one produced by irradiating the ^{159}Tb single crystal in a reactor - thus the ^{160}Tb activity is produced uniformly throughout the entire sample volume. Although the shape of our sample was not favorable to achieve magnetic saturation at the field that we used (1T) for these measurements, we were still able to deduce an approximate value for the quadrupole interacation. The latter enabled us to reduce the search region for the NMR-ON (nuclear magnetic resonance on oriented nuclei) experiment which was attempted again this past August in Berlin. (These measurements must be done on an implanted sample rather then a bulk one since the rf skin depth is only on the order of a few hundred angstroms. The radioactive ^{160}Tb is implanted in the surface of the ^{159}Tb single crystal sample using the isotope separator at Bonn Universitat.) The attempt in the summer of 1984 was unsuccessful since we had to search a large frequency range (~200 to ~1000 MHz) in small steps (2 MHz). The results of our latest search (the measurements are still going on in Berlin) indicated that the first resonance (transitions between the spin substates m = +3 and +2) is about 480 MHz. These results are very preliminary. If our measurements are successful (and we also find the resonance for $m = +2 \rightleftarrows +1$) then the $^{160}Tb^{159}\underline{Tb}$ (single crystal) system (either implanted or bulk samples) can be used for absolute thermometry in the temperature region from ~30 to 200 mK, complimenting the region defined by the $^{60}Co^{59}\underline{Co}$ (single crystal) thermometer. Some of these results will be written up shortly for a publication.

c) One of the problems often encountered in low-temperature experiments is that of being able to make accurate temperature measurements in a magnetic field. The only thermometers presently able to make absolute temperature measurements in a magnetic field are γ-ray anisotropy thermometers. Although some γ-ray anisotropy thermometers can operate without a magnetic field, e.g., the $^{60}Co^{59}Co$ (single crystal) thermometer, most of them require magnetic fields. Any field greater than that needed to achieve magnetic saturation simply adds to the hyperfine field already present at the nucleus. Thus the effect of the magnetic field can be accounted for exactly.

In order to demonstrate the usefulness of γ-ray anistropy thermometers (in a magnetic field) in fundamental metrology, we (Dr. G. Eska, Walter-Meissner Institute, Munich, West Germany; Prof. B. G. Turrell, University of British Columbia, Vancouver, Canada; Dr. R. M. Mueller, I.F.F. der KFA, Julich, West Germany; and H. Marshak) plan to measure the ^3He superfluid transitions. These measurements will be started this winter on Dr. Eska's nuclear demagnetization refrigerator in Munich.

IV. MEDICAL THERMOMETRY

(B. W. Mangum and G. Evans)

The goal of this program is to develop a set of temperature fixed points and a means of using them to calibrate transfer standards for the temperature region of interest (0 - 200 °C) to the medical community. The program is the responsibility of Dr. B. .W. Mangum who is assisted part-time by G. A. Evans.

The following table outlines the temperature fixed point program.

MEDICAL TEMPERATURE FIXED POINTS

Material	T_f (°C)	Status
Indium	156.63	Under study.
Succinonitrile	58.0805 ± 0.0015	SRM 1970 115 cells tested. NBS J. Res. paper written. SP-260 publication prepared.
Phenol	40.92	Under study.
n-Lauric acid	43.95	Under study.
n-Docosane	44.4	Under study.
Rubidium	39.303 ± 0.005	SRM 1969 SP-260 publication completed.
Ethylene carbonate	36.32	Alternative to Rb under study.
Gallium	29.772 ± 0.001	SRM 1968 Several papers published.

Specific accomplishments this FY include:

(1) Seventy-six triple-point cells of zone-refined succinonitrile were investigated this year (39 were tested last year) for their suitability to serve as SRM 1970, a new temperature reference standard at 58.080 °C. Since three cells (in some cases only two) are prepared from each zone-refined lot, the cells of each lot generally have slightly different freezing points due to the presence of different (small) amounts of impurities. Conseequently, it is necessary to test each cell for its suitability as SRM 1970. A total of 109 of the 115 cells prepared were deemed suitable to be used as SRM 1970 (their triple-point temperatures were not lower than 58.0785 °C). One of the 115 cells broke during tests. A histogram of the freezing-point temperatures of the 109 cells accepted , plus two of the cells rejected, as SRM 1970 is shown in Fig. 2. Figure 3 show how the cells of each lot were distributed. The mean value of the freezing points of the 109 cells accepted for SRM 1970 is 58.0796 °C, with an estimated uncertainty of ±0.0015 °C relative to the International Practical Temperature Scale of 1968. The total spread in the freezing-point temperatures of the 109 cells was 2.1 mK. The data on the 114 cells of succinonitrile were analyzed and a paper, entitled "SRM 1970: Succinonitrile Triple-Point Standard - A Temperature Reference Standard Near 58.08 °C" was written for the NBS Journal of Research and for the SP-260 series. This gives not only the results on the 114 cells, but also how the cells were prepared, and how the user of the SRM should proceed in realizing the temperature of this fixed point.

(2) We believe that an organic material, sealed in glass cells, with a fairly large heat of fusion would probably be easier for clinical laboratory personnel to use than the rubidium triple-point standard which by its nature must be sealed in stainless steel. With this in mind, some melting/freezing experiments on 2 large cell and several small cells of ethylene carbonate (melting point of 36.324 °C) were conducted to evaluate the suitability of this material to serve as a temperature fixed point near body temperature (37 °C). It appears that ethylene carbonate can be sufficiently purified that it can be used as a temperature reference point. Both melting and freezing experiments have been conducted on both the large and the small cells and from these preliminary experiments it appears that the freezing method, using the mush technique, yields results which are more reproducible than those obtained by the melting method. The material can probably be sufficiently purified that either method may be used for realizing the fixed point but the freezing method may be the simpler to use. In collaboration with Dr. John Cox of NPL, a study was made on the 2 large cells with SPRT's and also with thermistors. Both groups determined the triple-point temperature [we obtained the result that T(NBS) - T(NPL) = 0.3 ± 0.2 mK, maximum, using 3 SPRT's at NBS and 8 SPRT's at NPL], the purity, and melting/freezing behavior. In addition, B. Mangum investigated the time dependence of the approach to equilibrium after creating a mush condition following supercooling of the ethylene

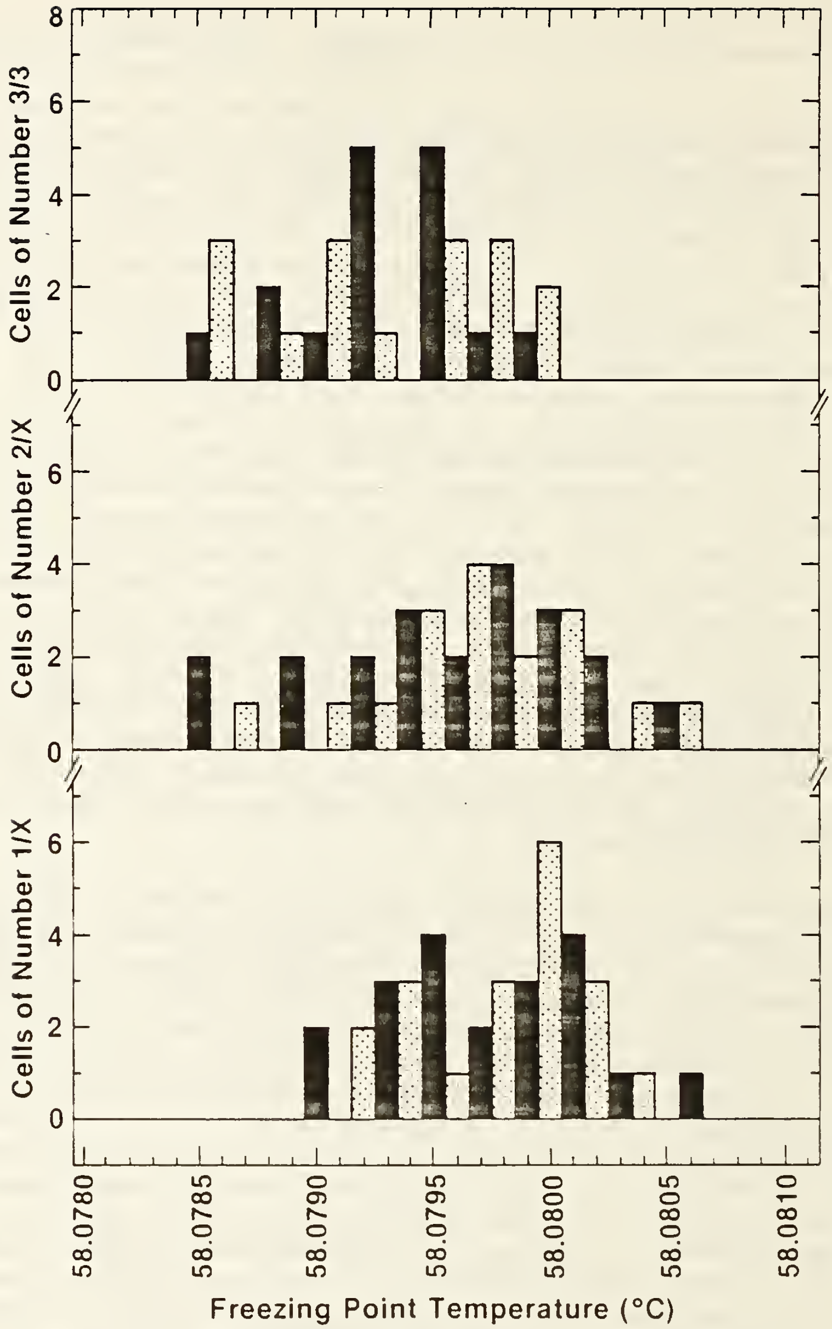

Fig. 2. Histogram of the triple-point temperatures obtained by freezing of all of the SRM 1970 cells. The histogram at the bottom of the figure is for cells designated -1/X; that in the middle of the figure is for cells designated -2/X; and that at the top of the figure is for cells designated -3/3.

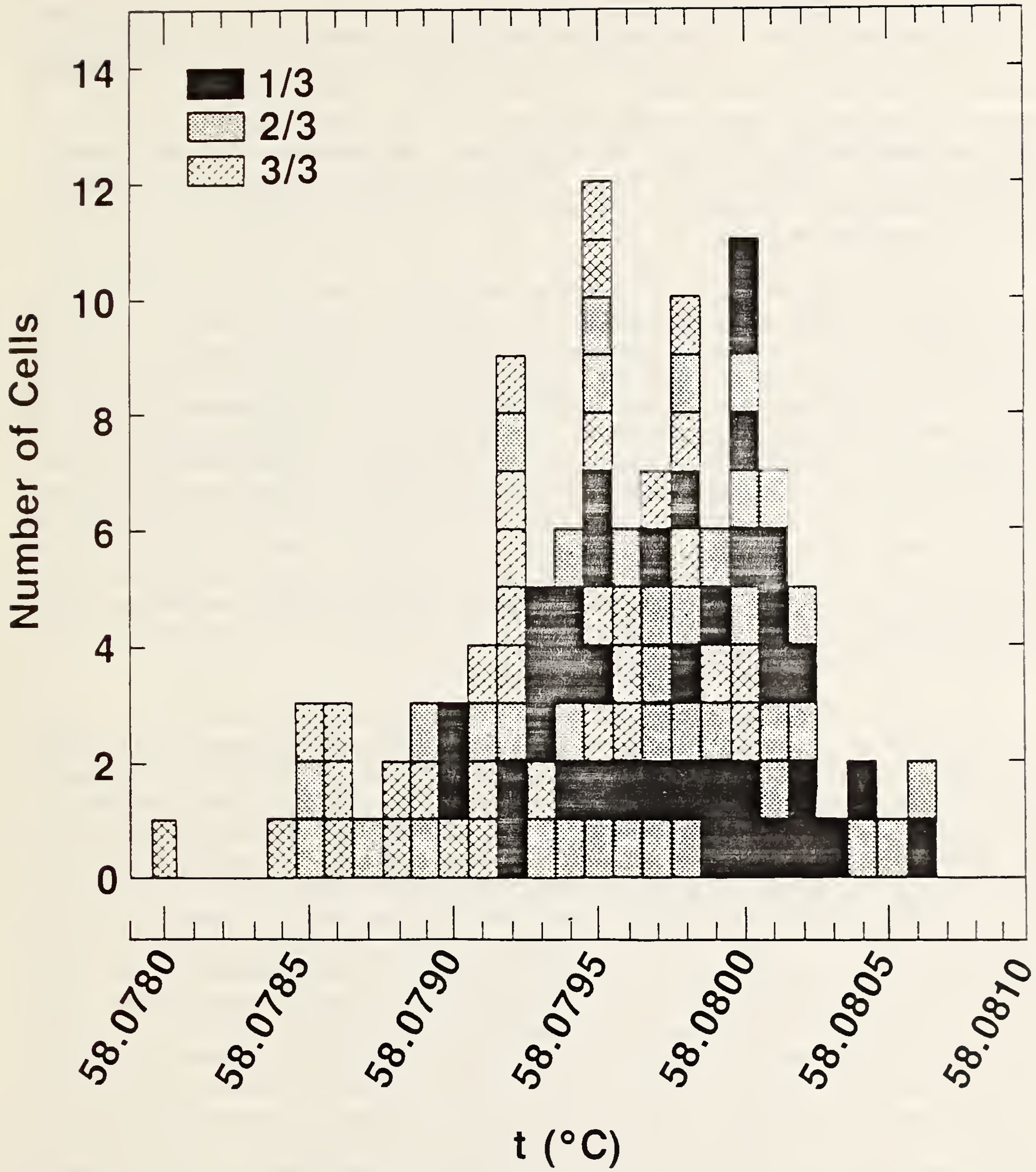

Fig. 3. Histogram of the triple-point temperatures of the 109 cells of SCN accepted as SRM 1970, plus those of two cells with temperatures below 58.0785 °C, which, consequently, were rejected as being unsuitable for SRM 1970.

carbonate, and showed that the technique being used by NPL was flawed. A compilation of our data has been made and a paper to Metrologia will be written shortly. We plan to investigate the melting and freezing behavior of some more small cells of this material next year to ascertain not only the agreement among the cells of a given lot but also that among the cells of different lots. The amount of purification necessary to produce cells with freezing points within a sufficiently narrow range of temperatures to make this material suitable as an SRM must be determined also.

(3) Just as there is a special need for a temperature fixed point near body temperature, so there is a special (even critical) need for two fixed points bracketing the hyperthermia range used in cancer therapy. Those two points should be at about 41 or 42 °C and 44 or 45 °C. Several materials have been selected as possibile candidates for those temperatures, and one small cell of phenol and 3 small cells of n-lauric acid, have been obtained. More cells of these materials have been ordered, as has cells for one other material, n-docosane. We made some preliminary studies of the small triple-point cells of phenol and n-lauric acid during the year and these materials look promising. Since hyperthermia is used in cancer therapy, some discussion with personnel of the National Cancer Institute has already taken place regarding their funding some of this work. The funding by the NCI, if successful, would not be available until mid-1986.

(4) The investigation of the melting/freezing behavior of high-purity indium in small Teflon cells has continued in order to further test the feasibility of using this point (and realized in such small cells) as a temperature fixed point, and to develop it into an SRM. A collection of cells of different sizes, different immersion depths and constructed with different kinds of high-temperature epoxy has now been prepared and tested. Based on the results of that work, a design of cells appropriate for SRM's has been made and an order for the construction of 100 cells has been put into the NBS instrument shops. In addition to the possible use of indium as an SRM temperature fixed point, there is the possibility of using it as a temperature fixed point for the International Practical Temperature Scale. In fact, a fixed point at about the melting point of indium is urgently needed for the calibration of capsule SPRT's, to provide a more accurate calibration for the most accurate and precise work needed in research, and to provide a check on the routine calibration of SPRT's. With this in mind, we are proceeding to make a thorough investigation of the indium melting/freezing behavior and of the reproducibility of the melting/freezing-point temperature. We have begun testing of our two cells of indium, filled with 99.9999% pure indium, the cells being of sizes sufficient for use with long-stem SPRT's and capsule SPRT's. We have had a lot of trouble with the oil bath being used in investigating the melting/freezing behavior of the indium in the two cells, but the problems have been solved now. Some preliminary results on the large cells indicate the pressure dependence of indium to be

4.95 ± 0.04 mK/std. atm. A preliminary value of the freezing-point temperature of one of the cells is 156.635 °C. We plan to continue measurements on the cells during the coming year.

(5) We have begun an investigation of the quality of diode thermometers at temperatures below about 400 K. The equipment required for this investigation was acquired and the computer program for controlling the experiments and acquiring the data has been written and, for the high temperature part, i.e., 77 K to 400 K, has been tested. A selection of 30 of "the best" diode thermometers were purchased and 10 of them were installed in the cryostat. In order to gain experience with the diodes, we have started the investigation by studying their and our equipment's behavior at temperatures above 77 K. Following completion of this aspect of the study, we will begin the investigation at temperatures below 78 K. Also, an investigation for NASA of 10 very small diodes designed for surface temperature measurements has begun in the range 77 K to 335 K. These also will be investigated at cryogenic temperatures during the next phase of the NASA project.

V. DYNAMIC PRESSURE AND TEMPERATURE

(G. Rosasco, W. Hurst and R. Dove)

Goal: The goal of this project is to develop the means of measuring P and T with high temporal response (10 ns) and high spatial resolution (mm^3). A laser diagnostic technique based on nonlinear optical spectroscopy is used. Specifically the project is designed to develop the algorithms for inferring P and T from spectral lineshapes and intensities. A second goal is to accumulate reference data and develop predictive theory for selected gases of importance in diagnostic applications.

Accomplishments in FY 85: We have completed measurements of the electronic contribution to the nonresonant third order nonlinear susceptibility of H_2. As discussed in earlier reports, the nonresonant electronic term in the third order susceptibility is important in CARS (coherent anti-Stokes Raman spectroscopy) diagnostics of temperature and pressure because the CARS signal depends on the squared magnitude of the third order susceptibility. Thus, there are terms in the response which are interferences between the (real) nonresonant contributions and the (complex) resonant contributions. These interference terms dramatically alter the shapes of the spectral bands and thereby can lead to uncertainties in the determination of temperature and pressure. (The values of these quantities are strongly dependent on fitting spectral shapes.)

Our measurements of the H_2 susceptibility generally followed the approach used previously for Ar and N_2. The experimental procedures and data analyses were improved and better precision achieved. The data and best fit model for the density dependence of the observed nonresonant signal normalized by the amplitude of the resonant susceptibility of the D_2 internal standard are shown in Fig. 4. The points labelled "M_{Best}" are the pressure dependent response of the optical system which was determined from two separate experimental runs (1 - 6 atm) on D_2:He reference samples. The best value for the ratio of the total nonresonant background of H_2 to the amplitude of the internal standard A_oN_o has an uncertainty of +0.0003 and -0.0005, i.e., approximately ± 3%. This level of precision is approximately 3 times better than that achieved in our earlier measurements. From this ratio we calculate the electronic contibution ($3\sigma/24$) (approximately 1/2 the total) to be 0.445×10^{-18} esu with an uncertainty (not including the uncertainty of the reference standard) of ± 6%.

In order to more accurately interrelate the values of the electronic susceptibility measured by other nonlinear optical techniques (see Table from last year's report) and thereby assess the accuracy of our knowledge of this quantity, we have used a simple model for the frequency dependence of the electronic term in the third order susceptibility. This quantity is a function of the four frequencies involved in the experiment, and the simple dispersion relation we have

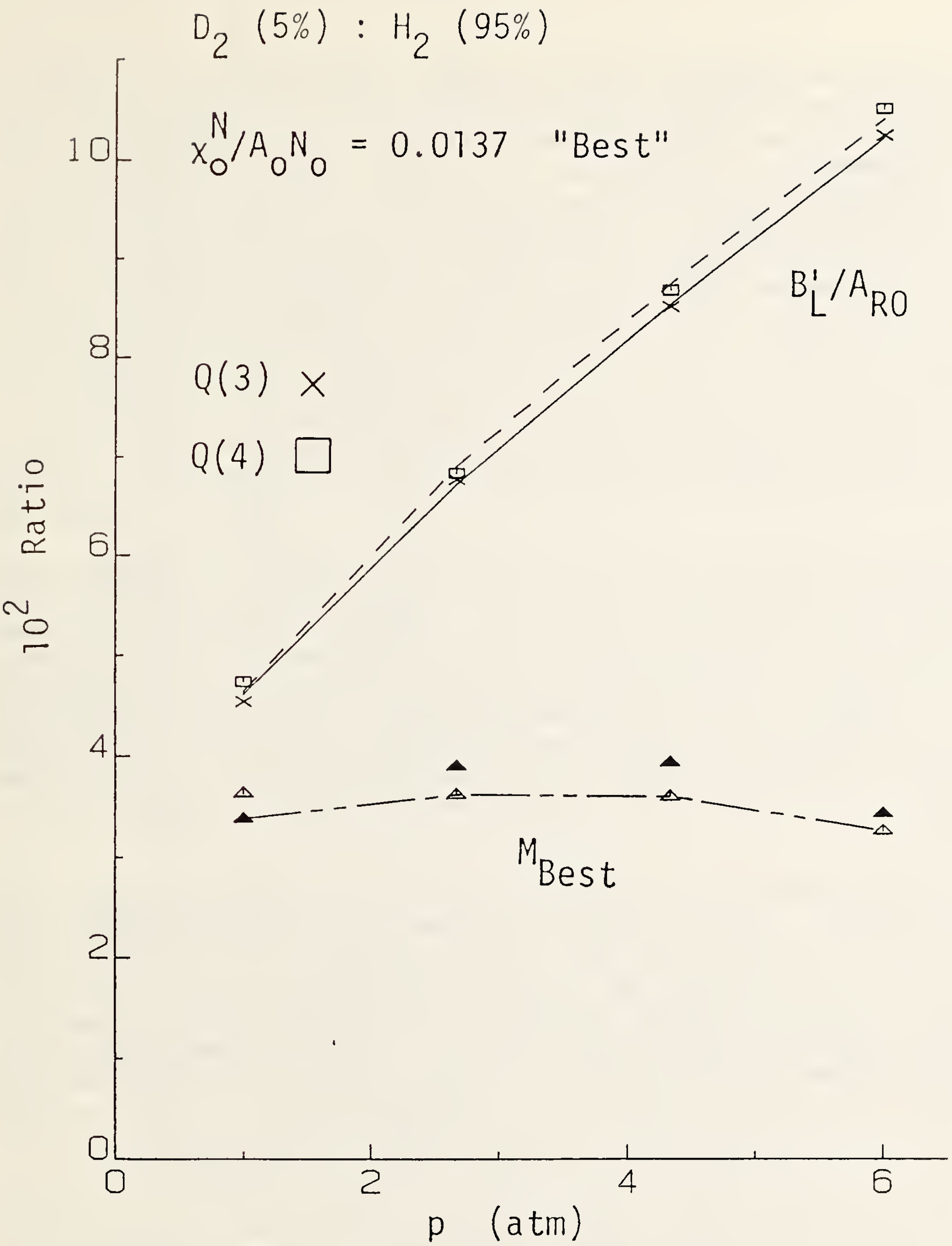

Fig. 4. Measured pressure dependence of the nonresonant signal normalized by the amplitude of the resonant susceptibility of D_2, obtained in determination of the nonresonant susceptibility of H_2 (top curve). The lower curve indicates the pressure dependent response of the optical system, a contribution included in the data analysis. The "best" value obtained for the normalized nonresonant background of H_2 is indicated.

used is based on approximating the electronic term as the product of four first order susceptibilities. This leads to a dispersion formula which depends on an effective squared frequency equal to the sum of the squares of these four frequencies. We applied this formula to the data compiled and measured in our earlier work, to recent measurements by Shelton of the dispersion of the susceptibility in field induced second harmonic generation (FISHG), and to the theoretical calculations of the susceptibility of He which is the (absolute) reference standard for the FISHG measurements. The results of this analysis are displayed in Fig. 5. Remarkably, all the data can be accounted for by this simple dispersion formula. Our analysis is the first demonstration of a unifying dispersion relation for all nonlinear optical techniques. We now feel confident that gas phase susceptibilities can be accurately (better than 5%) predicted for any technique of interest if a reliable value is available from any other technique or at some other wavelength.

Work also has continued on modelling the spectral lineshape under conditions where both velocity- and phase-changing collisions are important. The importance of accurate predictions of spectra under these conditions increases with increasing temperature, as discussed in last year's report. We have now developed a fast, rapidly convergent computer program for fitting experimental lineshapes to the two "standard" models which apply under these conditions. The standard models are the hard and soft collision models. Data for five systems (D_2:X, X=D_2, H_2, He, N_2, Ar) have been acquired and/or analysed over the past year.

The development of a (Raman) pump laser of high peak-power and narrow bandwidth also has been in progress during the past year. The requirements for the pump laser in the context of our work and some alternatives for providing the necessary performance were discussed in last year's report. We have pursued the development of an injection-seeded (also termed, somewhat inaccurately, injection-locked) high power flash lamp pumped dye laser (FLPL). Using a number of FLPLs, which we assembled from parts loaned to us by other groups at NBS, we have succeeded in building a system which produces ~10 mJ in a 1 μs pulse (10 pps) with a full bandwidth of under 8 MHz. The spectral purity of this laser is quite high in that the power at the peak of the 8 MHz component is of the order of 1000 times that at the peak of any residual broadband component in the output of the laser. We note that the non-seeded, free-running FLPLs typically produce outputs with bandwidths of 10's-100's of cm^{-1} ($1\ cm^{-1} = 30$ GHz). The spatial mode of this laser also is very good, being essentially TEM_{00}. The bandwidth of our system is at least 2-5 times more narrow than that of lasers based on (doubled) Nd:YAG pumped dye laser amplifiers. However, for our experimental needs the peak power of this laser is too low. We now are investigating a two stage FLPL system to increase the peak power by a factor of 5-10. We are confident that we can achieve the power requirements, but must determine if the spectral purity and spatial mode quality are sufficient for our needs. If successful, the two-stage FLPL system will be

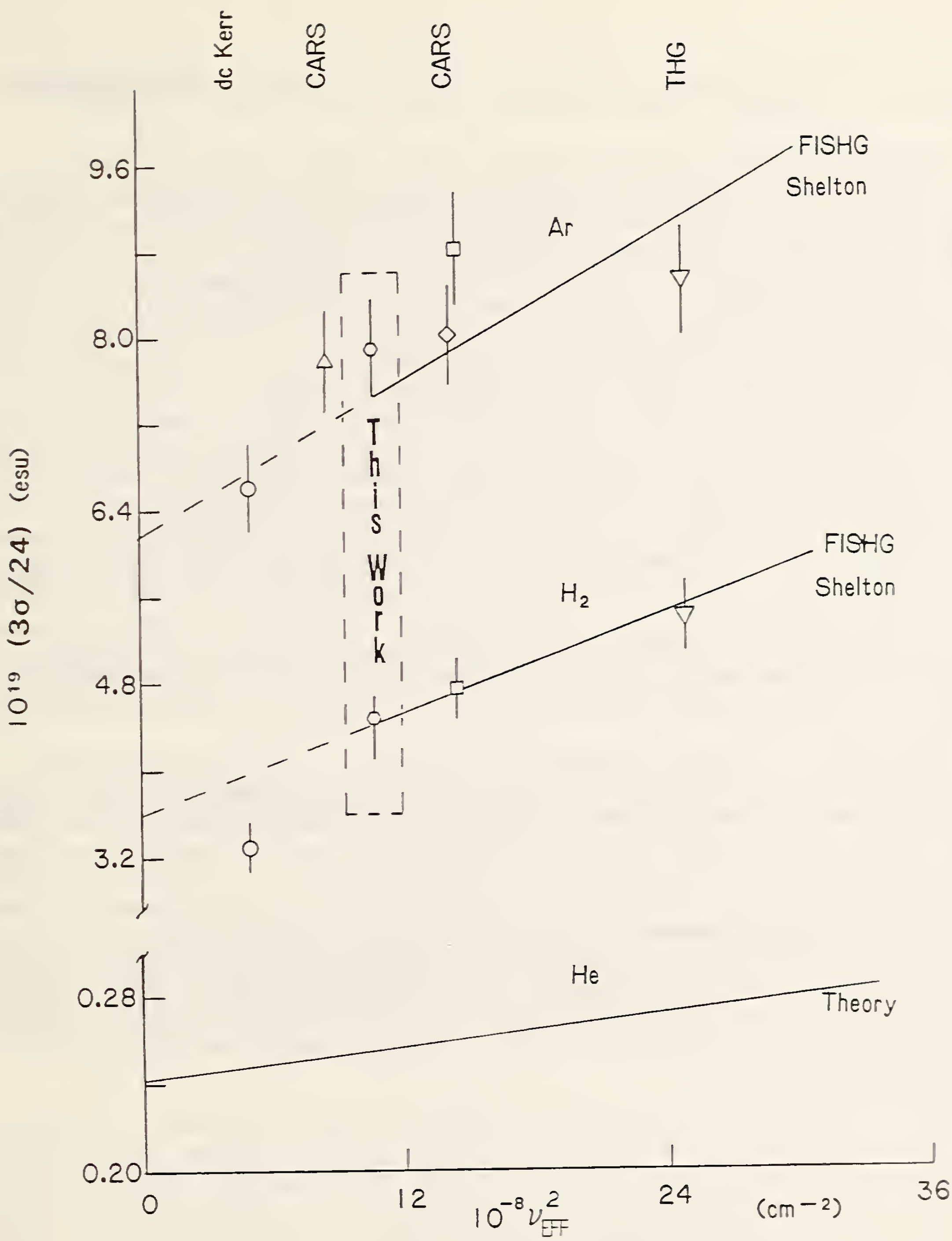

Fig. 5. Electronic hyperpolarizabilities of Ar, H_2 and He at 1 amagat, 296 K, measured by various workers using the labelled experimental techniques versus the square of the effective frequency obtained from the dispersion relation.

superior to any existing alternative for the needs of our experimental program.

Plans: In the coming year we have a number of projects planned which will be pursued in collaboration with scientists who will be joining our effort on a temporary basis. A postdoctoral trainee from Howard University, Dr. Larry Petway, will be working with us over the next year on the problem of the effects of velocity-changing collisions in diagnostic spectra. He will be exploring both experimentally and theoretically the prediction of line shapes for both heavy and light collision partners over a large range of temperature (to 1800 K). A guest worker collaboration has been established with Prof. David May of the University of Toronto, Physics Department. The experiments to be conducted at NBS with Prof. May involve line broadening and shifting of the Q-branch spectrum of HD. Our facilities are uniquely suited for these measurements and Prof. May's expertise in problems of pressure dependence of Q-branch spectra will be very helpful in our work. Dr. Kermit Smyth of the NBS Center for Fire Research will be joining us for an NBS Internal Sabbatical in October 1985. His interests are in learning more about the techniques of nonlinear Raman optical diagnostics and in determining a predictive basis for diagnostic spectra. The emphasis of this collaboration will be on experimental studies of foreign gas broadening and the temperature dependence of line widths.

The first few months of the experimental program for the coming year will be centered on the final stages of development of the high peak-power Raman pump laser, the variable T and P furnace, the gas mixing system, and the data acquisition system. The latter three systems are close to completion but do require final assembly and testing. Since there are still major questions to be resolved in the case of the performance the Raman pump laser, we have begun more serious planning for the development of the system based on a single longitudinal mode, injection-seeded Nd:YAG laser (see last year's report). Clearly, the laser systems remain a major challenge for our experimental program.

VI. PISTON GAGES

(V. Bean, G. Driver, W. Markus, B. Welch, and J. Houck)

Goal: The piston gage is the instrument of choice for precise pressure measurements in the range above the limits of manometry. The instrument consists of a carefully made piston fitted into a matching cylinder which is, in turn, connected to a pressure generating system. The piston is loaded with known weights, floated by adjusting the pressure using a transmitting fluid, and rotated to relieve friction and to assure concentricity. The pressure is calculated as the ratio of the downward force due to the weights loaded on the piston to the effective area of the piston-cylinder combination. Our goal is to determine the effective area at atmospheric pressure A_o, and the change in the effective area with pressure, in order to: (A) equal or surpass the other national standards laboratories; (B) provide American piston gage manufacturers with the needed calibration services to keep their products competitive in the world market; (C) meet the need for increased accuracy requested by our calibration service customers, such as the DoE and DoD laboratories.

Commercially available gages span the range from 2 kPa to 1.4 GPa and may be designed for use with gases or fluids in appropriate parts of the range.

Progress in FY 85: During FY 85 we have conducted a systematic search for those factors that can affect the accuracy of three special piston gages at the part-per-million level. We have demonstrated that:

A. A_o

1. In the absolute mode, gas molecules escaping out of the annular space between the piston and the cylinder and colliding with the underside of the weight hanger can change the pressure at one atmosphere by about 2 ppm. There is no effect in the gage mode since the mean-free path of the gas molecules is so short compared to gage dimensions.

2. When two gages having areas differing by a factor of 4 are balanced in the gage mode and then the space around the weights evacuated (the absolute mode), we find that the air bouyancy correction for the weights does not fully account for the resulting out-of-balance condition. The effect is a function of the gas used as the pressure medium. For example, for helium at one atmosphere it amounts to about 1 ppm, for nitrogen, it is 23 ppm. The effect is also a function of pressure and the width of the gap between the piston and the cylinder. There are two possible mechanisms by which gas molecules could exert a vertical force on the piston and create this effect. The first is momentum transfer due to molecular collisions with the piston; the second is electrostatic force due to the charge on the molecules. When the measured differences were plotted for six gases, the correlation with molecular weight was poor, while the plot versus the electrostatic

force term for the Van der Waals equation of state is rather monotonic (Fig. 6). This suggests that electrostatic force rather than momentum is the more likely explanation.

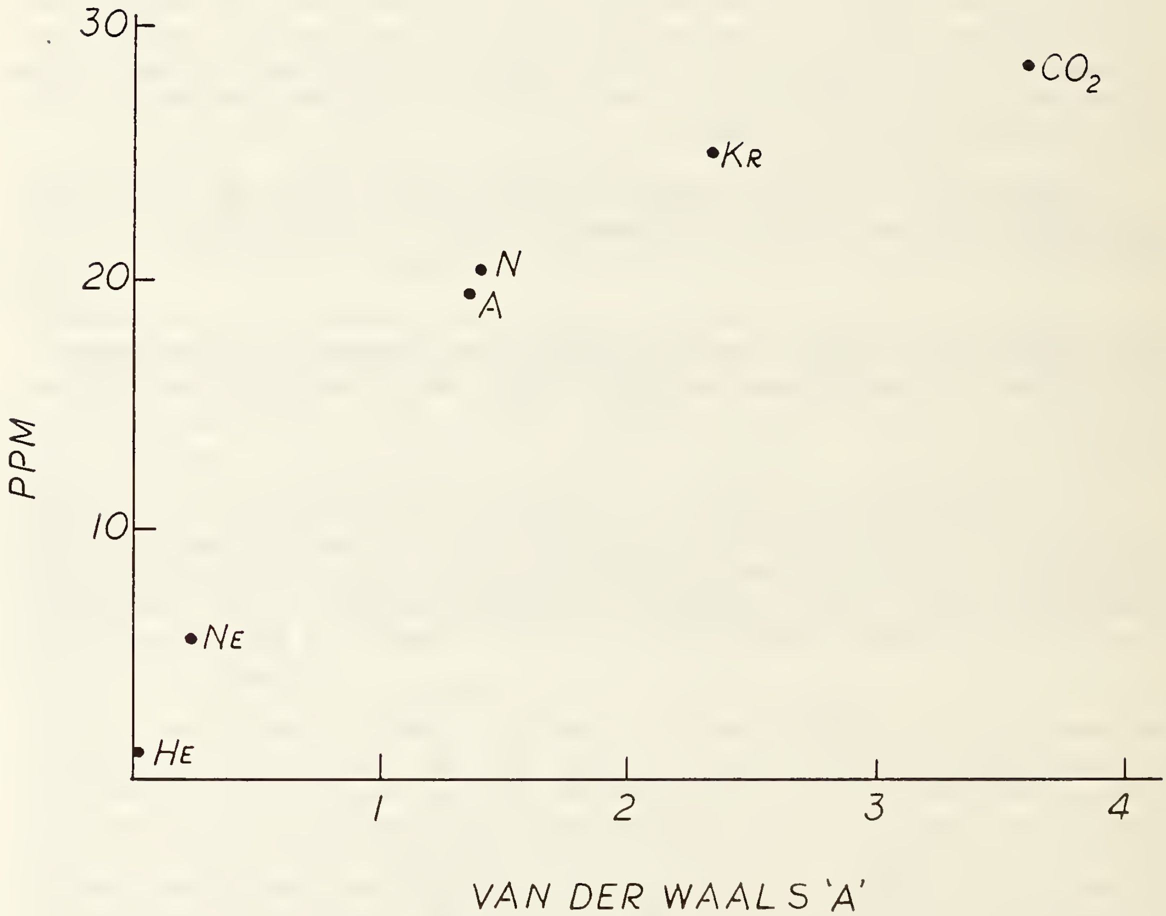

Fig. 6. Pressure differences between gage and absolute mode for several gases plotted as a function of the Van der Waals electrostatic term.

The next step in this investigation is to determine the gas density along the length of the annular space between the piston and cylinder while the gage is operating in both the absolute and gage modes. This density distribution will be studied as a function of pressure using several gases. Current practice in piston gages assumes that a calibration done in the gage mode is valid in the absolute mode. Clearly, in light of these new results, that is a poor assumption. We are now in a position to provide emperical corrections for the effect, but understanding of the underlying physics requires more work.

B. Distortion

1. Pressure coefficient. Work continues on improving methods to determine piston gage pressure coefficients. We have designed and built an apparatus to measure the change of the outer diameter of the cylinder of a piston gage as a function of pressure and length along the cylinder. The essential feature is a guarded capacitor electrode in the form of a thin ring surrounding the cylinder and mounted such that it can be moved with a micrometer head along the length of the cylinder. The instrument has nanometer sensitivity. Figure 7 shows the change in cylinder outer diameter at 25 MPa plotted as a function of length along the cylinder. When this preliminary data is confirmed with other measurements, then the results will be compared with calculations based on a rigorous solution of the biharmonic equation as a test of the suitability of the equation for calculating the distortion coefficient.

2. Controlled-clearange gages. At higher pressures, the only appropriate way to deal with the distortion problem is to use a controlled-clearance piston gage. We have begun the design of a new 280-MPa controlled-clearance gage which incorporates a commercially available piston and cylinder assembly. This gage is intended to become a new primary standard in that range.

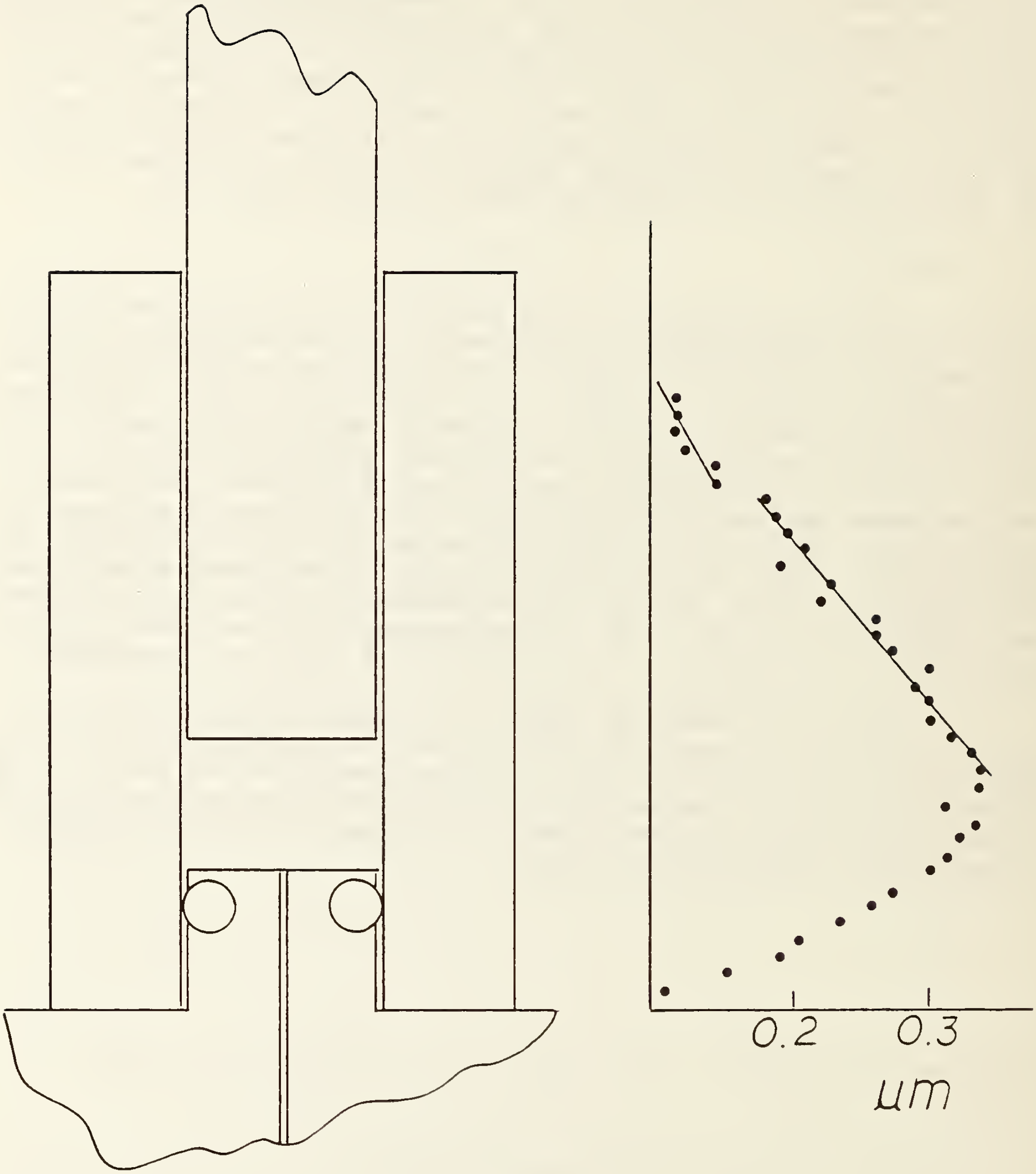

Fig. 7. The change of outer diameter of the cylinder of a piston gage at 25 MPa plotted as a function of length along the cylinder.

VII. VACUUM

(C. Tilford, D. Martin, S. Wood, R. Hyland, C. Ehrlich, A. Filippelli F. Long, and K. McCulloh)

VII.A. MANOMETRY

The cornerstone to this program is the ultrasonic interferometer manometer (UIM). It is used for calibrations, as a prototype for other manometers, and as a research tool. In the first category, the UIM has continued to serve as a workhorse for low pressure and vacuum calibrations, including those required to support in-house activities. The number of "for fee" calibrations of capacitance diaphragm gages increased only slightly to 14. However, a like number were performed to maintain the gages used in the leak and high vacuum flowmeters, and to verify the continued stability of the gages used in the BIPM-sponsored low-pressure round robin, for which NBS is the pilot laboratory. An increasing number of ball gages, widely used for low range differential pressure measurements, have been received for calibration on the UIM. This has required a considerable amount of time as we attempt to understand the low range performance of this type of gage.

The accuracy of the pressure measured by the UIM is currently limited by one major factor - the uncertainty in the speed of sound in mercury. A separate apparatus has been built to measure this quantity. The instabilities in these measurements are two to three times larger than expected, but the temperature uniformity and stability are somewhat better than expected. Some difficulty has been experienced in controlling the mercury levels, but the main problem at this time is the failure of an infrared detector and its backup spare, used to stabilize the CO_2 laser. Delivery of a replacement unit is expected shortly.

The precision of the UIM may be inferred from a comparison with another type of a gage (a piston gage, PG14). The precision is 2-4 ppm with comparable long-term stability.

Several design changes in the UIM have been developed, to the point that they can be implemented. They are intended to enhance the "high" pressure performance of this instrument. These include a better temperature control system, direct coupling of the ultrasonic transducer to the mercury, and improved RF electronics and microcomputer control systems. These will be implemented and tried out in instruments to be built for the Navy Engineering Metrology Center and the Sandia Primary Standards Laboratory. The Navy has requested a 2-3/4 meter manometer, 2-1/2 times the range of our present instrument. This will present significant fabrication and assembly problems, but will allow us to explore the upper limit to the range of this type of instrument.

A measurement survey of the accuracy of aircraft altimeter calibration facilities at 57 locations throughout the country was conducted with the assistance of A. McCoubrey and G. Driver under the sponsorship of the Federal Aviation Administration. The results are still being analyzed but it is clear that the accuracy varies greatly between facilities.

VII.B. HIGH VACUUM STANDARDS

The major effort has been in the extension of our vacuum standards to lower pressures and the development of leak rate standards. Concurrent with this has been a rapid increase in our high vacuum calibration work load, participation in an international vacuum standards comparison, and continuing investigations of the properties of vacuum transfer standards, most notably the spinning rotor gage. This has generated an intolerable overload on existing equipment, particularly our primary high vacuum standard. Thus, much of the past year has been spent building custom equipment, getting it into service, and finding the space to accomodate it. In February the high vacuum lab was shut down for three months and was doubled in size. The new space allowed us to install part of a vacuum system which we had obtained as surplus from NASA and modified to serve as part of an interim leak rate standard. We have also installed and are presently testing a new "bellows" flowmeter that will supplement our existing "piston" flowmeter and be used with both the leak standard and the vacuum pressure standard. A second part of the NASA system has been more extensively modified and intial testing begun. This sytem will initially be used for tests related to the development of ultra-high vacuum standards, but our intent is that it will ultimately become part of an improved leak standard. A third, entirely new, system has been designed and is nearly half fabricated in the NBS shops. It is intended to operate at lower pressures and take some of the overload from the primary high vacuum standard. It has also been designed to permit the experimental investigation of certain systematic errors that are difficult to theoretically model.

In spite of the disruption of the laboratory and the substantial effort expended on getting the new equipment designed and into service, there has been considerable progress made with available equipment. By refinement of our operating procedures and small modifications to the equipment we have been able to extend the range of the existing primary high vacuum standards two decades down, and confirm that we can make reliable measurements at 10^{-6} Pa (10^{-8} Torr), although with an increase in the uncertainty to 5%. An extensive series of measurements have been conducted on a group of spinning rotor gages as part of an international high vacuum round robin conducted under the auspices of the BIPM. These data (for our lab only) have been combined with other data as part of an error assessment that will appear, along with a description of the apparatus, in an archival journal publication. We also managed to perform 24 high vacuum "for fee" calibrations during the year, up from 12 the year before, but apparently a record soon to be surpassed, as 14 calibrations have already been scheduled for FY 86 as of the end of September.

Characterization of vacuum transfer standards continued at a somewhat reduced pace. The main activity was the investigation of the behavior of hot filament ionization gages in magnetic fields, a problem of particular interest to the magnetic fusion research program. The results were quite complicated, but did establish that radical changes in gage behaviour can occur at fields as low as a few hundred Gauss. The most dramatic changes are negative collector currents and oscillations within the gage structure in the 100 to 600 MHz range. Work on the spinning rotor gage has continued as an integral part of our high vacuum standards and calibration work. We have been attempting to correlate gage performance and signal characteristics, understand the frequency dependence of the residual drag, and accumulate a body of historical calibration data to assist in evaluating the long term stability of this type of gage. Most of our results to date have been published in archival journals. Bernd Lindenau, one of the co-developers of the spinning rotor gage, joined us in July as a guest worker, and has started a research program to address the factors limiting the low pressure range of the gage.

In spite of the pleasing success this last year in reducing the lower limit of our high vacuum standard it is apparent that future gains will be harder to make. We are now at pressures where we can no longer rely on the types of gages that we understand as a result of the previous year's work, and both lower range leak and pressure standards will require better understanding of UHV gages. Limited characterization work will soon start on UHV nude BA gages, modulated BA gages, and extractor gages. We will also begin preliminary work towards better understanding quadrupole mass spectrometers. We are further limited by the hydrogen background in our vacuum systems. One of the experiments scheduled for the second modified NASA vacuum chamber is a "low" temperature (450 °C) bake in a nitrogen atmosphere to determine if we can significantly deplete the interstitial hydrogen. If this fails we will have to pursue high temperature vacuum baking, or use of aluminum vessels. A broader concern is that, as we go lower in pressure, certain assumptions in the design of the standard become more critical and there is little or nothing in the way of other standards with which to make comparisons. Therefore, in the interest of developing an alternative measurement technique employing different physics, we have entered into and are providing financial support for a collaborative research program with Bruce Kendall of Penn State University to investigate a Brownian Motion gage. As an absolute standard the Brownian motion gage should in theory improve as the pressure is reduced, but there are several practical problems that must first be solved. Kendall's experience in this area should be very valuable in making a start in addressing these problems.

Last February two more training courses were held on the use of the spinning rotor gage. In spite of the time of year and limited publicity we quickly had capacity attendance, and the demand continues. The additional equipment and laboratory space now available will allow us to expand the class size, and, most importantly, avoid the complete shut down and removal of some experiments during the classes. We also had larger than expected attendance at a workshop cosponsored last spring with the Fusion Technology Division of the American Vacuum Society on the Calibration of Residual Gas Analyzers. A doubling of expected attendance to 80 necessitated a more formal format than we had desired. Workshops are being organized for the fall of 1986 on ultra high vacuum gaging and for the spring of 1987 on leak standards and calibrations. It is expected that a followup to the RGA Workshop will be held in 1987.

VIII. LEAK STANDARDS

(C. Tilford, R. Hyland, C. Ehrlich, S. Wood, F. Long, D. Martin)

The leak rate standards program has benefited greatly from the high vacuum standards development and is off to a fast start. A series of measurements were performed using the high vacuum primary standard and the piston flowmeter on two sintered metal transfer leaks calibrated by the Sandia Primary Standards Laboratory (SPSL). It became apparent that one of the leaks was not stable but measurements on the other leak, and subsequent recalibration by SPSL, indicate agreement between the two laboratories to within a few percent between 4×10^{-11} and 3×10^{-8} moles/sec (10^{-6} and 7×10^{-4} std cc/sec). A second series of measurements have been performed using the modified NASA vacuum chamber, using both the piston and the new bellows flowmeter, and a sintered silicon carbide transfer leak. These measurements have shown agreement between the two flowmeters at the low end to better than a percent and have been combined with the earlier measurements to establish a lower limit of our present measurement capability of 10% at 10^{-11} moles/sec (2×10^{-7} std. cc/sec). These results will appear in an archival publication.

The helium leak comparator contributed by the SPSL has been modified to broaden its temperature range. It has been used to investigate the temperature dependence and equilibration times of helium diffusion leaks. It is expected that it will be an integral part of the leak special test service that we plan to offer in the near future.

At the moment the primary technical problem preventing the early introduction of a leak calibration service is the lack of reliable transfer standards. The results with the sintered metal leak were disappointing. The results for the one SiC leak tested to date has been encouraging and several other transfer leaks have been fabricated, and will be tested.

An article was written which was chiefly educational in nature. The tradition of characterizing flow (leak) rates in terms of a "throughput" rather than a true flow rate has evolved over the years. This article addresses this problem and attempts to encourage users to use the more properly defined physical unit.

INVITED TALKS

Temperature and Pressure Division (522)

Vern E. Bean, "Pressure Metrology: Primary Standard Piston Gages", Proceedings of the 10th Conference of the International Association for the Advancement of High Pressure Science and Technology, Amsterdam, 8-11 July 1985.

George T. Furukawa, "Fixed Points of Thermometry" ASTM Committee E20 Technical Talk, Los Angeles, CA, 22 May 1985.

Richard W. Hyland, "Some Characteristics of Transfer Leaks", 14th Annual Symposium Applied Vacuum Science and Technology/Florida Chapter, American Vacuum Society, Clearwater, FL, February 4, 1985.

G. J. Rosasco, "Dispersion in the third-order nonresonant susceptibility", Gordon Research Conference on the Laser Diagnostics in Combustion, New London, NH, July 1985.

Robert J. Soulen, Jr., "Recent Advances in Pressure and Temperature Metrology at NBS", Physikalisch-Technische Bundesanstalt (PTB), Berlin, West Germany, 19 June 1985.

Robert J. Soulen, Jr., "Recent Developments in NBS Cryothermometry", Freie University of Berlin, Berlin, West Germany, 24 June 1985.

Sherry D. Wood, "Things Your Mother Never Told You About the Spinning Rotor Gage", Tennessee Valley Chapter, AVS, Knoxville, TN, April 30, 1985.

PUBLICATIONS

Temperature and Pressure Division (522)

IN PRINT:

1. J. C. Legras, **V. E. Bean**, J. Jager, S. L. Lewis, and G. F. Molinar, "Note on the results of the first phase of an international comparison in the pressure range 20-100 MPa organized by the High Pressure Working Group of the Comité Consultatif Pour la Masse, J. Phy. E: Sci. Instrum. 18, 361 (1985).

2. J. C. Legras, **V. E. Bean**, J. Jager, S. L. Lewis, and G. F. Molinar, "International comparison in the pressure range 20-100 MPa organized by the High Pressure Working Group of the Comité Consultatif Pour la Masse," BIPM Technical Report 84/2.

3. **J. H. Colwell, W. E. Fogle**, and **R. J. Soulen, Jr.**"The NBS Temperature Scale in the Range 15 to 200 mK", Proceedings of the 17th International Conference on Low Temperature Physics, Karlsruhe, FRG, August 15-22, 1984; (North-Holland, Amsterdam, 1984) p. 385.

4. **C. D. Ehrlich**, A. Deforge and R. Kiebert, "A Technique for Optimizing the Disc Uniformity of a Magnetic Scanning High Current Implanter", Nucl. Instrum. and Methods B6, 228 (1985).

5. R. Liebert, B. Pedgers, **C. Ehrlich** and W. Callahan, "Performance Characteristics of the Extrion 160-10 Ion Implantation System", Nucl. Instrum. and Methods B6, 16 (1985).

6. **J. P. Evans**, "Evaluation of Some High-Temperature Platinum Resistance Thermometers", NBS J. Res. 89, No. 5, Sept./Oct. 1984.

7. **W. E. Fogle, J. H. Colwell**, and **R. J. Soulen, Jr.**, "Determination of the Superconductive Transition Temperatures of Cd, Zn, and Al Using a Josephson Junction Noise Thermometer,", Proceedings of the 17th International Conference on Low Temperature Physics, Karlsruhe, FRG, August 15-22, 1984; (North-Holland, Amsterdam, 1984), p. 1149.

8. **R. W. Hyland**, "A Comparison of Some Thermodynamic Properties of H_2O from 273.15 to 473.15 K as Formulated in the 1983 ASHRAE Tables and the 1983 NBS/NRC Steam Tables", Moisture and Humidity 1985 - Measurement and Control in Science and Industry (1985) pp. 29-35. Proceedings of the 1985 International Symposium on Moisture and Humidity, Washington, DC, April 15-18, 1985.

9. **R. W. Hyland** and **C. R. Tilford**, "Zero Stability and Calibration Results for a Group of Capacitance Diaphragm Gages", J. Vac. Sci. and Tech. A3 (3), 1731 (1985).

10. Robert L. Berger, Thomas R. Clem, Victoria A. Harden, and **B. W. Mangum**, "Historical Development and Newer Means of Temperature Measurement in Biochemistry", chapter in Methods of Biochemical Analysis, Vol. 30, edited by David Glick, (John Wiley & Sons, New York, 1984), pp. 269-331.

11. **B. W. Mangum**, "Stability of Small Industrial Platinum Resistance Thermometers", NBS J. Res. 89, 305-316 (1984).

12. **H. Marshak** and C. H. Spiegelman, "Determining Multipole Mixing Ratios from Nuclear Orientation Experiments," Nucl. Instrum. and Methods A234, pp. 455-467 (1985).

13. **H. Marshak**, "Gamma-Ray Multipole Mixing Ratios Using Nuclear Orientation: ^{166}Er", Hyperfine Interactions 22, pp. 413-422 (1985).

14. **K. E. McCulloh, S. D. Wood** and **C. R. Tilford**, "Zero Stability of Spinning Rotor Vacuum Gages", J. Vac. Sci. Tech A, 3 (3), May/June 1985.

15. W. Lempert, **G. J. Rosasco**, and **W. S. Hurst**, "Rotational collisional narrowing in the NO fundamental Q-branch, studied with CW stimulated Raman spectroscopy," J. Chem. Phys. 81, 4241 (1984).

16. **G. J. Rosasco** and **W. S. Hurst**, "Measurement of resonant and nonresonant third-order nonlinear susceptibilities by coherent Raman spectroscopy", Phys. Rev. A 32, 281 (1985).

17. **G. J. Rosasco** and **W. S. Hurst**, "Phase-modulated stimulated Raman spectroscopy", J. Opt. Soc. B 2, 1485 (1985).

18. **James F. Schooley**, Thermometry, NBSIR 85-3133; also to be published as a CRC book.

19. **J. F. Schooley** and **J. H. Colwell**, "Superconductive Temperature Reference Points Above 0.5", Proceedings of the 17th International Conference on Low Temperature Physics, Karlsruhe, FRG, August 15-22, 1984; (North-Holland, Amsterdam, 1984), p. 409.

20. **Robert J. Soulen, Jr.**, "Status of the International Temperature Scale", Proceedings of Measurement Science Conference, Santa Clara, CA, Jan. 17-18, 1985. (Tied for best paper of the conference.)

21. **C. R. Tilford**, "Sensitivity of Hot Cathode Ionization Gages", J. Vac. Sci. Tech. A3, 546 (1985).

22. **C. R. Tilford**, "Characteristics of Ion Gages", in the Proceedings of the Int'l Symposium on Vacuum Technology and Nuclear Applications, edited by R. Krishnan, Ch. Verkate Swarlu, and S. P. Mhaskar (Indian Vacuum Society, Bombay, 1984), p. 139.

23. **C. T. Van Degrift**, "The Use of Tunnel Diode Oscillators as High Precision Transducers from 0.02 K to Room Temperature", in Proceedings of the Tenth International Cryogenic Engineering Conference, Helsinki, Finland, 31 July - 3 August 1984, ICEC10, edited by Dr. H. Collan, Dr. P. Berglund and Prof. M. Krusius (Butterworth & Co., England, 1984), pp. 349-352.

24. **C. T. Van Degrift**, "A Progress Report on the Development of a Small High Precision Pressure/Temperature Sensor For use at Low Temperatures," in Proceedings of the Tenth International Cryogenic Engineering Conference, Helsinki, Finland, 31 July - 3 August 1984, ICEC10, edited by Dr. H. Collan, Dr. P. Berglund and Prof. M. Krusius (Butterworth & Co., England, 1984), pp. 353-356.

25. **B. E. Welch** and **Vern E. Bean**, "Pressure and temperature measurements in the annulus between the piston and cylinder of a simple dead-weight gauge," Rev. Sci. Instrum. 55, 1091 (1984).

26. **S. D. Wood** and **C. R. Tilford**, "Long-term Stability of Two Types of Hot Cathode Ionization Gages", J. Vac. Sci. Tech. A 3 (3), May/June 1985.

APPROVED FOR PUBLICATION:

B. E. Welch, L. A. Guildner, and **Vern E. Bean**, "Factors Affecting the Precision of Gas-Operated Piston Gages at the Part per Million Level," Proceedings of the 31st International Instrumentation Symposium, San Diego, CA, 6-9 May 1985.

Ruben J. Lazos-Martinez and **Vern E. Bean**, "Elastic Distortion in Piston Gages", Proceedings of the Xth Conference of the International Association for the Advancement of High Pressure Science and Technology, Amsterdam, 8-11 July 1985.

V. E. Bean (Chairman), S. Akimoto, P. M. Bell, S. Block, W. B. Holzopfel, M. H. Manghnani, M. F. Nicol, and S. M. Stishov, "Another Step Toward an International Practical Pressure Scale: 2nd AIRAPT IPPS Task Group Report," Proceedings of the Xth Conference of the International Association for the Advancement of High Pressure Science and Technology, Amsterdam, 8-11 July 1985.

Vern E. Bean, "Pressure Metrology: Primary Standard Piston Gages", Proceedings of the 10th Conference of the International Association for the Advancement of High Pressure Science and Technology, Amsterdam, 8-11 July 1985.

Charles D. Ehrlich, "A Note on Flow Rate and Leak Rate Units", Journal of Vacuum Science and Technology A.

Richard W. Hyland, Charles D. Ehrlich, Charles R. Tilford and Steve Thornberg, "Transfer Leak Studies and Comparisons of Primary Leak Standards at NBS and SNL", Journal of Vacuum Science and Technology A.

B. W. Mangum, "Temperature and Thermometry", The Encyclopedia of Physics, 3rd Edition, edited by Robert M. Basancon, Van Nostrand and Reinhold Co., New York, 1985.

B. W. Mangum and S. El-Sabban, "SRM 1970: Succinonitrile Triple-Point Standard - A Temperature Reference Standard Near 58.08 °C", NBS Journal of Research, 1985 or 1986.

B. W. Mangum and S. El-Sabban, "SRM 1970 : Succinonitrile Triple-Point Standard - A Temperature Reference Standard Near 58.08 °C", NBS Special Publication SR 260-101, 1986.

K. E. McCulloh, C. R. Tilford, C. D. Ehrlich, and **F. G. Long**, "Low Range Flowmeter for Use with Vacuum and Leak Standards", to be published in J. Vac. Sci. Tech. A.

J. Tapping and **M. L. Reilly**, "The Index of Refraction of Sapphire Between 24 and 1060 °C for Wavelangths of 633 and 799 nm, to be published in J. Opt. Soc. America.

C. R. Tilford, K. E. McCulloh and **S. D. Wood**, "NBS Primary High Vacuum Standard", Journal of Vacuum Science and Technology A.

J. A. Wise and R. J. Soulen, Jr., "Thermometer Calibration: A Model for State Calibration Laboratories, to be published as NBS Monograph 174.

TECHNICAL AND PROFESSIONAL COMMITTEE PARTICIPATION AND LEADERSHIP

Temperature and Pressure Division (522)

V. E. Bean, Chairman, AIRAPT (International Association for the Advancement of High Pressure Science and Technology) Task Group on the International Practical Pressure Scale.

V. E. Bean, Member, BIPM (International Bureau of Weights and Measures) Consultative Committee for Mass and Related Quantities, Working Group on Medium Pressure.

V. E. Bean, Member, BIPM (International Bureau of Weights and Measures) Consultative Committee for Mass and Related Quantities, Working Group on High Pressure.

V. E. Bean, Member, ICSU (International Council of Scientific Unions) Committee on Data for Science and Technology, Task Group on Critical Interdisciplinary Survey of Property Data on High Pressure Phases.

G. W. Burns, Member, ANSI SP-1, American National Standards Institute Committee on Temperature Measurement Thermocouples.

G. W. Burns, Member, ASTM E-20, American Society for Testing and Materials Committee on Temperature Measurement, Subcommittee E-20.04, Thermocouples.

C. D. Ehrlich, Member, ASTM E-7, American Society for Testing and Materials Committee on Nondestructive Testing; Member, Subcommittee E7.08, Leak Detection Testing.

G. T. Furukawa, Member, ASTM E-20, American Society for Testing and Materials Temperature Measurement Committee; Subcommittee E-20.03, Resistance Thermometers; Subcommittee E-20.04, Thermocouples; Secretary, Subcommittee E-20.06, New Thermometers; Member, Subcommittee E-20.07, Fundamentals in Thermometry; and Subcommittee E-20.94, Publications.

W. S. Hurst, Member, ANSI MC088, American National Standards Institute Committee on Calibration of Instruments, Subcommittee SC.03, Temperature.

B. W. Mangum, Member, NCCLS C002, National Committee for Clinical Laboratory Standards, Area Committee on Clinical Chemistry, Subcommittee SC.01, Enzyme Assay Condition, Working Group WG.01, Temperature Measurement and Control; and Member, NCCLS C010, Area Committee on Instrumentation; Secretary, Subcommittee SC.01, Temperature.

B. W. Mangum, Vice Chairman, ASTM E-20, American Society for Testing and Materials, Temperature Measurement Committee; Member, Subcommittee E-20.03, Resistance Thermometers; Chairman, Subcommittee E-20.06, New Thermometers; Member, Subcommittee E-20.07, Fundamentals in Thermometry; Subcommittee E-20.08, Medical Thermometry, Working Group WG.02, Fever Thermometers; Working Group WG.02A, Electronic Fever Thermometers; Working Group WG.02B, Mercury-In-Glass Fever Thermometers; Working Group WG.02C, Disposable Fever Thermometers; Working Group WG.03, Continuous Clinical Temperature Monitoring Systems; Working Group WG.04, Clinical Laboratory Temperature Measurement; and Member, Subcommittee E-20.90, Executive Subcommittee.

B. W. Mangum, Member, OIML PS12, International Organization of Legal Metrology, Measurement of Temperature and Calorific Energy Committee, RS4, Electrical Thermistor Thermometers.

J. F. Schooley, Chairman, ANSI MC88, American National Standards Institute Committee on Calibration of Instruments.

J. F. Schooley, Delegate, 15th Meeting of International Committee on Weights and Measures (CIPM), Consultative Committee on Thermometry (CCT); and Delegate, Subcommittee WG3, Replacement of IPTS-68.

J. F. Schooley, Delegate, OIML PS12, International Organization of Legal Metrology Committee on Measurement of Temperature and Calorific Energy.

J. F. Schooley, Editorial Board, Metrologia.

J. F. Schooley, Member, Organizing Committee for 1986 Applied Superconductivity Conference, Baltimore, MD.

R. J. Soulen, Jr., Member, ASTM E-20, American Society for Testing and Materials Temperature Measurement Committee.

R. J. Soulen, Jr., Member, ASTM B001, American Society for Testing and Materials Committee Electrical Conductors, Subcommittee SC.08, Superconductors.

R. J. Soulen, Jr., Member, International Committee on Weights and Measures (CIPM), Consultative Committee on Thermometry (CCT), WG4.

C. R. Tilford, Member, ASTM E021, American Society for Testing and Materials Space Simulation and Applications of Space Technology Committee, Subcommittee SC.04, Space Simulation Test Methods, Working Group WG.01, Revision of Standards E296-70 and E297-70.

C. R. Tilford, Chairman, AVC C004, American Vacuum Society Standards Committee; Member, Subcommittee SC.01, Gaging.

C. R. Tilford, Chairman, BIPM C002, International Bureau of Weights and Measures Consultative Committee on Mass and Related Quantities, Working Group WG.02, Working Group on Low Pressures.

C. R. Tilford, Chairman, RTCA SC150, Radio Technical Commission for Aeronautics, Special Committee for Minimum Performance Standards for (Aircraft) Vertical Separation Above Flight Level 290.

C. R. Tilford, Member, Board of Directors, Vacuum Technology Division of the American Vacuum Society.

J. A. Wise, Secretary, ASTM E-20, American Society for Testing and Materials, Temperature and Measurement Committee; Member, Subcommittee E-20.05, Liquid-in-Glass Thermometers and Hydrometers; Secretary, Subcommittee E-20.90, Executive Subcommittee; and Member, Subcommittee E@20.91, Editorial and Nomenclature.

LENGTH AND MASS DIVISION

SUMMARY OF ACTIVITIES

FISCAL YEAR 1985

I. Overview

The Length and Mass Division (LMD) has the responsibility to: maintain the U.S. primary standards for length, mass, and density; provide the first level of transfer to secondary standards; and improve the standards and measurement instrumentation through basic and applied ressearch. As of October, 1985, the Division has responsibility for the NBS mass calibration service.

Many activities occur in support of these responsibilities. Comparisons of the U.S. standards are made with the International Bureau of Weights and Measures (BIPM) and with other national laboratories to ensure international compatibility. A close working relationship is maintained with the divisions in the National Engineering Laboratory which provide length and force calibration services to the public. This cooperation not only concerns the first level of transfer of dimensional quantities but also includes the transfer of measurement techniques and instruments, such as the portable laser length standard, the submersible balance, and the load cell mass comparator, which were developed in the LMD. Cooperative projects with outside institutions, such as state metrology laboratories, universities, and private corporations, ensure that our activities are revelant to the problems of the measurement community. The Division is frequently requested to provide information and assistance to public and private organizations which need state-of-the-art length and mass measurements and cannot obtain adequate support from the private sector.

Length activities this year involved: use of the NBS Portable Laser Length Standard in several experiments at NBS and other laboratories to measure fundamental constants and base units; and the development of a servo-system for the NBS Scanning Tunneling Microscope.

Activities in the mass program focussed on: development of servo-controlled kilogram balances for primary mass comparisons; development of retro-fitted servo-systems and automated weight changers for commercial balances used in the calibration program; analysis and publication of the results of the BIPM calibration of the U.S. mass standards; initiation of an international round-robin to measure solid density artifacts; and completion of the new transportable mass measurement package and liquid densimeter.

Two theoreticians in the Division, John Cooper and Helen Holt, are developing methods to treat field effects on atomic processes and the time-dependence of excitation processes under varying field conditions. In addition to his theoretical work, Cooper collaborates with scientists in the Center for Radiation Research on experimental spectroscopic measurements.

Robert Cutkosky transferred into the Division in October, 1984. He has collaborated with Randy Schoonover on several projects in the mass program to automate the commercial balances in the calibration laboratory and to develop a servo-controlled flexure kilogram balance. He has also continued his DoD sponsored work on the development of the automated NBS Type 3 Capacitance Bridge and related standards in collaboration with Lai Lee of the Electricity Division. Cutkosky and Lee earned a 1985 I-R 100 award for the design of the automated capacitance bridge.

II. Technical Activities

1. Length Measurements and Standards

The length activities this year included the usual responsibilities of realizing and disseminating the length standard to industrial and scientific laboratories and also included new ventures into other fields which involve high precision length measurements.

A. NBS Portable Laser Length Standard

The interest in the NBS portable laser length standard continues to be high, not only from domestic sources, but also from foreign countries which are in the process of building metrology laboratories to support industrialization. Activities this year involved promoting the use of the length standard in measurements of fundamental units and atomic constants for programs at NBS and other laboratories. Howard Layer also visited the national laboratories of India and Egypt to present a series of lectures on length standards and related metrology and to work with the metrologists in the laboratories to transfer technology which can be used to fulfill present measurement needs in these countries.

ACCOMPLISHMENTS: The NBS portable laser length standard is currently being used in two new measurements of the ohm by means of the calculable capacitor: one in the Van Swinden Laboratory in Delft, the Netherlands, and the other in the NBS Electricity Division. These measurements are part of the effort by the electrical standards community to establish the quantized Hall effect as the primary standard of resistance. A meeting of the CCE has been scheduled for the summer of 1986 to compare the results of national laboratories worldwide. Howard Layer has also helped the NBS Electricity Division make several changes in the existing calculable capacitor to improve its precision and accuracy by relating the measurements directly to the length standard, providing better isolation between the laser and the interferometer, and by improving the servo-system.

The Division is also providing length measurement support to the Electricity Division's experiment to measure gamma-p and to the Quantum Metrology Group's experiment to measure the silicon lattice spacing.

The collaboration with Dr. William Lichten of Yale Univeristy on the measurement of the Rydberg constant is continuing. This effort, to date, has resulted in a value which has a precision of one part in 10^9

using crossed atomic and optical beams. Several modifications to the apparatus are now being implemented which should allow further improvement in the accuracy of the Rydberg value and reduce its uncertainty to a value which is very near the limit set by the uncertainty of the length standard.

PLANS FOR FY 86: Work involving the NBS laser length standard will continue at approximately the same level as in FY 85. Emphasis will again be placed on encouraging the application of the NBS system when other length measuring instruments do not provide sufficient accuracy.

B. Servo-system for the NBS Scanning Tunneling Microscope

In the course of developing a capacitance motor and highly stabilized electronic driver for the electrostatically servoed mass comparator, the Electron Physics Group in the Radiation Physics Division of CRR inquired about the suitability of these devices as a servo-system for a new scanning tunneling microscope (STM) which they had just started to develop. Results at IBM in Zurich indicated that such an instrument was capable of making high quality pictures of surfaces with atomic resolution. However, the length measuring capability of instruments built up to that time only provided information about atomic surface symmetries but was insufficient to provide reliable dimensional information. The new STM provided an excellent opportunity to test the balance servo electronics and to provide an extension of length measurements to the atomic domain in a direct way that had not been done before.

ACCOMPLISHMENTS: The initial application of the high voltage amplifier to the STM uncovered several deficiencies which were subsequently corrected by a completely revised design. The new amplifier, which can be designed to have an output voltage range as large as 4000 volts, has a low noise level and a stability that is better than one part per million. This level of stability enables one to servo distance measuring probes to about one picometer in a system with a bandwidth of several hundred Hz. Using the new amplifier in the STM servo circuit, the Electron Physics Group has been able to obtain topographs of metalic surfaces with vertical resolution better than 10 picometers. This level of performance is sufficient to resolve atomic steps on crystal surfaces. The NBS Surface Characterization Group has used the STM to examine gratings and optical surfaces produced by diamond turning machines with unprecedented resolution. The STM will provide NBS with a new measurement technology for scientific studies as well as a wide range of metrology applications.

With the completion of his collaboration on the servo-system for the STM, Howard Layer will redirect his efforts toward completion of the electrostatically-servoed kilogram comparator.

2. Mass Measurements and Standards

A. Servo-controlled Primary Kilogram Comparators

The Division's efforts to improve the operational Voland balance and develop new automated primary kilogram comparators involved three activities this past year. The Voland balance was retrofitted with the electromagnetic beam servo-system developed by Schoonover and Cutkosky. Two parallel projects are underway to develop a completely new type of automated mass comparator. Both use the same basic structural design: cast aluminum base plates, symmetrical cast beam, etc. They differ in that one will use laser sensing of the beam position, an electrostatic servo-motor to restore the beam, and knife-edge pivots while the other will use the simpler electromagnetic beam servo-system and commercial flexure pivots.

ACCOMPLISHMENTS: The Voland balance is now operating under servo control. Enough experience has been gained to compare its operation under servo control to that in the free-swinging mode. The most striking improvement is that the balance sensitivity is now constant from day to day and throughout a complete set of mesurements. The sensitivity has also been shown to be linear over the full 20 mg range of the balance. The overall standard deviation of a set of measurements did not improve under servo control. A careful study of thermal gradients within the balance has shown that thermal effects do not contribute significantly to the standard deviation. The Voland is operating sufficiently well to serve as our present primary kilogram comparator and no futher major modifications are anticipated.

All of the major components, except for the electrostatic beam servo motor, have been completed and assembled for the new laserservoed knife-edge balance. A capacitance motor has been chosen for this balance because it does not require the use of magnetic materials even though a magnetic system would be advantageous from many other points of view. A very highly stabilized, low noise, high voltage (4000V) electronic driver for the capacitance motor has been developed and successfully tested on the Scanning Tunneling Microscope. The capacitance motor is now under development.

A new project was initiated this year by Schoonover and Cutkosky to construct a automated kilogram comparator with flexure pivots, the simpler electromagnetic servo system, and the same cast beam and structural components designed for the balance discussed above. This project is divided into the following four steps:

1) Servo a beam with flexure pivots and demonstrate the required sensitivity.
2) Demonstrate precision by repeated weighings of a 1 kg weight.
3) If precision is adequate, develop a weight changing mechanism for intercomparing six 1 kg masses.
4) Investigate vacuum weighing.

The first step has been completed and the construction for the second step is well underway.

PLANS FOR FY86: Development of the new kilogram comparators will continue. Working prototypes of both designs should be complete by the end of FY86.

B. Recalibration of the U.S. Kilograms

The goal of this project is to ensure that the mass calibrations performed by NBS are compatible with the international system of mass measurements. The first step in this process -- the recalibration of the U.S. national protoptye kilograms, K20 and K4, and two stainless steel kilograms at BIPM -- has now been completed and documented. Work is now underway to develop and calibrate an group of stainless steel check standards and working standards for the calibration service. A new set of quality control procedures will be developed and implemented in the calibration laboratory to monitor the working standards.

ACCOMPLISHMENTS: The results of the BIPM recalibration have been analyzed and published. The major conclusions from that work can be briefly summarized in the following comments. The Pt-Ir standards must be cleaned in exactly the same manner as that used by BIPM in order to achieve comparable results. When the cleaning is properly done, repeated mass measurements agree to within 5 micrograms. After cleaning, the U.S. national prototype K20 was found to be only 1 microgram below its 1948 value -- a difference that is well within experimental uncertainties. The cleaning process removed approximately 20 micrograms. Repeated calibrations of the two stainless steel weights, both at NBS and BIPM, indicate a repeatability better than 30 micrograms. The majority of the non-reproducibility seems to be due to the difficulties associated with the air buoyancy correction.

The six stainless steel kilograms which will be used as check standards and working standards in the calibration service are now being monitored for stability. Their densities have been determined to high accuracy by hydrostatic weighing against our silicon transfer standards. Their masses have been measured against the stainless steel standards which were calibrated by the BIPM.

PLANS FOR FY86: We will continue to monitor the stability of the new stainless steel standards and recalibrate N1 and N2, the present working standards of the calibration service, to carefully document any differences between the recalibrated and presently assigned mass values.

C. Retro-fitted Automation of Commercial Balances in the Calibration Program

There is a growing need in the NBS mass calibration laboratory and in the outside mass metrology community for automated mass comparators which perform as well as or preferably better than the mechanical balances now in common use. Modern electronic balances lack the combination of range and, most importantly, the precision required in the NBS mass calibration program. This deficiency has been overcome with the development of beam servo system that has been installed on existing high-precision mechanical balances.

The initial goal of the project was to automate the data acquisition of the balance observations and then to examine the possibility of automating the total calibration process.

ACCOMPLISHMENTS: A successful electromagnetic beam servo system has been developed. It has been installed on the Voland kilogram comparator and on a Mettler model H315 balance used to calibrate the kilograms for the portable mass measurement package.

The servo system has enabled us to examine several ways to avoid the systematic errors that are known to be caused by thermal effects and arise from the presence of the balance operator. One method would replace the operator with a mechanical weight changer. A second approach goes one step further and forces thermal equilibrium between the weights being calibrated and the air in the balance chamber. Both approaches have been successfully tested and can be adapted to some of the mechanical balances used in the mass calibration program.

The remotely operated mechanical weight changers developed and tested on the Mettler balance so far have been manually operated systems with limited applications. A fully automatic robotic arm which is capable of loading the balance with weights in various combinations from a preloaded matrix is now being developed.

PLANS FOR FY86: Research and testing will continue on all of these automated components until adequate performance has been demonstrated. They will then be adapted to the mechanical balances in the calibration program.

D. Density of Solids

Working Group 5 of the Consultative Committee for Mass and Related Quantities (CCM) has organized an international round robin of solid density intercomparisons. NBS is serving as the pilot laboratory for these measurements.

ACCOMPLISHMENTS: The Working Group 5 met in Japan in September, 1984 to formulate its final plans. The round robin has begun. NBS has made initial measurements of the artifacts and shipped them to the next participating laboratory. The artifacts include two stainless steel kilograms and two 800 g silicon crystals.

PLANS FOR FY86: NBS will remeasure the density artifacts at the end of the seven-laboratory round robin. As the pilot laboratory, we will also analyze the data obtained by all participating laboratories and write the preliminary report.

E. Liquid Densimeter

The objective of this project is to develop a new type of liquid densimeter for the Standard Reference Materials Program to be used in the certification of liquid density SRMs in the NBS Chemical Process Metrology Division. The SRMs are designed to satisfy the need in metrology for a family of liquid density standards in the range from 0.6 g/cm^3 to 2.0 g/cm^3 for calibrating hydrometers to 100 ppm and the most precise vibrating tube densimeters to 100 ppm or better.

ACCOMPLISHMENTS: The densimeter has been constructed and tested to determine its precision and linearity. As soon as the internal density standard, a gold plated aluminum sphere, has been calibrated hydrostatically, the instrument will be turned over to the Chemical Process Metrology Division.

F. Portable Mass Measurement Package

This project, sponsored in part by the NBS Office of Weights and Measures, is developing a transportable mass measurement package to assist State and industrial metrology laboratories in assigning mass values to kilograms, particularly those which have unusual shapes and densities and require significant air buoyancy corrections. Most laboratories have adequate balances but some lack the necessary auxillary equipment and experience to make accurate air buoyancy corrections. This package will help to overcome these deficiencies. The package includes:

1. Calibrated kilogram masses of various geometries and densities,
2. Fractional mass standards for trimming mass differences at various altitudes,
3. Computer hardware and software for standardized data reduction and statistical control,
4. Air density instrumentation to measure temperature, barometric pressure, and relative humidity, and
5. Automatic data acquisition system for those laboratories equipped to use it.

ACCOMPLISHMENTS: The complete package has now been assembled and calibrated. It will be shipped to the California State Metrology Laboratory to begin the first round robin which will include several other state labs and two industrial labs, Sandia and the 3M Company.

PLANS FOR FY86: The Division will monitor the results of the round robin and make any further modifications that are required. One of the most important long-term objectives of this project is the training that participants will receive by using the package. Many participants will be exposed for the first time ot state-of-the-art weighing techniques and laboratory automation. It may be desirable later to develop a formal training seminar based on the instrumentation and techniques used in this package. A second objective is to extend the mass calibration capability of the package from the 1 kilogram level down to 1 mg.

G. Other Service Projects

The Division collaborated with the piston gage calibration group of the Temperature and Pressure Division to improve the uncertainties of mass values assigned to piston gage weights. A new weighing station was designed with an insulated weighing enclosure to minimize the systematic errors due to thermal effects that normally occur when weights of large surface to mass ratio are calibrated.

The Division also made some special measurements for the Thermophysics Division which is conducting experiments to measure the ideal gas constant. Their experiment measures acoustic resonances in a large spherical cavity. The internal volume of the cavity must be determined to 1 ppm using mercury picnometry. The Division's activities included: weighing the picnometer, designing 20 kg of stainless steel counterweights, and determining the masses and volumes of the counterweights against laboratory standards. Preliminary picnometer measurements have been successfully completed. The final measurements should be completed in November.

3. Atomic Theory

Work during the past year has focused on completion of the experiments on field effects of autoionizing states and preparation to make high resolution measurements of field perturbed absorption spectra using the 6.5 m VUV spectrometer recently installed at the NBS storage ring (SURF-II) by the University of Maryland.

The experimental work on field effects on barium autoionizing states, condusted in collaboration with D. Kelleher and E. Salomon of the Center for Rasiation Research, has been completed. All of the experimental data have been transferred to computer storage and a detailed analysis of the results is underway. Two papers describing some of the work have already been published. One of the papers (Phys. Rev. Letters 55, (1985)) describes an interesting interference effect caused by field mixing and the second paper contains a general description of the work and a sample of the results obtained. At least one additional paper will be prepared based on the data now available.

In preparation for measurements on SURF-II, a gas handling system has been built, tested, and used to measure the degree of polarization of the light entering the spectrometer slit. Light from the storage ring was focused on the entrance slit via a three-mirror system designed to produce nearly 100% polarized light. Our measurements indicated that the light was at least 96% polarized and, in addition, provided information about the flux levels to be expected when spectra are recorded.

Plans for the next year include completing the analysis of the barium data and beginning work on the high resolution absorption spectra as soon as the spectrometer is operational.

PUBLICATIONS

1. E.B. Salomon, J.W. Cooper, and D.E. Kelleher, "Electric-field induced interferences in autoionizing resonances," Phys. Rev. Letters 55, 193 (1985).

2 E.B. Salomon, J.E. Cooper, and D.E. Kelleher, "Studies of Electric Field Effects on Barium Autoionizing Resonances," Atomic Excitation and Recombination in External Fields, M.H. Nayteh and C.W. Clark, editors, Gordon & Breach, N.Y., p. 325 (1985).

3 E.B. Salomon, J.W. Cooper, and G. Mehlman, "Photoabsorption Cross Section of Barium from 237.9 to 120 nm," Phys. Rev. A **32**, 1878 (1985).

4. C.W. Clark and J.W. Cooper, Conference Report on "Field Effects in Rydberg Atoms," to appear in July-August issue of NBS Journal of Research.

5. V.I. Mishin, G. Lombardi, D.E. Kelleher, and J.W. Cooper, "Field-Enhanced Autoionization in Gadolinium," (to be submitted to JOSA).

6. A. Peuto and R.S. Davis, "Comparison of Solid Density Standards Between IMGC and NBS," J. Res. NBS **90**(3), 217-227 (1985).

7. J.B. Patterson and R.S. Davis, "A Density Comparison of Silicon Artifacts Between NML (Australia) and NBS (U.S.)," J. Res. NBS **90**(4), (1985). In press.

8. R.S. Davis, "Recalibration of the U.S. National Prototype Kilograms," J. Res. NBS **90**(4), (1985). In press.

9. P. Carre and R.S. Davis, "Note on Weighings Carried Out on the NBS-2 Balance," J. Res. NBS. Accepted for publication.

10. R.S. Davis and G. Girard, "Rapport sur la comparason d'etalons de masse de 1 kg en platine iridie et an acier inoxydable entre le National Bureau of Standards et la Bureau International des Poids Mesures," Recueil de Travaux de BIPM. In press.

11. T.J. Quinn, C.C. Speake, and R.S. Davis, "A 1 kg Comparator using Flexure-strip Suspensions; Preliminary Results," Metrologia. To be submitted.

12. R.S. Davis, "Note on the new formulations of f, p_{SV}, and Z," Document CCM/85-10, Consultative Committee for Mass and Related Quantities.

13. R.M. Schoonover, "A Large Capacity High Precision Electronic Mass Comparator," Proceedings of the 10th Conference of IMEKO TC-3 on Measurement of Force and Mass, Kobe, Japan, p. 101 (1984).

14. R.M. Schoonover, "A Force Balance Liquid Densimeter," Proceedings of the 10th Conference of IMEKO TC-3 on Measurement of Force and Mass, Kobe, Japan, p. 107 (1984).

15. R.M. Schoonover, "Mass Comparator for In-Situ Calibration of Large Mass Standards," J. Res. NBS **90**(4), (1985). In press.

16. T.F. Scrivener and R.M. Schoonover, U.S. Patent No. 4,523,653, "Load Cell Mass Comparator," June 18, 1985.

17. R.D. Cutkosky, "An Automatic High-Precision Audiofrequency Capacitance Bridge," IEEE Trans. Instr. & Meas., IM-34(3), 383 (1985).

INVITED TALKS

Richard S. Davis, "Romancing the Kilogram," An After Dinner Talk to the Regional Conference of Deans of Engineering, Hartford Graduate Center, Hartford, CT, May 3, 1985.

Richard S. Davis, "Recalibration of the U.S. Prototype Kilogram," National Conference of Wseights and Measures, Washington, DC, July 15, 1985.

Howard Layer, Presented a Series of Lectures on Length Metrology at the Advanced Metrology Conference, National Physical Laboratory, New Delhi, India, February 1985.

Howard Layer, Presented a Series of Lectures on Length Metrology at the National Institute of Standards, Cairo, Egypt, March 1985.

Howard Layer, "Servo Systems Using PZTs," 3rd International Precision Engineering Seminar, Interlaken, Switzerland, May 1985.

Randall M. Schoonover, Presented a Series of Lectures on Mass and Density Metrology at the Advanced Metrology Conference, National Phycical Laboratory, New Dehli, India, February 1985.

Randall M. Schoonover, "Mass Comparator for the In-Situ Calibration of Large Mass Standards," OIML Seminar on Testing of Bulk Weighing Installations, Paris, France, April 1985.

Randall M. Schoonover, Lectured at the George Washington University Standards Laboratory Course, October 1984 and April 1985.

TIME AND FREQUENCY DIVISION
FISCAL YEAR 1985

I. INTRODUCTION

The National Bureau of Standards (NBS) is responsible for the development and maintenance of a system of measurements required to support science and industry. The specific functions of NBS were assigned to the Department of Commerce by the Bureau's enabling legislation (15 U.S.C. 272). Portions of this legislation state:

"The Secretary of Commerce is authorized to undertake the following functions:

(a) The custody, maintenance, and development of the national standards of measurement, and the provision of means and methods for making measurements consistent with those standards,...

(e) Advisory service to Government agencies on scientific and technical problems.

(f) Invention and development of devices to serve special needs of the Government."

In carrying out these functions, the Secretary has authorized specific activities including:

"(1) the construction of physical standards;
(2) the testing, calibration and certification of standards and standard measuring apparatus;
(3) the study and improvement of instruments and methods of measurements,...
(11) the broadcasting of radio signals of standard frequency;"

The Time and Frequency Division located in Boulder, Colorado is primarily responsible for the standards of time and frequency. The standard of length is based on the frequency standard and the division has worked on the realization of the meter as well. However, primary responsibility for the meter resides in the Length and Mass Division. The most important product of the division is the service provided to science, industry, and other government agencies. There is no sense in establishing and maintaining standards of measurement unless they are efficiently disseminated. Standards operation, research on new standards, and development of methods of measurement all closely support the services of the division. The extension of standards and methods in range and accuracy and into new fields should receive sufficient emphasis to keep NBS prepared to satisfy the demands for improved services. Basic research related to standards is performed to challenge the talents of the staff and to stimulate the development of new ideas. Advisory service to

Government agencies and the development of devices to serve the special needs of Government are important NBS roles which increase the efficiency of government by applying the special expertise of NBS to significant Government problems. The expertise needed to provide this advice to other agencies is derived from involvement in both basic research and goal-oriented research and development.

The division is organized into seven groups which meet different aspects of the division's responsibilities. These groups are:

- Time and Frequency Services (Section II)
- Time Scale and Time and Frequency Coordination (Section III)
- Hydrogen Masers (Section IV)
- Atomic Beam Standards (Section V)
- Ion Storage (Section VI)
- Optical Frequency Metrology and Devices (Section VII)
- Geophysical Measurements (Section VIII)

In order to more clearly show the program emphasis, this report will be presented with these group names as section titles, and the staff working in each area will be listed at the beginning of each section. There is considerable overlap between the work of several of the groups, but no attempt is made to separate the work into clean categories since this would add confusion.

Each section of the report begins with a short description of the general program and objectives of the group. This is followed by a list of specific FY 1985 accomplishments and the plans for FY 1986. The accomplishments are keyed to the plans outlined in last years report, but tracking between the two will be difficult because the arrangement of this years report has been significantly altered. Nevertheless, every specific planning item described last year can be located in this report.

In an effort to relate the division's work to the division's mission, a set of objectives have been used. Any one of the objectives which are listed below may appear in the description of the work of several groups since there is heavy overlap and collaboration between a number of the groups.

OBJECTIVES

- Generate NBS time scales, UTC(NBS) and TA(NBS)
- Broadcast time and frequency signals from radio stations WWV, WWVH and WWVB and the GOES satellites.
- Provide seminars, calibrations and measurement assurance on a fully reimbursable basis.
- Maintain international coordination of time scales and frequency standards using the Global Positioning System
- Develop advanced methods for time transfer using communication satellites.
- Provide reference frequencies from the microwave to the visible region of the spectrum.
- Establish the units of the International System for the "second" and the "meter".
- Make fundamental improvements in atomic spectroscopy for future application to primary frequency standards.
- Develop metrology for precise time, frequency and length measurements.
- Perform basic studies in program areas related to future time and frequency standards.
- Advise and work with other governmental agencies and industry to incorporate advanced time and frequency metrology into their programs.
- Measure far infrared frequencies of atoms and molecules (especially transient species) for radio astronomy and upper atmospheric science.

II. Time and Frequency Services

The Time and Frequency Services Group has the primary focus of direct industry and other agency support. The division broadcast services, the new Frequency Measurement Service, and the Time and Frequency Bulletin all fall within their responsibility. In addition to these on-going services the group is working on four other projects: coordination of clocks using two-way satellite time transfer, development of time transfer techniques appropriate to a tactical (military) communication environment, synchronization of space-borne communications nodes, and a broad study of timing methods useful to the electric power industry. At a later date the two-way time coordination function will be transferred to the Time Scale and Coordination Group. The group's work is described in more detail below.

Staff:
- D. W. Hanson, Project Leader
- W. J. Bonner (Part-time)
- D. A. Howe
- J. L. Jespersen
- G. Kamas
- M. A. Lombardi
- D. L. Real
- R. E. Beehler (Broadcast Manager)

WWV, WWVB, Ft. Collins	WWVH, Hawaii
J. E. Folley (Part-time)	A. Fabro (Part-time)
J. M. Maxton	E. F. Farro
J. B. Milton, Chief Eng.	Ferguson (Part-time)
C. S. Snider	N. Hironaka
A. R. Trevarton	C. L. Trembath, Chief Eng.

In order to have useful standards of time, frequency, and length it is essential to provide convenient access to these standards. This is accomplished primarily via the radio broadcasts of stations WWV, WWVH, and WWVB and a time code broadcast by the GOES satellites. NBS also provides telephone time-of-day services, publications of time and frequency values of other radio stations as received at NBS, portable clock comparisons and calibrations. The meter is now defined in terms of a fixed value for the speed of light and the standard of frequency (time). The very accurate measurements needed to implement this definition are largely complete and the practical dissemination of the meter is handled by the Length and Mass Division. Seminars concerning time and frequency metrology are regularly scheduled to educate new entrants to the field.

The division's services are important in many applications involving commercial, government, and scientific activities. These include:

Navigation

Celestial navigators need time to determine their precise location. An error of 2 seconds could cause a ship to miss its destination by about one kilometer. Thus military and commercial shipping and small boat owners depend in a life and death sense on the availability of the signals from WWV and WWVH.

More sophisticated electronic navigation systems such as LORAN-C and the Global Positioning System (GPS) must maintain time much more accurately. An error of only 3 microseconds could produce the same one kilometer error for the navigator.

Systems Control and Synchronization

The electric power industry uses both frequency and time information in the management of generation and distribution of electric power. Frequency measurement has been fundamental to the industry for many years and is satisfied by signals from WWVB and GOES. Time is becoming increasingly important in the recording of fast occurring events (faults), system control, measurement of power flow, avoiding outages caused by exceeding stability limits, and for fault location on long transmission lines.

Radio and TV stations need accurate frequency to broadcast signals at exactly their assigned frequencies. They need accurate time to set station clocks so they can join the network at the right instant.

The aviation/aerospace industry needs accurate time for aircraft traffic control systems and for synchronization at satellite and missile tracking stations.

The telecommunications industry needs time accurate to one microsecond and better to synchronize communication's nodes spread over wide geographical areas.

Data Acquisition

The FAA records accurate time on its audio tapes along with the air-to-ground communications from airplanes. Having an accurate record of when particular events happened can be an important factor in determining the cause of a plane crash or equipment malfunction.

Geophysicists/seismologists studying lightning, earthquakes, weather, and other geophysical disturbances need time to enable them to obtain data synchronously and automatically over wide geographical areas. They use it for labeling geophysical events. Other scientists use time for controlling the duration of physical and chemical processes.

Astronomers use time for observing astronomical events, such as lunar occultations, eclipses, and pulsars.

Science and Metrology

Manufacturers need time and frequency to calibrate counters, frequency meters and test equipment.

Accurate spectra of molecules are needed to measure atmospheric concentrations.

Laser frequency measurements provide accurate calibration frequencies for spectroscopists and for radio astronomy as well as the means for realization of the meter.

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OBJECTIVE: Broadcast time and frequency signals from radio stations WWV, WWVH and WWVB and the GOES satellites.
****

NBS offers several around-the-clock time and frequency dissemination services to the general public. In 1923, radio station WWV was established by NBS and has been operated since that time. A sister station, WWVH was established in 1948, on the Hawaiian Island of Maui, and relocated to Kauai in 1971. In 1956, WWVB began low frequency broadcasts. WWV's signal is also offered by a telephone service, not toll-free, by dialing (303) 499-7111. A similar service from WWVH is available by dialing (808) 335-4363 in Hawaii.

Broadcasts from WWV and WWVH can be received on conventional shortwave receivers nearly anywhere in the world. Broadcast frequencies include 2.5, 5, 10, and 15 megahertz for both stations and 20 megahertz from WWV only. Accuracies within one millisecond can be obtained from these broadcasts if one corrects for the station's distance from the receiver. These services also provide standard frequencies, a BCD time code, astronomical time corrections, and certain public service announcements from other government agencies. The telephone service offers to individuals without receivers, the capability of obtaining NBS time and audio frequency signals. The caller can receive a time signal accurate to 30 milliseconds or better, about the maximum delay in cross-country telephone lines. WWVB offers a direct path signal of greater accuracy than WWV or WWVH, but a special 60-kilohertz low frequency receiver is required. WWVB's signal includes a binary coded system, needing special decoding equipment. WWVB's coverage area is shown in Figure 1. These broadcast services are coordinated with similar operations in other countries through active participation in the international CCIR organization.

NBS time and frequency signals covering about 40 percent of the earth have been relayed via geostationary satellites since 1975. The coverage area is shown in Figure 2. More than 10 years of experience has shown that such a system does provide continuous time and frequency reception that is much more dependable than ground-based AM and FM radio stations, is free from propagation anomalies, and has a 100-microsecond accuracy. Table I summarizes the principal NBS time and frequency dissemination services. Table II gives some details of the HF radio broadcasts.

FY 1985 Plans

Plan - Conduct a major survey of users of the NBS time and frequency dissemination services.

Accomplishment - The performance of this survey has been delayed until the first half of FY86 due to higher priority tasks. Approval for the survey has been obtained and a preliminary design of the survey has been completed.

Plan - Study the needs and alternatives for replacing the WWV transmitters with more energy-efficient units.

Accomplishment - The energy and economic analysis was completed on schedule. Replacement of the three main transmitters should reduce our power requirement by 100 kW with a resultant energy saving of 73,000 kWH/month. The projected cost recovery period for purchase and installation of the transmitters is three to four years. A budget request for these transmitters was included for FY 1987, but this was rejected by DoC. Further efforts to find funding for the transmitter replacement are underway.

Plan - Develop a capability to monitor and control selected functions at the NBS radio stations from remote locations. The goal is to reduce the number and cost of out-of-hour visits made to the station sites.

Accomplishment - The system was completed on schedule and the station status and diagnostic information is now available remotely. This should reduce some unnecessary trips to the station during non-work periods.

Plan - Complete improved software and hardware documentation for the GOES satellite time code systems.

Accomplishment - A large part of the documentation has already been done and completion is scheduled for 11-30-85. This is a major effort covering all facets of the GOES operation.

FY 1986 Plans

Complete a major survey of the users of the NBS time and frequency dissemination services and document the results.

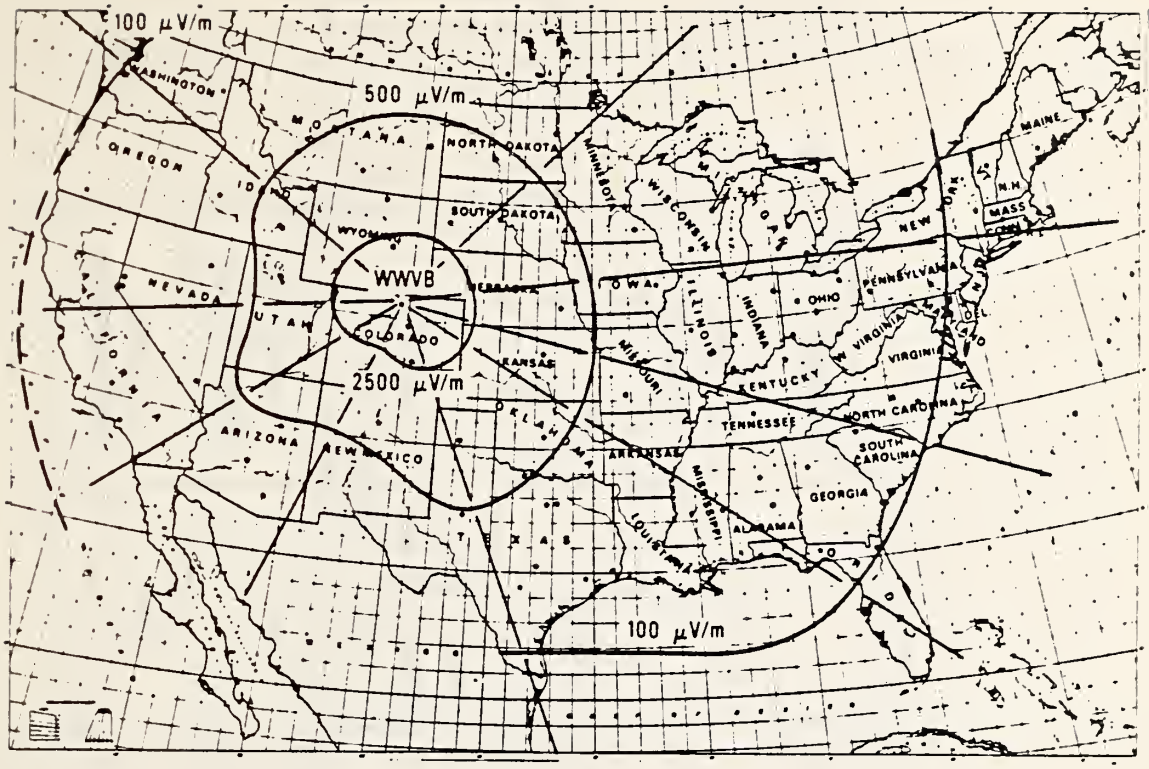

Figure 1

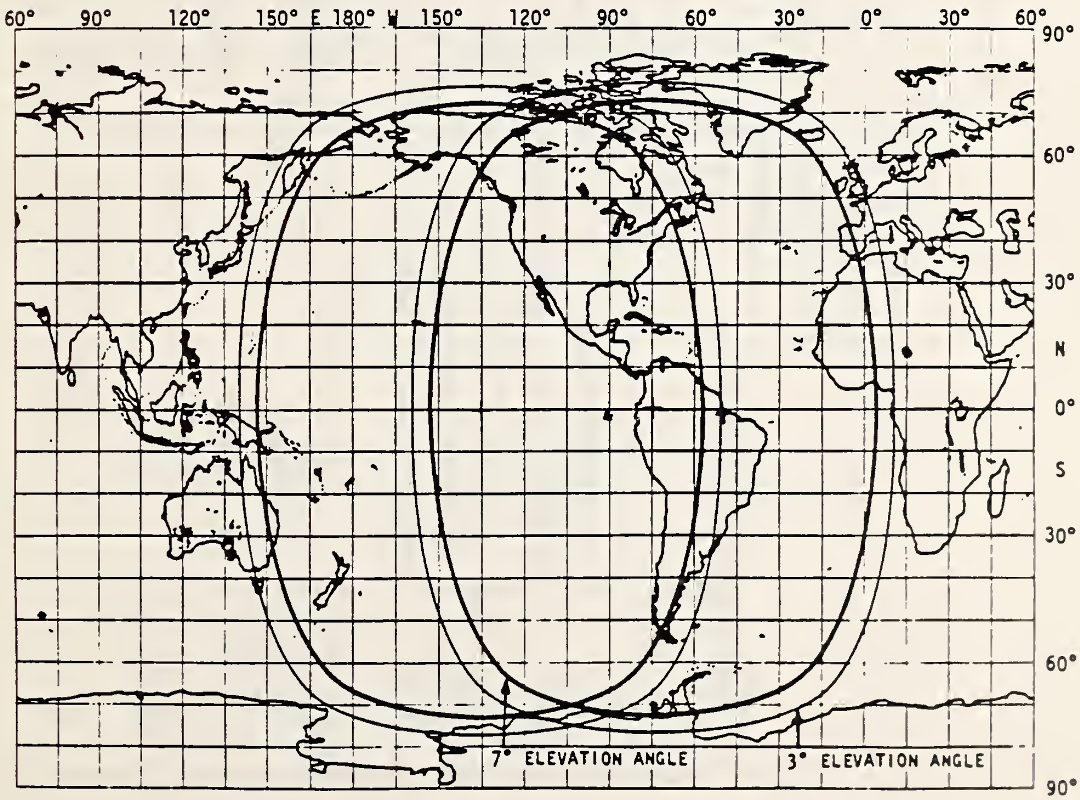

Figure 2

TABLE I.

CHARACTERISTICS OF THE MAJOR NBS T&F DISSEMINATION SYSTEMS

DISSEMINATION TECHNIQUES		ACCURACY FREQUENCY SYNTONI-ZATION	ACCURACY FOR DATE TRANSFER	AMBIGUITY	COVERAGE FOR STATED ACCURACY
LF RADIO	STANDARD FREQUENCY BROADCAST (e.g., WWVB)	1×10^{-11} PHASE 24 h	ENVELOPE 1 - 10 ms	YEAR	USA - LIMITED (WWVB)
HF/MF RADIO	STANDARD FREQUENCY BROADCAST (e.g., WWV)	1×10^{-7}	1 ms	CODE - YEAR VOICE - 1 DAY TICK - 1 s	HEMISPHERE
PORTABLE CLOCKS	PHYSICAL TRANSFER	1×10^{-13}	100 ns	N/A	LIMITED BY TRANSPORTATION
SATELLITE	GOES	3×10^{-10}	100 μs	NONE	WESTERN HEMISPHERE

TABLE II.

NBS STANDARD FREQUENCY AND TIME SIGNAL BROADCASTS IN THE HIGH FREQUENCY BAND

STATION	LOCATION LATITUDE LONGITUDE	POWER (kW)	ANTENNA	STANDARD FREQUENCIES USED CARRIER (MHz)	MODULATION (Hz)	TIMES OF UT TRANSMISSIONS	TRANSMITTED ACCURACY	DUT1 CODE
WWV	Ft. COLLINS, COLORADO 40° 41' N 105° 02' W	2.5 10.0 10.0 10.0 2.5	VERTICAL λ/2 DIPOLES	2.5; 5.0; 10.0; 15.0; 20.0	1; 440; 500; 600	CONTINUOUS	1×10^{-11}	CCIR CODE: DOUBLE PULSE
WWVH	KEKAHA, KAUAI, HAWAII 21° 59' N 159° 46' W	5.0 10.0 10.0 10.0	PHASED VERTI- CAL λ/2 DIPOLE ARRAYS	2.5 5.0 10.0 15.0	1; 440 500; 600	CONTINUOUS	1×10^{-11}	CCIR CODE DOUBLE PULSE

Upgrade WWVH data acquisition system for more convenient data transfer operations to NBS/Boulder.

Transfer operational GTDS satellite orbit determination program and related operations from Boulder Cyber 750 to appropriate components of the new NBS Cyber 840/855/205 computer system. Investigate alternative links to new NOAA/Suitland computer facility.

Develop an upgraded operational software package of GOES procedures that combines separate programs into a menu-driven, fully integrated program. Update related documentation accordingly.

Maintain reliable operations from WWV, WWVB, WWVH, and the GOES satellites.

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OBJECTIVE: Provide seminars, calibrations and frequency measurement assurance on a fully reimbursable basis.
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Frequency Measurement Service

This new frequency measurement service is highly automated, modest in cost, and provides traceability to NBS at a level of one part in 10^{12}, although even applications which do not require this level of performance can be readily supported. The service is based on common-view reception of low frequency signals from stations such as WWVB or Loran-C. The NBS service consists of assisting the user to set up a low frequency receiver and data logger system which is the most appropriate for his needs and his location. A typical system contains a receiver, microcomputer, disc units and printer-plotter. The user's responsibility is to provide a dedicated phone line and modem so that his data can be compared with data recorded at NBS, thus providing assurance that the measurements are valid. The user also receives a bulletin which reports the performance of many of the accurate signal sources. To assist the user in getting the most out of this system NBS provides specific training using the actual equipment.

Time and Frequency Bulletin

The Division has continued the distribution of its Time and Frequency Bulletin to over 1200 users of NBS services. The preparation and mailing of this bulletin has been constantly improved to reduce costs and to increase its usefulness. The bulletin has been expanded to support our new calibration services and will continue to be improved.

Seminars

The Division seminars provide industry, calibration labs and the military with information and training on the use of frequency standards. One seminar was offered in 1985 and it was well attended. This will be continued as long as the demand is there. A special effort is made to have the seminar support the introduction of new services and to be of particular interest to the nations's calibration laboratories.

FY 1985 Plans

Plan - Continue Measurement Assurance for frequency calibrations. Provide information on service through published articles and the NCSL newsletters.

> Accomplishment - A paper describing the Frequency Measurement Service was presented at the 1985 Workshop and Symposium of the National Conference of Standards Laboratories (NCSL), July 15-18, 1985. A working system, demonstrated at a booth during the four days of the meeting, attracted a great deal of attention. This interaction has resulted in a number of new customers for the service.

Plan - As demand dictates, provide a comprehensive Time and Frequency Seminar on a fully reimbursable basis.

> Accomplishment - A seminar on Time and Frequency was held August 13 through 15, 1985. Paid attendance was 45 and and the seminar was favorably received by most of the attendees. A waiting list developed well before the conference started, since a maximum practical attendance of 45 has been set. Consideration is now being given to an offering of the seminar during the spring.

Plan - Achieve an income level of $36,000 per year for the Frequency Measurement Service.

> Accomplishment - Income level for the service has recently exceeded $50,000 per year. It may be a little early to conclusively determine the growth rate, but it seems to be accelerating. Twenty-one systems are in place with important industrial and government customers. All comments from these users are highly favorable.

FY 1986 Plans

Continue operation of Frequency Measurement Service. Provide information on service through published articles. Develop training on disk for system users.

As demand dictates, provide a comprehensive Time and Frequency seminar on a fully reimbursable basis.

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OBJECTIVE: Develop advanced methods for time transfer using communication satellites.

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The use of communications satellites for time transfer at all levels of performance appears to be widely accepted in light of the success of several efforts during the last few years. Much of this is also due to a number of favorable changes in the available technology, economics, and demand. At the higher levels of performance, work reported by Japan and unpublished tests involving NBS, USNO, and COMSAT Laboratories have demonstrated one-half nanosecond time comparison precisions using two-way time exchanges through a communications satellite. Additional laboratory tests have indicated that 20 picosecond comparisons are possible using the same techniques with higher transmission power levels. The tests were encouraging and resulted in an informal agreement between NBS, USNO and the NRC in Canada to work together to develop a permanent network to serve these three laboratories. All of the necessary equipment has been acquired and tests will begin next year.

The use of communication satellites for the delivery of time and frequency information on a subscription basis also appears feasible with the application of technology originally developed and used by the DoD. The integration of this technology with careful baseband design (representation of the time and frequency information) could yield a viable (and fully reimbursable) delivery system serving important industrial and government needs in a very economical and reliable fashion. Preliminary system examination by calculation and consultation with satellite industry engineers and scientists have confirmed feasibility. Potential industrial consumers of such a service have strongly urged NBS to further develop these concepts.

<u>FY 1985 Plans</u>

Plan - Install and bring into operation at Boulder the equipment for two-way time transfers using communication satellites and spread spectrum techniques.

> <u>Accomplishment</u> - A 6.1-meter, parabolic antenna has been installed on the main NBS-Boulder facility. Final integration of electrical and electronic systems must be completed before full operation can begin. This is expected to occur just after the start of calendar year 1986.

Plan - Perform preliminary evaluation of the two-way time transfer technique for international time coordination.

> <u>Accomplishment</u> - Longer than anticipated design time for the roof installation of the antenna has caused a delay in evaluation of the

system. The design work started in March 1985 with installation projected for May, but that was delayed until the last week of August, 1985.

FY 1986 Plans

Complete two-way time transfer system and, using the system, begin coordination with the US Naval Observatory (USNO) and the National Research Council (NRC) in Canada.

****
OBJECTIVE: Advise and work with other governmental agencies and industry to incorporate advanced time and frequency metrology into their programs.
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FY 1985 Plans

Plan - Pending outside funding, conduct a study on how a fully reimbursable, one-microsecond time service might be implemented. The study will stress low cost and reliability using available leased telecommunication services.

Accomplishment - Funding for a one-year study was received from the Department of Energy in December 1984. Preliminary results suggest that a reimbursable service is realistic. Several alternate approaches are still under consideration. The study is on schedule and will be completed in December 1985.

Plan - Pending outside funding, develop time transfer techniques and systesms to initiate and maintain mission timing in a tactical communication environment.

Accomplishment - Funding for this work was received for FY85 and work is in progress. The program is to continue in FY86 with a change in emphasis to space-borne communication platforms.

FY 1986 Plans

Pending other agency funding, conduct studies on the synchronization of space-borne communication nodes.

Complete study of a one-microsecond reimbursable time service. Pending additional funding, continue work on this topic in the direction indicated by the study conclusions.

III. Time Scale and Time and Frequency Coordination

This group has the responsibility for the operation and further development of the NBS time scales and for coordination of these time scales with other standards laboratories and the Bureau International de L'Heure (BIH). The time scale is, of course, a key responsibility since it not only provides the basis for all services, but also serves as the stable reference against which much of the division gauges its' research. The group has developed a coordination scheme based on common view of the Global Positioning System (GPS) satellites which has become the de facto coordination approach for the world.

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OBJECTIVE: Generate NBS time scales, UTC(NBS) and TA(NBS)
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NBS atomic time is generated from an ensemble of approximately twelve commercial and one laboratory cesium beam frequency standard and two laboratory hydrogen masers. The time of all the clocks is automatically measured every two hours with a precision of a few picoseconds. The UTC(NBS) time scale is computed immediately following a measurement cycle using a weighted-average algorithm. The small dispersion of the clocks during the two hour interval between measurements makes it possible for NBS to provide UTC(NBS) to users with 1 ns precision at all times. Coordinating with the Bureau Internationale de L'Heure, UTC(NBS) is steered toward and kept within a few microseconds of UTC.

At the end of each month, the TA(NBS) time scale is computed using a Kalman algorithm. This computation is optimum in the statistical sense for clocks having both white frequency noise and random walk frequency noise, a good model for the clocks in the NBS ensemble. The second of TA(NBS) is steered toward NBS's best estimate of the SI second based on yearly calibrations of the ensemble by NBS-6.

FY 1985 Plans

Plan - Establish policies and procedures for the routine operations of the time scale and fix responsibilities for their implementation.

Accomplishment - Considerable attention has been given to the time scale during FY85. Howard Machlan was moved from WWV in Fort Collins to assist with the effort. Remodeling of part of the time-scale space is underway and power back-up systems are now in operation. Redundancy has been added to several systems to increase reliability. Documentation is in progress. The time scale has been shown to be operating at the theoretical performance level, that is, the scale performance is limited only by the individual clocks in the ensemble and the algorithm which combines them. The major concern is the long-term reliability and adequate management of the large data base associated with the time-scale. This includes not only data on clocks in the NBS ensemble, but also data on the many clocks (and primary standards) which are transferred in through the GPS system.

Plan - Use the system with receivers at WWV and WWVH to relate the performance of the clocks at those sites to (UTC)NBS and study the possibility of including them in the time scale.

Accomplishment - NBS/GPS receivers have been installed at both sites. Data from these receivers is now routinely filed in the time-scale computer giving back-up redundancy at the level of performance of the clocks at the radio stations. Time transfer accuracy is better than 10 nanoseconds. Because of the non-independent method of operation of these cesium standards, they are not useful as independent additions to the time-scale ensemble. The GPS receivers assure that UTC(NBS) is accurately available at the station sites.

Plan - Complete and put into operation the new emergency power backup system and the measurement backup system.

Accomplishment - System has been completed and is in operation. It performed well during a scheduled, 10-hour power outage. A few additional problems were identified during this outage and solutions for these have been developed.

Plan - Develop the appropriate interface between environmental monitoring equipment (recently ordered) and the time scale computer (PDP 11/70), and begin study of the influence of environmental parameters on clock behavior.

Accomplishment - All equipment for environmental monitoring has been received and tested. Most of it is fully installed and operating, but completion of the system is awaiting remodeling of part of the time-scale space and computer interfacing of some of the equipment. This monitoring equipment proved to be especially useful during the recent scheduled power outage.

FY 1986 Plans

Complete modifications and improvements of emergency power backup systems and develop procedures for their routine testing to assure reliability.

Study alternatives for acquisition of a backup computer for the time scale. Consider long-term needs for replacement of current computer.

Pending outside funding, initiate development of a "best research clock" as a reference for study of the millisecond pulsar. This work would be collaborative with Arecibo Observatory, Princeton, Berkeley, etc.

Complete implementation of time-scale environmental monitoring systems. System will trip alarm to alert staff when environmental parameters go out of operating range.

****
OBJECTIVE: Maintain international coordination of time scales and frequency standards using the Global Positioning System.
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A satellite based time transfer system which technique was developed in the Time and Frequency Division between 1979 and 1982 is now operational. Based on this approach a number of receivers are operating; e.g., at PTB in Braunschweig, West Germany; at OP in Paris, France; Goldstone, California; Madrid, Spain; Canberra, Australia; at NRC in Ottawa, Canada; at IEN in Torino, Italy; at RRL in Tokyo, Japan; at VSL in Delft, The Netherlands; at USNO in Washington, D.C.; as well as at NBS in Boulder, Colorado. A computer based automatic data collection network acquires the data from the receivers. This data is combined with the data from the NBS Atomic Time Scale so that the time of the remote clock is known with respect to UTC(NBS) to a precision better than 10 nanoseconds after one day of averaging.

JPL employs three receivers in the same mode used by NBS for international coordination to provide frequency calibrations between the sites of the NASA Deep Space Network at a few parts in 10^{14}. In fact, JPL funded part of the receiver development at NBS. The receivers at Boulder, Paris, Ottawa, Torino, Tokyo and Braunschweig, are being used to transfer clock data from NBS, OP, NRC, IEN, RRL, VSL and the PTB to the International Time Bureau in Paris. This new system has replaced Loran-C as the principal time and time interval transfer link for the SI second and the International Atomic Time Scale (TAI) for all major national standards laboratories.

FY 1985 Plans

Plan - Work through CCDS to establish responsibilities, cost sharing, and limits of coverage for NBS supported GPS time coordination.

Accomplishment - The CCDS has fully endorsed use of the NBS/GPS Common-View Technique for international coordination. It is now the de facto coordination method for all of the primary standards and 50% of all other clocks in TAI. BIH plans to send a guest worker to NBS to learn more about the technique. NBS is currently handling the tracking schedules for the system, but BIH will take over that responsibility in the future.

FY 1986 Plans

Cooperate with BIH guest worker to transfer GPS coordination methods and tracking procedures to this international organization. This is, of course, contingent upon the visit of this guest worker.

Publish paper summarizing procedures used in GPS time and frequency coordination.

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OBJECTIVE: Develop metrology for precise time, frequency and length measurements.
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Techniques for characterization and measurement of frequency and frequency stability

The need for frequency measurements range from sub-audio to the ultraviolet. NBS has been a world leader in developing and disseminating the measures of frequency stability, their practical implementation, and accuracy. For example articles in the Feb. 1966 issue of Proc. of IEEE and the 1971 IEEE I&M laid the foundation for specifying a practical way of defining frequency stability, which has become the defacto international standard in the field. The dual mixer concept of measuring time, frequency, and frequency stability makes it possible to easily measure the difference between state-of-the-art frequency standards even if they are nominally the same frequency. This concept was introduced in 1975 by NBS and NRC (Ottawa, Canada), and is used in the new NBS time scale measurement system. Now, picosecond precision time difference measurements can be made automatically on virtually any number of state-of-the-art clocks. Work in 1975 illuminated the limitations on frequency multiplication due to the phase noise in the standard or the multiplier chain, explaining numerous previous failures at precision infrared synthesis. This new understanding of the multiplication process then stimulated considerable improvement in the phase noise of crystal oscillators and signal processing equipment. In the rf region, the lowest noise crystal oscillators, buffer amplifiers, isolation amplifiers, and frequency multipliers presently available are a direct outgrowth of prototype designs and analysis developed at NBS. These new low noise devices have numerous applications in precision metrology as well as in the development of new frequency standards such as the passive hydrogen maser, stored ions, and cesium.

Techniques for characterizing noise in clocks

As part of the generation and dissemination of the SI second it is necessary to have an ensemble of clocks as a memory of the rate given by the primary frequency standard. This is accomplished by running a set of clocks based on commercial frequency standards which, in general, don't have the accuracy of the primary standard but have very good frequency stability. These clocks, when properly characterized, act as a good flywheel for the rate of NBS-6. The memory accuracy of the clock ensemble can be improved by either increasing the number of clocks or by wisely utilizing the clocks available. NBS has chosen to use a modest number of clocks with sufficient reliability, redundancy and variety (to avoid systematics from a particular manufacturer) from the available vendors making clocks, but then to characterize the clocks with enough care so that optimum time and frequency can be generated from the ensemble as memory of the rate given by the NBS primary frequency standard.

One of the current time scale algorithms had its philosophical basis in 1968 and has evolved into different programs with different computers. It became important to know how well this algorithm was approaching optimal performance given the set of clocks at hand. A cooperative effort was engaged in with the Statistical Engineering Group and out of that work came some very important contributions. First, a method was developed using Kalman filters to model atomic clocks and obtain maximum likelihood estimates of the model parameters from data on the ensemble of clocks. Tests for the validity of the model and confidence intervals for the parameter estimates were made and shown to be statistically significant. Techniques were also developed on the statistical significance of frequency drift and yielded some very important insights. In addition, a Kalman or recursive algorithm for estimating time from the ensemble of atomic clocks was developed. The algorithm allows for the addition or deletion of clocks and provides for automatic error detection and correction. Because of the success of this program, this Kalman algorithm is now used to generate the time scale TA(NBS) and the previous algorithm mentioned is still used to generate UTC(NBS). With this effort also came the conclusion that the past algorithm was very near optimum in its performance.

FY 1985 Plans

Plan - Initiate examination of the systematics in clock behavior through improvement of the statistical software routines.

Accomplishment - Performed some preliminary experiments on the effect of environmental changes on clock performance. More complete studies will require completion of environmental monitoring system and automated recording of selected environmental parameters on the time-scale computer.

FY 1986 Plans

Continue study of correlations between clock performance and environmental parameters.

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OBJECTIVE: Provide seminars, calibrations and measurement assurance on a fully reimbursable basis.

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Global Time Service

The division now offers a service, based upon the NBS designed receiver, which provides for extremely high precision time and frequency data at the users site. A receiver which is located at the users facility communicates its data automatically to an NBS computer which stores the raw data, determines which data elements are suitable for time transfer calculations and provides an optimally filtered value for the time and frequency of the user's clock with respect to the NBS Atomic Time Scales. The user is given an account on one of the NBS computers through which he may access the results of the NBS analysis. Tests between receivers in Colorado and Canada, Germany, France, Spain, Wyoming, Louisiana, Washington, DC and California have demonstrated an ability to perform time comparisons with a precision of a few nanoseconds using an averaging time of 13 minutes and frequency comparisons with a precision of 1 part in 10^{14} for averaging times of four days and longer.

Calibration of Atomic Standards

In conjunction with its new time scale algorithms NBS has developed a time and frequency measurement system which is unsurpassed in many of its capabilities. This new system has vastly improved capability of calibrating any clock that might be sent to NBS. The full accuracy of the NBS time scale and primary frequency standard is readily available and measurements are made automatically every two hours on a clock being calibrated. These data are logged in the NBS time scale computer and the standards characteristics and performance are readily documentable. Similarly, the person for whom the clock is being calibrated can be given an account in one of the NBS computers through which he may access the data as taken in real time.

FY 1985 Plans

Plan - Achieve an income level of $150,000 per year for the GPS Service.

Accomplishment - Net income for the service in FY85 was $140,000. The purchase of 21 receivers of the NBS design effectively transferred the receiver design to industry. The NBS purchase resulted in announcement by the company of a commercially available product with a price tag which is very attractive. As a result, new users of the NBS service will purchase their own receiver (ie. NBS is no longer involved with providing receivers for the service).

FY 1986 Plans

Finish remodeling of calibration facility (room 2047).

Shift staff responsibility for Global Time Service to more effectively distribute work load within the group.

****
OBJECTIVE: Advise and work with other governmental agencies and industry to incorporate advanced time, frequency and length metrology into their programs.
****

FY 1985 Plans

Plan - Advise Air Force Space Division on time and frequency aspects of operation of Global Positioning System.

Accomplishment - NBS characterization of GPS clocks and the Kalman filter parameters has continued to enhance the performance of the GPS system. The NBS/GPS Time Service was installed at Rockwell International to support calibration of GPS clocks.

FY 1986 Plans

Continue to advise Air Force Space Division on operation of Global Positioning System. Pending outside funding, develop time-scale system for GPS ground control.

Pending JPL funding, develop methods for remote steering of a clock using GPS.

IV. Hydrogen Masers

The primary goal of this effort has been to develop a passive hydrogen maser with good medium-term to long-term stability for DoD requirements and for use in the NBS clock ensemble. The project, which has been funded by the Navy, has been quite successful. Two masers are currently operating in the ensemble and they have been out-performing the commercial cesium standards by a wide margin. The maser technology has been transferred to industry through the Industrial Research Associate Program. The project has also addressed a number of issues which are of importance to the division. These include: line-center errors in high performance servo systems and phase noise in frequency multipliers and synthesizers.

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OBJECTIVE: Generate NBS time scales, UTC(NBS) and TA(NBS).

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Active hydrogen masers have long been touted for their excellent short-term stability, but long-term stability has generally been poor. The NBS maser project has focussed on improving long-term stability in a passive maser which is relatively simple and small. The goal has been a system which will fit into a package equivalent to that of a commercial cesium standard.

The results obtained to date have been impressive. The best of these masers provides medium-to-long-term stability equivalent to that of a cesium ensemble of approximately 25 high performance tubes. The fundamental design advance has been the servo locking of the physical cavity resonance to the hydrogen reference. The system also locks the slave oscillator to the same atomic resonance. The obvious conclusion is that the long-term stability of active hydrogen masers has been severely degraded by cavity pulling effects and that variations in the wall shift are extremely small relative to the present accuracy of primary standards.

FY 1985 Plans

Plan - Add hydrogen masers to NBS ensemble to improve its stability.

<u>Accomplishment</u> - Two masers, PHM-4 and MPH-14, are now part of the time scale. Both are performing extremely well out to at least several weeks. Moreover, in evaluating their frequencies, we have shown that MPH-14 is reproducible to better than 3×10^{-13} exclusive of the wall shift. Since the wall shift has been shown to be stable to

better than 1×10^{-13} per year, this represents a major advance for portable clocks. This work generated an extensive study of servo errors reported at a recent meeting and scheduled for submission to IEEE Transactions on Instrumentation and Measurement. The servo work provides a useful guide for development of NBS-7.

FY 1986 Plans

Add a third NBS passive hydrogen maser to the NBS ensemble.

Pending available funding, purchase a commercial version of the passive hydrogen maser to improve reliability of the NBS ensemble.

Study correlation between frequency noise in the passive masers and environmental parameters (e.g. humidity, pressure, and temperature).

Complete study of servo errors and begin transfer of servo technology to primary standard project.

****
OBJECTIVE: Provide seminars, calibrations and measurement assurance on a fully reimbursable basis.
****

Measurement of Phase Noise

The improved phase stability of components developed for the passive maser have enhanced the division capability to provide special calibrations of phase noise in oscillators, amplifiers, frequency multipliers and synthesizers from 5 MHz to 700 MHz. The present level of precision and accuracy for the NBS systems exceeds the performance of any commercial device over this frequency range.

FY 1985 Plans

Plan - Establish policies and procedures for the routine operation of calibration services and fix responsibility for their implementation.

Accomplishment - Calibration systems were upgraded to handle a broader range of frequencies. The descriptions of NBS calibrations in the central NBS catalogue of services (SP250) were completely rewritten. A room adjacent to the time scale has been set aside for calibration activities and renovation of that space has started. Once all systems are in place in this space, the procedures and policies for their operation will be finalized.

Plan - Determine user needs and upgrade calibration capability as appropriate (e.g., for signals at 10 MHz or stability at one-second averaging time).

Accomplishment - Ultra-low-noise multiplier chains were developed and tested. New circuits providing references at 10 MHz and 100 MHz have been fabricated and tested. The new systems improve resolution for measuring $\sigma_y(\tau)$ at three seconds from ~ $3 \times 10^{-12}\tau^{-1/2}$ to ~ $1 \times 10^{-12}\tau^{-1/2}$. New computer hardware will be needed to automate measurements at one second.

FY 1986 Plans

Extend capability for phase noise measurement to 18 GHz.

Extend calibration capability for $\sigma_y(\tau)$ down to a one-second averaging period.

****
OBJECTIVE: Establish the units of the International System for the "second" and the "meter".
****

FY 1985 Plans

Plan - Complete low phase noise synthesis chain for multiplication to 10 GHz in support of both the optically pumped cesium standard and as a candidate element of a future chain for synthesis into the visible region.

Accomplishment - A new 5 MHz to 100 MHz multiplier was designed, fabricated and tested. Four printed circuit versions of this circuit have been assembled and final testing will be completed shortly. Three low-noise, x-band oscillators have been acquired and circuits are ready for locking them to the multiplied 100 MHz systems.

FY 1986 Plans

Renovate and "recalibrate" electronics for NBS-4 and NBS-6.

Finish synthesis to x-band. Multiply x-band signal to 70 GHz and phase lock the two systems.

****
OBJECTIVE: Advise and work with other governmental agencies and industry to incorporate advanced time and frequency metrology into their programs.
****

Hydrogen maser technology

The passive hydrogen maser developed at NBS with partial military funding has demonstrated exceptional frequency stability from a few seconds to a few weeks. Based on 2 months of data, the stability is ~ 5×10^{-15} at 1 day and ~ 2×10^{-15} at 8 days. At a level of resolution of ±

3×10^{-16}/day, the drift is unobservable. The time dispersion per day is a factor of 4 to 5 times better than the best available commercial cesium frequency standards.

Several Industrial Research Associates have worked with NBS for three years on this program. This cooperation continues and the first passive hydrogen maser to be constructed in this program is now in operation.

Low acceleration sensitivity quartz crystal resonators

Vibration sensitivity is presently one of the most severe difficulties encountered when using a frequency standard in non-laboratory environments. Although NBS no longer has an experimental quartz crystal research program, consulting support is being provided to the U.S. Army and its industrial contractors.

FY 1985 Plans

Plan - Continue collaboration with Industrial Research Associates in the development of a passive hydrogen maser field standard.

Accomplishment - The collaboration with Industrial Research Associates has resulted in successful transfer of the passive-hydrogen-maser technology to industry. NBS's industrial partner is now close to testing an engineering design model of a commercial version of the NBS miniature passive hydrogen maser. This unit should achieve performance equal to or better than MPH-14 with the reliability characteristics of a 3rd-generation system.

FY 1986 Plans

Continue collaboration with Industrial Research Associates on the passive hydrogen maser.

V. Atomic Beam Standards

This program has just received sufficient additional NBS funding to allow construction of NBS-7, the next generation primary frequency standard which will be based on optically pumped cesium. The objective is a standard which can be easily operated in a nearly continuous mode with semi-automatic assessment of systematic errors at an accuracy level of 1 part in 10^{14}. The project is built upon successful tests of the concept on field-size standards pumped by laser diodes.

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OBJECTIVE: Establish the units of the International System for the "second" and the "meter".
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Operate NBS-6, the U.S. primary frequency standard

Since 1968 NBS has designed and developed three new cesium devices: NBS-4, NBS-5, and NBS-6. NBS-4 has a medium-length cavity of 50 cm, and was built to test new ideas for improving the stability of cesium devices. This standard is one of the most stable cesium clocks in the world, achieving a stability of 7×10^{-15}. It should be noted here that no previous NBS cesium frequency standards directly drove a clock; instead, they were used periodically to calibrate the frequency of an ensemble of commercial cesium beam clocks that ran continuously. NBS-4, because of its excellent stability, has served as a working clock in the time-scale ensemble.

NBS-5 was built on the framework of NBS-3 and in turn served as the basis for NBS-6, completed in 1975. The refinements incorporated over the years include greatly improved components to provide narrower resonance lines (25 hertz), the ability to reverse the direction of the atomic beam (which allows errors due to asymmetries in the cavity to be diagnosed), and other features aiding analysis of performance. It can also undergo routine maintenance without being completely turned off. NBS-6 has an accuracy of 8×10^{-14}; more accurate but not quite as stable as NBS-4. Used together, these two standards generate the U.S. standard second. A clock ensemble is used to carry the second forward in real time so that it is continuously available.

FY 1985 Plans

Plan - Evaluate NBS-6 by the end of FY 1985.

Accomplishment - Major modifications to the vacuum system and refurbishing of the electronic components are in progress. The evaluation will begin when these are completed. It now appears that the evaluation will be delayed approximately three months.

Plan - Use NBS-6 to calibrate TA(NBS).

Accomplishment - The last calibration of TA(NBS), completed in late 1984, showed no shift in TA(NBS) within the stated systematic errors of NBS-6, that is, within eight parts in 10^{14}. This again confirms that the time-scale stability is sufficient to continue evaluations with an interval of one year. When and if the systematic errors of the primary standard are reduced, a shorter calibration interval may be required.

Plan - Continue work on field-size optically pumped cesium standards in collaboration with an Industrial Research Associate. Focus on those elements which directly affect the development of a primary standard (e.g., laser stability requirements, laser stabilization schemes, and the Majorana effect).

Accomplishment - Studies of the laser noise and clock stability have resulted in the development of a model which relates laser noise to clock performance. This has helped clarify the requirements for laser diode performance. Simple methods for stabilization, line-narrowing, and tuning of the laser diodes are now under study. A third-generation, field-size standard has been designed and incorporates the ideas generated by theoretical study of Rabi line pulling and Majorana transitions. This new tube will allow for study of a number of systematic effects.

Plan - As appropriate, modify and upgrade components of NBS-4 and NBS-6 to alleviate operational difficulties associated with aging and damaged components.

Accomplishment - Major modifications and rework of the vacuum system and electronics of NBS-6 are nearing completion. The ion pumps are being replaced, new pumping and vacuum monitoring parts are being added, and a system for relieving the sliding seal problems is under construction. New connectors, cabling, and grounding have been added to improve reliability and reduce instabilities in the electronic subsystems. Modifications to NBS-4 have been delayed until the work on NBS-6 is complete.

FY 1986 Plans

Complete modifications and rework of NBS-6.

Complete evaluation of NBS-6 by Jan. 31, 1986. Use evaluation of NBS-6 to calibrate TA(NBS).

Continue study of the field-size standard with emphasis on development of design information for NBS-7.

Initiate upgrade and modification of NBS-4 to bring it up to its earlier performance level.

****
OBJECTIVE: Make fundamental improvements in atomic spectroscopy for future application to primary frequency standards.
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Primary cesium standard development

The known limitations to the accuracy of NBS-6 lie with the microwave cavity phase shifts, exacerbated by the dispersive nature of the state selection magnets. In addition, there are unknown shifts of the cesium clock frequency associated with systematic effects which cannot be readily studied in conventional systems. Replacing the magnets in a cesium standard with optical pumping and detection using laser diodes should allow the reduction of cavity phase shift uncertainties, and permit a better understanding of the limitations of cesium standards. A small laboratory version of the optically pumped cesium atomic beam frequency standard has been constructed and performance demonstrated at $\sigma_y(\tau) < 7 \times 10^{-12} \tau^{-1/2}$. Long-term data showing the "flicker" floor has not yet been obtained.

FY 1985 Plans

Plan - Develop detailed plans for a test bed to evaluate the potential for an optically pumped primary standard and initiate construction of the system.

Accomplishment - A detailed study of the Ramsey-cavity design has been completed. The optical pumping concept allows excellent control of end-to-end cavity phase shift, so the new cavity has been designed to minimize the distributed cavity phase shift. The design selected is relatively radical and considerable outside review is planned before an irreversible commitment is made to it. This review will run parallel to testing of a prototype cavity which is now being fabricated. The cavity geometry and dimensions have set the stage for completion of the system design from the inside outward. The performance requirements for the laser diodes have been established and techniques for achieving required performance have been demonstrated. Considerable work on electronic subsystems has also been initiated. This includes:

1. A new frequency synthesis concept has been developed and tested.
2. A model for the phase modulator has been developed and characterization of a test system is near completion.
3. A major study of servo errors has been undertaken and is near completion.
4. A new staff member is addressing the demodulator and integrator circuits.

FY 1986 Plans

Complete design of a frequency standard (test bed) based on optically pumped cesium, and initiate construction of the system.

****
OBJECTIVE: Advise and work with other governmental agencies and industry to incorporate advanced time and frequency metrology into their programs.
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Cesium beam technology

Recent advances in cesium beam technology which have come from Division studies of optically pumped cesium clocks could improve the performance of commercial devices which are used in military applications. For example, this research could improve both the long-term stability and the reproducibility after turn-on of satellite based cesium clocks. These improvements involve the use of laser diodes, cesium heat pipe ovens, optical pumping, and fluorescence detection of atoms.

Much of this work is performed under contract for other governmental agencies. In addition, the Division has formed two Industrial Research Agreements with manufacturers of cesium clocks. These agreements permit the transfer of NBS research results to the private sector, and also bring guest scientists from industry to the governmental laboratory.

FY 1985 Plans

Plan - Complete testing of cesium heat pipe ovens and publish the results.

Accomplishment - A detailed, quantitative model for these ovens was developed and measurements confirm that it is reasonably accurate. The model suggests a design modification which should substantially improve performance. Oven-life testing continues and results of the work have been submitted for publication. This work has been funded by another agency and has potential for large benefits for commercial cesium standards.

Plan - Continue collaboration with an Industrial Research Associate (IRA) in the development of an optically pumped cesium field standard.

Accomplishment - This IRA agreement involves a commitment on the part of NBS's collaborator to fabricate field-size cesium tubes modified for optical pumping. Two such tubes have already been fabricated and tested and a third has been designed. The collaborative work has resulted in clear demonstration of the optical-pumping concept. The measured performance of $\sigma_y(\tau) < 7 \times 10^{-12} \tau^{-1/2}$ is still above the flicker floor for the system.

FY 1986 Plans

Fabricate modified recirculating (heat-pipe) cesium oven and compare its' performance with the model.

Continue collaboration with an Industrial Research Associate on the development of an optically pumped cesium standard.

VI. ION STORAGE

The long term plans for primary frequency standards for the division involve an eventual shift to ion storage and radiative cooling. For the present the effort of this group is being directed toward development of the physics of the concepts. The group has already demonstrated a Be^+ ion clock which operates at a performance level equal to that of NBS-6, the present NBS primary standard. While the focus of this work is ion standards, the techniques are also applied to other problems of fundamental interest.

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OBJECTIVE: Make fundamental improvements in atomic spectroscopy for future application to primary frequency standards.
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Atomic clock based on stored ions

As a step towards realizing a primary frequency standard based on stored ions, the Division has made a clock based on a ground state hyperfine transition in $^9Be^+$. The combined uncertainties in all systematic frequency shifts (such as those due to Doppler effects) are at the same level as those of the present U.S. primary time standard, NBS-6 which has an uncertainty of about one part in 10^{13}.

In these experiments, a few hundred $^9Be^+$ ions were confined in a Penning trap and laser cooled to temperatures less than 1 K. An oscillator was locked to a magnetic field independent hyperfine transition (~ 300 MHz) using an optical pumping, double resonance technique. Measured stabilities were about equal to a commercial cesium clock. The hyperfine transition was driven for 20 s on each cycle which produced a linewidth of 0.025 Hz. During this time, the laser was shut off to avoid light shifts; this also allowed the ions to heat slightly from background gas collisions causing a second order Doppler shift of about 2×10^{-13}.

Other systematic effects are below this level. Frequency stability and accuracy performance can be improved in the future by using an ion with a higher hyperfine frequency. For this reason, mercury ions with hyperfine transitions at around 30 GHz are now being studied. The heating problem is discussed below.

Farther in the future, it appears that the most accurate clocks will be based on optical transitions in atoms or molecules. The main reason for this conjecture is that the Q's for such transitions can be extremely high ($\geq 10^{15}$). With this in mind, the two-photon S→D transition in Hg^+ has been studied. The transition was observed for the first time in a miniature rf trap. The present linewidth is limited by the laser bandwidth, but this transition has a fundamental Q of about 0.5×10^{15} (radiatively limited).

Ion-cloud/trapped-ion studies

Studies are made of ion dynamics and the relation of these dynamics to trap design. It appears that the principle limitation to accuracy of a frequency standard based on stored ions will be the uncertainty in the second-order-Doppler (time-dilation) frequency shift due to the rotation of the ion cloud. This rotation is a non-thermal effect and is independent of the internal temperature of the cloud. Therefore detailed studies of ion-cloud temperature, density and rotation are being made using a two-laser, optical-optical double resonance technique.

A new concept for a frequency standard based on "sympathetic cooling" is being studied theoretically and experimentally. In sympathetic cooling, one ion species is cooled by Coulomb coupling with another ion species which is laser cooled. This was proposed and demonstrated (on the Mg^+ isotopes) a few years ago at NBS and is now being considered for use in the mercury standard. The advantage is that the "clock" ions can be continuously cooled, but ac Stark shifts from the cooling radiation can be made negligibly small. This should result in substantially narrower linewidth (less than 1 millihertz) and reduction of errors due to the second-order Doppler shift.

FY 1985 Plans

Plan - Continue investigation of laser cooling of Hg^+ in Penning and rf traps with emphasis on improved vacuum and increased laser power.

> Accomplishment - Direct laser cooling ($\lambda \cong 194$ nm) of Hg^- ions in an rf trap has been observed. The best cooling and largest signals were obtained for single ions. For the near term, this result indicates that there is no fundamental limitation in achieving direct laser cooling in the Penning trap experiments. For the longer term, the result demonstrates feasibility for the trapping and cooling aspects of a Hg^+ optical frequency standard.

Plan - Further investigate (theoretically and experimentally) "sympathetic cooling", that is, cooling of one ion of spectroscopic interest by another ion which is laser cooled. Upon completion of the $^9Be^+$ experiments, begin construction of two-ion traps for this investigation.

Accomplishment - A computer solution for spatial shapes of two-component ion clouds has been accomplished. At T=0, the species separate, but cooling is maintained by the long-range Coulomb coupling. A Be^+/Hg^+ trap has been fabricated and tested for Be^+ and Hg^+ separately. Sympathetic cooling experiments will be initiated in the near future. A Mg^+/Be^+ trap is in the final design stages. This apparatus will allow a more complete evaluation of the concept.

Plan - Initiate fabrication of "array" detector to facilitate studies of cloud shape and size.

Accomplishment - The position-sensitive, photon-multiplier tube, the "array", was received in June, 1985. The electronic interface is nearing completion and testing of the entire system will take place in the near future.

FY 1986 Plans

Continue investigation of laser cooling of Hg^+ in rf traps. Study mechanisms which limit the linewidth of the two-photon transition in Hg^+ and develop methods for reducing this linewidth.

Complete fabrication of array detector and use it to observe single Hg^+ ions.

Conduct experimental studies of sympathetic cooling. Correlate results with computer solutions and study alternatives for using the concept as a basis for a primary frequency standard.

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OBJECTIVE: Perform basic studies in program areas related to future time and frequency standards.
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As an outgrowth of studies on ion clouds stored in Penning traps for possible frequency standard application, several closely related basic studies have been undertaken.

Search for Spatial Anisotropy

Frequency standards, including those based on atomic or nuclear (Mössbauer) transitions, have traditionally played an important role in testing gravitational theories. One example is measurements of the gravitational red shift. In addition, the very high resolution attained in trapped ion spectroscopy enables other sensitive tests of the Einstein

Equivalence Principle (EEP). All metric theories of gravity (including General Relativity) are founded on the EEP, according to which, any nongravitational physics experiment done in a local freely falling frame near a strongly gravitating mass will have the same outcome when done in a freely falling frame far away from all such masses. Also included in the EEP is local Lorentz invariance which states that the outcome of the experiment is independent of the velocity of the freely falling frame. In particular, two different atomic clocks (i.e., clocks based on transitions in two different kinds of atoms) located at the same point in space-time will have relative rates which are independent of (1) the velocity of the freely falling lab, and (2) the position and mass of strongly gravitating bodies. As a test of the EEP the frequency of the $^9Be^+$ "clock" transition (M_J = 1/2, M_I = -3/2) → (M_J = 1/2, M_I = -1/2) has been compared to the frequency of a passive hydrogen maser to see if a correlation can be found with orientation in space. Two gravitational interactions have been proposed which violate the EEP and shift the $^9Be^+$ "clock" transition relative to the hydrogen transition. Our experiments have searched for sidereal variations of the $^9Be^+$ "clock" transitions relative to the hydrogen transition. These experiments have achieved resolution better than 0.1 mHz and see no such variation. These results decrease previous experimental limits by a factor of 300 and in the future we expect to gain a further increase of two orders of magnitude in resolution.

Non-neutral plasmas

In the language of plasma physics, the ion clouds in a Penning or rf trap comprise a one component, non-neutral ion plasma. In a small plasma of laser cooled $^9Be^+$ ions stored in a Penning trap we have observed behavior which is indicative of the liquid state. In this case the Coulomb coupling constant Γ was as high as 10. Calculations predict that at $\Gamma \cong 2$, the pair correlation function should begin to show oscillations characteristic of a liquid, and at much larger values of Γ ($\Gamma \cong 170$) crystallization may take place. In our experiment a second laser was used to probe the ion plasma and measure the temperature of the ions from the Doppler broadening of the optical probe transition. The ion number density was determined by measuring the ($\vec{E}\times\vec{B}$) cloud rotation frequency. Because the trap electric field and magnetic field were known, the space charge electric field was extracted from the cloud rotation frequency and used to determine the ion number density. Ion number densities of ~ 2 x $10^7/cm^3$ and temperatures of ≲ 100 mK produced values of $\Gamma \cong 10$. Values of Γ large enough to observe a liquid-solid phase transition should be accessible in future versions of this experiment. If the theoretical cooling and density limits can be obtained, values of Γ as large as 15,000 are perhaps possible for Be^+ ions. Because experimental information on three-dimensional, strongly coupled plasmas is almost non-existent, these experiments can provide some useful tests of the theoretical calculations.

FY 1985 Plans

Plan - Initiate study of magnetic susceptibility perturbations to hyperfine structure in $^9Be^+$ (success will rely upon how many field independent transitions it is possible to measure).

Accomplishment - Attempts were made to study all of the field-independent transitions in $^9Be^+$, however the low-field transitions ($B \cong 1.6$ T) were not accessible due to parasitic heating (apparently caused by trap asymmetries). To circumvent this problem a new trap with a high degree of axial symmetry has been designed.

Plan - Continue search for spatial anisotropy in $^9Be^+$.

Accomplishment - A first experiment has been completed and reported in the Physical Review Letters. The result shows no anisotropy at a level which is 300 times lower than the limit set by Hughes, et al. and Drever in 1961.

Plan - Study three-dimensional cooling of $^9Be^+$. Look for liquid-solid phase transition.

Accomplishment - Three-dimensional cooling (that is, simultaneous, direct laser cooling of the cyclotron, magnetron and axial degrees of freedom) has been done. Γ's as high as 100 were observed indicating "fluid" behavior very near the transition to a "solid" (the solid should appear at $\Gamma \cong 170$). Future efforts will be devoted to diffusion and interference experiments aimed at directly observing order in the plasma.

FY 1986 Plans

Complete fabrication of a highly symmetric (axially) ion trap and use it to conduct a study of the magnetic susceptibility perturbations to hyperfine structure in $^9Be^+$ or $^{25}Mg^+$.

Using the trap described above, improve sensitivity of system for studying anisotropy of space.

Continue study of phase transitions in $^9Be^+$ plasmas using three-dimensional cooling. Initiate design of system for study of low-angle (Bragg) scattering in these plasmas.

Study statistics of fluorescence from a single ion.

Study stimulated Raman technique for measuring plasma temperature.

VII. OPTICAL FREQUENCY METROLOGY AND DEVICES

This group retains the expertise and facilities which were used in earlier measurements of the speed of light and the subsequent work which led to the redefinition of the meter in terms of the second. More recently, this frequency synthesis has proven to be extremely useful as a basis for spectroscopic standards in the infrared and far infrared. Of particular note is the generation of tunable far infrared radiation (TuFIR) using either second or third order mixing. The radiation generated completely spans that part of the spectrum. The group continues to improve devices and concepts for frequency synthesis. This will prove to be especially valuable should the stored ion work move to an optical frequency.

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OBJECTIVE: Provide reference frequencies from the microwave to the visible region of the spectrum.
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Spectroscopic frequency references (measured with respect to the cesium standard)

The pioneering work done by the laser frequency synthesis group in extending direct frequency measurements from the microwave to the visible portion of the electromagnetic spectrum is now being used to measure the frequencies of atomic and molecular transitions which are of importance to spectroscopists, astronomers, and atmospheric scientists. Before the advent of heterodyne optical spectroscopy (in which the frequency is measured with respect to cesium) the wavelengths of spectral features were measured. These measurements were hundreds of times less accurate than the new direct frequency measurements. The knowledge of the frequencies of selected species allows the spectroscopist, astronomer or atmospheric scientist to carefully calibrate spectrometers and receivers to the appropriate frequencies (or wavelengths).

The generation of reference frequencies with requisite accuracy involves accurate heterodyne frequency measurements and the reliable fitting and analysis of the spectral data. Coordinated activity at NBS (between the Time and Frequency Division in Boulder and the Molecular Spectroscopy Division in Gaithersburg) involves selection of suitable molecular calibration candidates, measurement of their frequencies, and the analysis, and dissemination of the results in the form of reference frequency tables.

To meet current needs absorption frequency calibration standards must be readily obtained and easily handled with at least one calibration point every few gigahertz. The reference lines must be well resolved and free of accuracy-limiting fine structure each to an accuracy of one part in 10^8.

The far infrared (0.1 to 5 THz, 3 mm to 60 μm)

The frequencies of several hundred optically pumped lasers have been measured and are used by laboratory spectroscopists to measure absorption features. Laser Magnetic Resonance (LMR) spectroscopy has been developed into one of the world's most sensitive techniques for observing and measuring frequencies of molecules. Laser magnetic resonance spectroscopy uses these known frequencies to predict the frequencies of free radicals used by astronomers and upper atmospheric researchers. The new technique of tunable far infrared spectroscopy (Tufir), developed by NBS, promises a much more general technique for measuring frequencies in this region. Further mention of this concept is made later in this section.

The CO_2 laser which is stabilized to CO_2 itself furnishes the main frequency grid for all of our measurements and is widely used for reference purposes.

The infrared region (25 to 200 THz, 1.5 to 12 μm)

The frequencies of hundreds of lines of OCS, DBr, CO, N_2O, and NO now furnish reference grids for this region. The methane line used to stabilized the He-Ne laser is especially noteworthy. It serves as a particularly accurate reference for both metrology and spectroscopy. Work on a number of the other molecules has been funded for a number of years by NASA in support of the Clean Air Act Amendments of 1977. Accurate spectroscopic measurements of molecules which are important in upper atmospheric chemistry provide the basis for heterodyne studies of the upper atmosphere. This work is thus helpful in resolving questions about pollution issues (e.g. acid rain).

Carbonyl Sulphide, 815-2140 cm^{-1}

Tables of OCS absorption lines have been provided for use as frequency calibration standards in the following regions of the infrared: 815-892 cm^{-1}, 1008-1092 cm^{-1}, 1649-1738 cm^{-1}, 1850-1921 cm^{-1} and 2013-2140 cm^{-1}. The absorption line frequencies and approximate intensities are calculated from spectroscopic constants which have been determined by fitting selected data from the literature. This data includes NBS heterodyne frequency measurements for all except the 2013-2140 cm^{-1} region. The uncertainties of most of the recommended frequency standards are on the order of 1 to 10 MHz. Hot band transitions and transitions for some of the less abundant isotopic species are included in the tables in order to provide patterns for the unambiguous identification of the lines as well as to provide additional calibration standards in some cases. The calibrations atlas contains over 6600 entries.

Deuterium bromide (1-0 band), 1630-1985 cm^{-1}

Heterodyne frequency measurements have been made on selected deuterium bromide 1-0 band transitions ranging from P(20) to R(17). The measurements include electric quadrupole split triplets comprising the R(0) and P(1) transitions in the $D^{79}Br$ isotope. New DBr constants have been determined and a table of frequencies, believed to be accurate to 3 MHz, is available. Separation between line pairs ranges from about 6 cm^{-1} at 1980 cm^{-1} to 11 cm^{-1} at 1630 cm^{-1} hence this molecule has limited utility. It does however, span the OCS gap between 1738 and 1850 cm^{-1} and partially covers another OCS gap between 1921 and 2013 cm^{-1}.

Nitrous and Nitric Acids (Tunable Diode Laser)

Heterodyne frequency measurements on N_2O at 5.3 μm and 9.0 μm have been completed and measurements at 7.7 μm are partially complete. Two papers describing this work present calibration tables covering the following regions: 2135-2268 cm^{-1}, 1816-1930 cm^{-1} and 1207-1304 cm^{-1}. The nitric oxide fundamental spans the 1741-1980 cm^{-1} region for calibration purposes and is also of intrinsic interest for the atmospheric scientists as well.

Carbon monoxide (2-0), 4120-4350 cm^{-1}

The 2-0 ro-vibronic band of $^{12}C^{16}O$ has been studied extensively by Fourier Transform Spectroscopy techniques and has become a widely accepted calibration standard. Current developments with a color center laser spectrometer have permitted use of an alternate technique not only to confirm these results, but also to lead to an improved set of molecular constants. The data were combined in a least squares fit with seven unpublished microwave results to determine new constants which are an order of magnitude improved over prior results. A new frequency calibration table with some entries differing by as much as 15 MHz from Fourier Transform technique results has been published.

Nitrous oxide (color-center laser)

The absolute frequencies of 39 lines in the 00^02-00^00, 20^01-00^00, and 12^01-00^00 bands of N_2O in the 4300 - 4800 cm^{-1} range have been measured by heterodyne frequency techniques. The lines were each measured in Doppler-limited absorption with a color-center laser as a tunable probe of the N_2O and two stabilized CO_2 lasers as reference frequencies. New ro-vibrational constants have been fitted to these measurements. Tables of calculated transition frequencies are given with estimated absolute uncertainties as small as 10^{-4} cm^{-1}. The pressure shifts of four lines have been measured, and the values fall within the range of 0 to -2 MHz/kPA (0 to -0.2 MHz/Torr).

Visible Region

Measurements in the visible region are described in the next section.

FY 1985 Plans

Plan - Publish results of frequency measurements in $^{13}CH_2F_2$ and CD_3OH.

Accomplishment - The paper on CD_3OH was submitted and has been accepted for publication. The paper on $^{13}CH_2F_2$ is in preparation.

Plan - Initiate measurements with LN_2-cooled CO laser and TDL spectrometer on N_2O bands at 7.7 and 8 μm.

Accomplishment - Approximately half of the measurements in these bands have been completed and a paper on them has been accepted by the Journal of Molecular Spectroscopy. These are the first heterodyne measurements in this region which are traceable to the cesium frequency. The CO laser used in these studies performed exceptionally well with operation at the highest vibrational transition ever reported.

Plan - Measure NO band at 5 μm.

Accomplishment - Measurements on NO in this region are complete and a paper reporting them is in preparation. This molecule is important for spectrometer calibration as well as for studies of the upper atmosphere.

FY 1986 Plans

Compete measurements on N_2O bands in the 7.7 μm region. Initiate measurements on N_2O at 10 μm.

Use N_2O calibration frequencies for tunable-diode-laser spectroscopic studies of HNO_3 at 7.7 μm.

Measure the OCS band at 5 μm.

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OBJECTIVE: Establish the units of the International System for the "second" and the "meter".
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Provide frequency measurements of lasers suitable for realizing the new definition of the meter

IN 1982 the Comité Consultatif pour la Définition du Métre (CCDM) proposed a new definition for the meter, namely that: "The meter is the length of the path travelled by light in vacuum during a time interval of 1/299 792 458 of a second." In October of 1983 the General Conference of Weights and Measures approved this change which is based to a large extent on both pioneering work and exacting measurements made by NBS. With this definition the meter can be realized from the wavelength of any laser which is stabilized to a narrow atomic or molecular absorption for which the frequency is known. The wavelength λ is determined from the relation $\lambda=c/\nu$, where c is the fixed value of the speed of light and ν is the measured frequency of the laser. Thus, the realization of the meter will require the measurement of the absolute frequency of suitable spectral lines in the visible spectral region. To this end, the Division has performed two highly accurate frequency measurements of hyperfine transitions in molecular iodine used for laser stabilization. One is in the yellow spectral region, and the other, red.

The absolute frequency of a dye laser stabilized on the o hyperfine component of the $^{127}I_2$ 17-1 P(62) transition at 520 THz (576 nm) in iodine was measured with respect to the CH_4 stabilized 88 THZ (576 nm). A 26 THz CO_2 laser, a color center laser at 130 THz, and a He-Ne laser at 260 THz, were used as transfer oscillators. The measured I_2 frequency was 520 206 808.547 MHz with a total uncertainty of 1.6 parts in 10^{10}.

The absolute frequency of the 473 THz He-Ne laser (633 nm), stabilized on the i hyperfine component of the $^{127}I_2$ 11-5 R(127) transition, was measured by comparing its frequency with a known frequency synthesized by summing the radiation from three lasers in a He-Ne plasma. The three lasers were an 88 THZ CH_4 stabilized He-Ne laser (3.39 µm), a 125 THz color center laser (2.39 µm) with its frequency referenced to the $R_{II}(26)$ $^{13}C^{18}O_2$ laser, and a 260 THz He-Ne laser (1.15 µm) referenced to an I_2 stabilized dye laser at 520 THz (576 nm). The measured frequency is 473 612 214.789 MHz for the i hyperfine component with a total uncertainty of 1.6 parts in 10^{10}.

These frequencies, when used to realize the new meter, represent a 25-fold improvement over the present Krypton length standard.

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OBJECTIVE: Develop metrology for precise time, frequency and length measurements.
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Techniques for characterization and measurement of frequency and frequency stability.

Frequency metrology from the far infrared to the visible has been greatly stimulated by the work at NBS. The early work on W-Ni point contact metal-insulator-metal (MIM) diodes, carried out simultaneously and independently by MIT and NBS, laid the groundwork for precision frequency synthesis in this spectral laser region.

An extremely important outgrowth of this work was the first frequency measurement of the 3.39 micron line of CH_4 followed by the wavelength measurement of the same line. The product of the frequency and wavelength produced a value for the speed of light nearly 100 times more accurate than the previously accepted value. This work coupled with recent frequency measurements of visible spectral lines has led to the replacement of the Krypton lamp as the length standard and the assignment of an exact value for the speed of light.

Recent work on the MIM diode has expanded the frequency difference range over which measurements can be made by a factor of 100 (in the visible). This is expected to greatly simplify frequency metrology because of the reduction in the number of frequency markers to reference lines necessary to fully cover this spectral region.

Techniques for laser frequency synthesis

Frequency synthesis is usually achieved in some non-linear device which adds, subtracts and multiplies the frequencies of the radiations incident on it. In the Time and Frequency Division we have used W-Ni metal-insulator-metal (MIM) point contact diodes as detectors, harmonic generators, and mixers of coherent radiation from the microwave to the visible region of the electromagnetic spectrum. The MIM diode plays a major roll in the Laser Frequency Synthesis Chain which connects the cesium clock to the visible I_2-stabilized lasers and hence provides the realization of the meter from the new definition.

The MIM diode has been used for the past 15 years and the mechanical and electrical engineering improvements have been steady. Recent use of conical coupling along with off-axis parabolic focusing mirrors has led to an exciting new technique of generating tunable far infrared radiation.

Tunable coherent radiation can be generated in the uv, visible and near infrared regions of the electromagnetic spectrum with the use of tunable lasers and non-linear optics. Only recently have tunable sources been available in the far infrared and these did not allow complete coverage since the technique involved the addition of microwave sidebands to several of the stronger far infrared lasers. Division scientists have now succeeded in generating tunable cw far-infrared radiation via CO_2 difference frequency mixing in a tungsten-nickel, (MIM) diode. Previously, the MIM diode had been used mainly to make direct frequency measurements from 0.3 to 200 THz.

Six tenths of a microwatt of tunable, cw far infrared radiation has been generated by mixing 180 mW of radiation from each of two CO_2 lasers in a MIM diode. The difference frequency was radiated from the MIM diode, and was detected in a calibrated germanium bolometer. The use of a waveguide CO_2 laser with its greater frequency tunability as one of the lasers used to generate the difference frequency promises a complete coverage of tunable cw radiation in the entire far infrared band from 100 to 6000 GHz with the additional advantages of simplicity and high accuracy. Using this technique, it has been possible to readily detect the $J=5 \leftarrow J=4$ transition of CO (576 GHz) and the $J=1 \leftarrow J=0$ transition of HF (1.23 THz). Just recently the HCl spectrum from 0.5 to 5.5 THz has been measured and this simple molecule now provides for an excellent calibration standard in that frequency range.

FY 1985 Plans

Plan - Perform analysis of entire TuFIR spectrometer in order to determine relative importance of the performance of each component. Look for methods to further improve sensitivity.

Accomplishment - An analysis of the TuFIR spectrometer was completed and the key limit to sensitivity was found to arise from inadequate CO_2 laser feedback isolation. When this problem was rectified, the system sensitivity improved by an order of magnitude. Considerable study of the low-frequency properties of the MIM mixers was carried out in FY 1985. It was found that different diode characteristics are required for second-order and third-order mixing. Second-order mixing is best where the diode exhibits the traditional rectification in its I-V characteristic. Third-order mixing is best when the I-V characteristic is anti-symmetric about the origin. Some empirical rules regarding the electrode work functions were developed.

Plan - Complete study of the range of application of TuFIR spectroscopy by making measurements in the range of 5 to 7 THz.

Accomplishment - Completion of this study has been delayed by difficulty in obtaining an appropriate detector. The detector is now on order and scheduled to arrive shortly.

FY 1986 Plans

Bring second TuFIR spectrometer (using third-order FIR generation) into operation

Increase TuFIR sensitivity through use of a ^{3}He bolometer and a cooled grating prefilter.

Study properties of diodes for second-order and third-order mixing. Search for diodes with improved mixing properties

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OBJECTIVE: Measure far infrared frequencies of atoms and molecules (especially transient species) for radio astronomy and upper atmospheric science.
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High resolution spectroscopic measurements in the far infrared have been advanced significantly through development (at NBS) of two measurement techniques. These techniques are used to make unique laboratory measurements, previously inaccessible, which have bearing on difficult atmospheric and astronomical studies.

Laser Magnetic Resonance (LMR) spectroscopy has been developed into an ultrasensitive technique (i.e., several orders of magnitude more sensitive than microwave spectroscopy) for observing and measuring reactions involving molecules. LMR techniques are singularly effective in measuring parameters necessary to model the effects of pollutants (e.g., fluorocarbons, nitric oxide, etc.) in the atmosphere.

Subsequently LMR was used to make the first laboratory observation of the CH_2 spectra. The CH_2 radical is an important building block for all organic molecules and is present as a free radical intermediary in many chemical reactions. Measurements of CH, CD_2 and CD were completed and the spectra of GeH_3, GeH, SiH, and Si were identified.

The new techniques of Tunable Far Infrared (TuFIR) spectroscopy promises to enhance the LMR technique by measuring some of the same free radicals at zero field. Zero field measurements will have a greater accuracy. The technique, an outgrowth of NBS frequency synthesis work involving MIM diodes, also allows the measurement of all far infrared active molecules, not just paramagnetic ones. Measurements of OH frequencies have been completed. Tables of far infrared transition frequencies for the molecule are now available.

<u>FY 1985 Plans</u>

Plan - Remeasure rotational frequencies of CH using TuFIR spectroscopy.

<u>Accomplishment</u> - These measurements have been deferred to FY 1986 in order to meet higher priority objectives.

Plan - Study LMR spectra of ^{17}OH and complete analysis of LMR data on GeH.

Accomplishment - These studies have been completed and a paper is in preparation. An atlas of frequencies is now available to the radio astronomy community.

Plan - Search for LMR spectra of molecular ions.

Accomplishment - Using LMR, the OH^+ ion was observed only to find that the Berkeley group had observed it two weeks earlier. HCO^+ lines in the FIR were observed and measured for the first time using TuFIR methods.

Plan - Publish paper on tunable far-infrared spectroscopy of OH.

Accomplishment - Paper has been completed and submitted.

FY 1986 Plans

Using TuFIR methods, search for spectra of molecular ions.

Perform OH line-broadening measurements for use in upper atmospheric studies.

VIII. GEOPHYSICAL MEASUREMENTS

This is a small program conducted in JILA by Time and Frequency Division staff. One of the projects involves construction and demonstration of an apparatus for measuring intermediate baselines (25 km to 50 km) with an uncertainty of 1/2 cm or less. The multiple-wavelength technique that is used is closely related to satellite navigation and timing problems which also require a complete accounting for atmospheric dispersion. A second project involves use of an array of tilt detectors to study properties of the earth's mantle and core-mantle boundary. A third program which is just starting, is a feasibility study for using GPS timing signals for very accurate geodesy.

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OBJECTIVE: Develop metrology for precise time, frequency and length measurements.
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Distance measurement techniques

The need to accurately determine the lengths of baselines on the surface of the earth arises in many different contexts, ranging from the calibration of tracks used for rocket tests to estimation of the relative motions of large geographical regions in seismically active zones. This work is particularly timely, since the use of timing techniques for such distance measurement is expected to grow and a key roadblock to improved resolution involves the dispersion of the atmosphere.

FY 1985 Plans

Plan - Continue field and laboratory evaluations of the system and evaluate systematic errors.

> Accomplishment - Tests of the complete system uncovered a systematic variation of the apparent refractivity with wind speed. The refractivity changed by several percent on windy days, an unreasonably large effect. We believe the effect is produced by a coupling of phase shift with entrance angle in the primary optical chain and we are in the process of constructing new input optics in order to resolve the difficulty.

FY 1986 Plans

Complete field and laboratory evaluation of the system.

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OBJECTIVE: Evaluate the utility of nano-radian level tilt measurements in studying earth structure.
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FY 1985 Plans

Plan - Complete analysis of the remaining data and finish work on the theoretical model of the Yellowstone Caldera.

> Accomplishment - The preliminary analysis of the measurements is complete. The construction of the model is finished, but a final comparison between theory and experiment has been delayed for few months by the change in computing systems (to the 205 in Gaithersburg).

FY 1986 Plans

Complete comparison between theory and experiment on the model of the Yellowstone Caldera.

INVITED TALKS

Time and Frequency Division (524)

D. W. Allan, "How and When to Perform Allan Variance Calculation or Phase Noise Measurements, Measurement Science Conference, January 18, 1985.

D. W. Allan, "NBS Time and Frequency MAP Program, Measurement Science Conference, January 18, 1985.

D. W. Allan, "Relativity in Celestial Mechanics and Astrometry, IAU Symposium, May 28, 1985 in Liningrad, Russia.

D. W. Allan, "Status of Time and Frequency Program at NBS", Consultative Committee for the Definition of the Second (CCDS), June 5, 1985 in Paris, France.

D. W. Allan, A Review of International Time and Frequency Comparisons Via the NBS/GPS Common View Technique, 1985 North American Radio Science Meeting and International IEEE/AP-S Symposium, June 19, 1985 in Vancouver, Canada.

J. C. Bergquist, "Fluorescence Detection of Trapped Ions," Federation of Analytical Chemistry and Spectroscopy Societies, September, Philadelphia, PA, 1984.

J. C. Bergquist, "Two-Photon Optical Spectroscopy in HgII," Frequency Control Symposium, Philadelphia, PA, May 1985.

J. C. Bergquist, "Two-Photon Optical Spectroscopy in HgII," Seventh International Conference on Laser Spectroscopy (SEICOLS), Maui, Hawaii, June 1985.

J. J. Bollinger, "Generation of Strongly Coupled Ion Plasmas," 26th Annual Meeting of the Division of Plasma Physics, Boston, MA, October 29, 1984.

J. J. Bollinger, "Strongly Coupled Non-Neutral Ion Plasma," Institute of Theoretical Physics, Workshop on Strongly Coupled Plasmas, Santa Barbara, CA, February 1985.

R. E. Drullinger, "On the Fluorescent Light Shift in Optically Pumped Cesium Standards," 39th Annual Symposium on Frequency Control, Philadelphia, PA, May 1985.

R. E. Drullinger, "Optically Pumped Small Cesium Beam Standards: A Status Report," 39th Annual Symposium on Frequency Control, Philadelphia, PA, May 1985.

K. M. Evenson, "Advances in Far-Infrared Spectroscopy", NASA Headquarters, November 1984.

K. M. Evenson, "Tunable Far-Infrared Spectroscopy," NBS Gaithersburg, November 1984.

K. M. Evenson, "The New Meter," Physics Department, University of Wyoming, Laramie, WY, October 23-24, 1984.

K. M. Evenson, "Tunable Far-Infrared Spectroscopy," University of Michigan, Ann Arbor, MI, February 1985.

K. M. Evenson, "Tunable Far-Infrared Spectroscopy," Ford Motor Company, Detroit, MI, February 1985.

K. M. Evenson, "Tunable Far-Infrared Spectroscopy," Seventh International Conference of Laser Spectroscopy (SEICOLS), Maui, Hawaii, June 1985.

K. M. Evenson, "Frequency Spectroscopy: The Last Measurement of the Speed of Light: And The New Meter," the Sculoa Normale, Pisa, Italy, September 1985.

K. M. Evenson, "Tunable Far-Infrared Spectroscopy," High Resolution Spectroscopy Meeting, Riccioni, Italy, September 1985.

W. M. Itano, "Radiative Lifetime of the Metastable $^2D_{5/2}$ State in Hg^+," Annual Meeting of the Division of Electron and Atomic Physics, May 1985.

J. Levine, "Techniques for Computing Fourier Transforms," Computational Physics Seminar," University of Colorado, Boulder, CO, November 1984.

J. Levine, "Tiltmeters," Amoco Oil Company, Tulsa, OK, June 1985.

J. D. Prestage, "Limits on Spatial Anisotropy By Use of $^9Be^+$ Ions," Gordon Research Conference, Wolfboro, NH, July 1985.

D. B. Sullivan, "Time," Precision Measurement Association, February 1985.

D. B. Sullivan, "A Recirculating Oven for Atomic Beam Frequency Standards," 39th Annual Frequency Symposium, Philadelphia, PA, May 1985.

F. L. Walls, "Errors in Sinusoidal Frequency (Phase) Modulation Derived Servo System," 39th Annual Frequency Control Symposium, Philadelphia, PA, May 1985.

F. L. Walls, "Noise in Resonators, Filters and Oscillators," 39th Annual Frequency Control Symposium, Philadelphia, PA, May 1985.

F. L. Walls, "Precise Phase Noise Measurements of Oscillators," Proceedings of rf Technology Expo '85, Anaheim, CA, January 1985.

D. J. Wineland, "Laser Cooled Ions, Rice University, November 15, 1984.

D. J. Wineland, "Optical Pumping of Stored Atomic Ions," Symposium Alfred Kastler, Paris, France, January 1985.

D. J. Wineland, "High Precision Spectra of Laser Cooled Ions," California Institute of Technology, February 1985.

D. J. Wineland, "Laser Cooled Ion," University of Georgia, April 15, 1985.

D. J. Wineland, "Laser Cooled, Trapped Ions," University of Hamburg, West Germany, January 1985.

D. J. Wineland, "Laser Cooled, Trapped Ions," Max Plank Institute, Garching, West Germany, January, 1985.

D. J. Wineland, "Laser Cooled, Trapped Ions," M. A. Ferst Symposium honoring Prof. Norman Ramsey, Georgia Tech, June 1985.

PUBLICATIONS

Time and Frequency Division

The Direct Measurement of the $3\ ^3P_0$-$3\ ^3P_1$ Fine-Structure Interval and the g_J-Factor of Atomic Silicon by Laser Magnetic Resonance, M. Inguscio, K. M. Evenson, V. Beltran-Lopez, and E. Ley-Koo, Astrophysical Journal, 278:L127-L130, (1984).

Optical Frequency Synthesis Spectroscopy, K. M. Evenson, D. A. Jennings, F. R. Petersen, J. S. Wells, and R. E. Drullinger, Prog. Quant. Electr. Vol. 8, 143-151 (1984).

Infrared and Far-Infrared Transition Frequencies for the CH_2 Radical, T. J. Sears, A. R. W. McKellar, P. R. Bunker, K. M. Evenson, and J. M. Brown, Astrophysical Journal 276:399-402, (1984).

New Time and Frequency Services at the National Bureau of Standards, S. R. Stein, G. Kamas, and D. W. Allan, Proceedings or the 16th Annual Precise Time and Time Interval Planning and Applications Meeting, December 1984.

A Wideband Frequency-Offset Locked Dye Laser Spectrometer Using a Schottky Barrier Mixer, J. C. Bergquist and H.-U. Daniel, Optics Communications, 48, 327-334 (1984).

Efficient Single Mode Operation of a cw Ring Dye Laser with a Mach-Zehnder Interferometer, J. C. Bergquist and L. Burkins, Optics Communications, 50, 379-385 (1984).

A New Miniaturized Passive Hydrogen Maser, F. L. Walls and K. B. Persson, Proc. of the 38th Ann. Freq. Control Symposium, 1984.

Position Location with the NBS/GPS Time-Transfer System, M. Weiss, PLANS '84 Conference Proceedings, 1984.

Test of Wall Coatings for Controlled Moist Air Experiments, H. J. Liebe, V. L. Wolfe, and D. A. Howe, Rev. Sci. Instrum. 55(10), 1702-1705, 1984.

A Simplified GPS C/A Receiver Front End with Low Noise Performance, D. D. Davis and A. D. J. Clements, Proceedings of the 16th Annual Precise Time and Time Interval Planning and Applications Meeting, December 1984.

Spectroscopy of Stored Ions, D. J. Wineland, in Precision Measurement and Fundamental Constants II, B. N. Taylor and W. D. Phillips, eds. National Bureau of Standards (US) Spec. Publ. 617, 83-92 (1984).

Progress Toward a Stored Ion Frequency Standard at the National Bureau of Standards, W. M. Itano, D. J. Wineland, J. C. Bergquist, and F. L. Walls, in Precision Measurement and Fundamental Constants II, B. N. Taylor and W. D. Phillips, eds. National Bureau of Standards (US) Spec. Publ. 617, 83-92 (1984).

A Consistent Coordinate Time On and Near the Earth, N. Ashby and D. W. Allan, Phys. Rev. Lett. 53, (1984).

High Resolution Spectrum of the ν_5 Band of Nitric Acid (HNO_3) Near 880 cm^{-1}, A. G. Maki and J. S. Wells, J. Mol. Spectrosc. 108, 17-30 (1984).

Frequency Standard Research Using Stored Ions, D. J. Wineland, Wayne M. Itano, J. C. Bergquist, J. J. Bollinger, and H. Hemmati, Prog. Quant. Electr. 8, 139-142 (1984).

Pressure Effects on the Frequency of Continuous-Wave Optically Pumped Far-Infrared Lasers, M. Inguscio and K. M. Evenson, Opt. Lett. 9, 443-444 (1984).

Strongly Coupled Nonneutral Ion Plasma, J. J. Bollinger and D. J. Wineland, Phys. Rev. Lett. 53, 348-351 (1984).

Rotational Structure of $^{16}O_2$, $^{16}O^{17}O$, and $^{16}O^{18}O(X^3\Sigma_g^-)$ from Laser Magnetic Resonance Spectra, J. Mol. Spectrosc. 107, 395-404 (1984).

Laser-Magnetic-Resonance Detection of Magnesium Atoms in the Metastable $^3P_{0,1,2}$ States, M. Inguscio, K. R. Leopold, J. M. Murray, and K. M. Evenson, J. Opt. Soc. Am. B/Vol. 2 (1985).

Accuracy of International Time and Frequency Comparisons Via Global Positioning System Satellites in Common-View, D. W. Allan, D. D. Davis, M. Weiss, A. Clements, B. Guinot, M. Granveaud, K. Dorenwendt, B. Fischer, D. Hetzel, S. Aoki, and M. -K. Fujimoto, L. Charron, and N. Ashby, Conference on Precision Electromagnetic Measurement, IEEE Trans. on Instrumentation and Measurement, IM-34, 118 (1985).

Hyperfine Structure of the $2p^2P_{1/2}$ State in $^9Be^+$, J. J. Bollinger, J. S. Wells, D. J. Wineland, and W. M. Itano, Phys. Rev. A 31, 2711-2714 (1985).

Trapped Ions, Laser cooling, and Better Clocks, D. J. Wineland, Science 226, 395-400 (1984).

Heterodyne Frequency Measurements on N_2O at 5.3 and 9.0 μm, J. S. Wells, D. A. Jennings, A. Hinz, J. S. Murray and A. G. Maki, JOSAB Vol. 2, 857-861 (1985).

Spectroscopy of Stored Atomic Ions, D. J. Wineland, W. M. Itano, J. C. Bergquist, J. J. Bollinger and J. D. Prestage, in Atomic Physics 9, R. S. Van Dyck, Jr., and E. N. Fortson, Eds., (World Scientific, Singapore, 1985), p. 3-27.

Laser Cooled Atomic Frequency Standard, J. J. Bollinger, J. D. Prestage, W. M. Itano, and D. J. Wineland, Phys. Rev. Lett. 54, 1000-1003 (1985).

Limits for Spatial Anisotropy by Use of Nucelar-Spin-Polarized $^9Be^+$ Ions, J. D. Prestage, J. J. Bollinger, W. M. Itano, and D. J. Wineland, Phys. Rev. Lett. 54, 2387-2390 (1985).

New Time and Frequency Services at the National Bureau of Standards, S. R. Stein, G. Kamas, and D. W. Allan, published in the Proceedings of the Measurement Science Conference, 1985.

The Microwave and Far-Infrared Spectra of the SiH Radical, (J. M. Brown), (R. F. Curl), and K. M. Evenson, Astrophysical Journal, 292, 188-191 (1985).

Clock Characterization Tutorial, D. W. Allan, published in the Proceedings of the Measurement Science Conference, 1985.

Measurements of the g_J-Factors of the 6s $^2S_{1/2}$ and 6p $^2P_{1/2}$ States in $^{198}Hg^+$, W. M. Itano, J. C. Bergquist, and D. J. Wineland, J. Optical Soc. Am. B, 1392-1394 (1985).

PUBLICATIONS IN PROCESS

Recent Trends in NBS Time and Frequency Distribution Services, R. E. Beehler and D. W. Allan, to be published Proceedings IEEE Special Issue, Jan. 1986.

Frequency Standards Based on Optically Pumped Cesium, R. E. Drullinger, to be published in Proceedings of IEEE Special Issue, 1985.

Measurements of Frequency Stability, F. L. Walls and D. W. Allan, to be published in Proceedings of the IEEE Special Issue, Jan. 1986.

Long Term Behavior of Cavity Phase Difference in NBS-6, A. DeMarchi and R. E. Drullinger, to be published in Metrologia, 1985.

Separating Some of the Error Sources in the Global Positioning System by Variance and Linear Analysis, D. W. Allan and M. Weiss, accepted for publication in Radio Science.

Frequency Standards Based on Stored Ions, D. J. Wineland, to be published in IEEE Special Issue on Radio Measurements and Standards, 1984.

Optical Pumping of Stored Atomic Ions, D. J. Wineland, W. M. Itano, J. C. Bergquist, J. J. Bollinger, and J. D. Prestage, to be published in the Proceedings Symp. Alfred Kastler, Paris, Jan. 1985.

A New Way to Measure Frequency, G. Kamas and M. Lombardi, to be published in the Proceedings of the 1985 NCSL Workshop.

Coordinate Time in the Vicinity of the Earth, D. W. Allan and N. Ashby, to be published in the Proceedings of the IAU Symposium No. 114, Relativity in Celestial Mechanics and Astronomy, 1985.

Time Scale Stabilities Based on Time and Frequency Kalman Filters, J. A. Barnes and D. W. Allan, to be published in the Proceedings of the 39th Annual Frequency Control Symposium, 1985.

Precise Phase Noise Measurements of Oscillators and Other Devices from 1 MHz to 20 GHZ, F. L. Walls, Proc. '85 RF Technology Expo, 1985.

Frequency Standards Based on Atomic Hydrogen, F. L. Walls, Proc. of IEEE Special Issue, Jan. 1986.

Frequency and Time Standards Based on Stored Ions, J. J. Bollinger, D. J. Wineland, W. M. Itano, J. C. Bergquist and J. D. Prestage, Proc. 16th Ann. Precise Time and Time Interval (PTTI) Applications and Planning Meeting, Naval Research Laboratory, Washington, DC, Dec. 1984, to be published.

New Far Infrared Laser Lines Obtained By Optically Pumping $^{13}CD_3OD$, by K. M. Evenson and E. C. C. Vasconcellos, submitted to International Journal of Infrared and Millimeter Waves, July 1985.

Frequency Measurement of the Solitary Ethyl Alcohol Laser Line, by E. C. C. Vasconcellos and K. M. Evenson, submitted to the Journal of Infrared and Millimieter Waves.

Far Infrared Spectrooscopy of NH(D) ($a'\Delta$) and NaH($X'\Sigma^+$), K. R. Leopold, L. R. Zink, D. M. Evenson, and D. A. Jennings, to be published in the Proceedings of the 17th International Symposium on Free Radicals.

Measurement of Optical Frequencies, D. A. Jennings, K. M. Evenson, D. J. Knight, Special Issue of IEEE, 1985.

Two-Photon Optical Spectroscopy of Trapped HgII, J. C. Bergquist, D. J. Wineland, W. M. Itano, and H. Hemmati, submitted to the Proceedings of the Seventh International Conference on Laser Spectroscopy, 1985.

The Microwave and Far-Infrared Spectra of the ^{18}OH Radical, E. R. Comben, J. M. Brown, T. C. Steimle, K. R. Leopold and K. M. Evenson, submitted to Astrophysical Journal, September 1985.

Energy and Radiative Lifetime of the $5d^9\ 6s^2\ ^2D_{5/2}$ State in HgII by Doppler-Free Two-Photon Laser Spectroscopy, J. C. Bergquist, D. J. Wineland, W. M. Itano, H.-U. Daniel, and G. Leuchs, to be published in Phys. Rev. Lett.

New FIR Laser Lines and Frequency Measurements for Optically Pumped CD_3OH, R. J. Saykally, K. M. Evenson, D. A. Jennings, and F. R. Petersen, submitted to International Journal of Infrared and Millimeter Waves, 1985.

Tunable Far Infrared Spectroscopy, K. M. Evenson, D. A. Jennings, K. R. Leopold, and L. R. Zink, submitted to Proceedings of the Laser Spectroscopy Conference, 1985.

Infrared and Far-Infrared Laser Magnetic Resonance Spectroscopy of the GeH Radical: Determination of Ground State Parameters, J. M. Brown, K. M. Evenson, and T. J. Sears, submitted to the Journal of Chemical Physics, 1985.

Errors in Servo Systems Using Sinusoidal Frequency (Phase) Modulation, to be published in the Proceedings of the 39th Annual Frequency Control Symposium, 1985.

On the Fluorescent Light Shift in Optically Pumped Cesium Standards, J. H. Shirley, to be published in the Proceedings of the 39th Annual Symposium on Frequency Control, 1985.

Optically Pumped Small Cesium Beam Standards: A Status Report, A. Derbyshire, R. E. Drullinger, M. Feldman, D. J. Glaze, D. Hilliard, D. A. Howe, L. L. Lewis, J. H. Shirley, I. Pascaru and D. Stanciulescu, to be published in the Proceedings of the 39th Annual Symposium on Frequency Control, 1985.

Doppler-Free Two-Photon Laser Spectroscopy of HgII, J. C. Bergquist, D. J. Wineland, Wayne M. Itano, H. Hemmati, to be published in the Proceedings of the 39th Annual Frequency Control Symposium, 1985.

Recovering Files from a Damaged Files-11 Disk, J. Levine, submitted to RSX Multitasker, 1985.

A Beam Reversal Experiment on NBS-6 Primary Cs Standard Including Rabi Pulling Evaluation, A. DeMarchi, G. D. Rovera, R. E. Drullinger, and D. A. Howe, to be published in the 39th Annual Frequency Control Symposium, 1985.

A Recirculating Oven for Atomic Beam Frequency Standards, R. E. Drullinger, D. J. Glaze, and D. B. Sullivan, to be published in the 39th Annual Frequency Control Symposium, 1985.

Angular Momentum of Trapped Atomic Particles, D. J. Wineland, J. J. Bollinger, W. M. Itano, J. D. Prestage, to be published in J. Opt. Soc. Am. B.

SEMINARS ORGANIZED

NBS Time and Frequency Seminar, August 13-15, 1985, Boulder, Colorado.

SPECIAL REPORTS

"NAVSTAR" Global Positioning System, Air Force Space Division Final Report, 1984.

"NBS Industrial Time Service Phase II Study for Bonneville Power Administration," July 15, 1985.

TECHNICAL AND PROFESSIONAL COMMITTEE PARTICIPATION AND LEADERSHIP

D. W. Allan, Study Group VII, International Radio Consultative Committee (CCIR).

D. W. Allan, IEEE IM TC-3 Frequency and Time.

D. W. Allan, NASA Team Member for Shuttle Timing Experiment.

D. W. Allan, member and US delegate, Commission A International Radio Scientific Union.

R. E. Beehler, CCIR Study Group 7; International Chairman of Interim Working Party 7/4 on "Improved Time Coordination and Dissemination Using Satellites".

K. M. Evenson, URSI Commission D.

D. A. Jennings, Member CCDM

J. L. Jespersen, Chairman IRIG Timing Committee.

D. W. Hanson, Member Technical Advisory Committee for TDRSS, NASA Satellite Program.

G. Kamas, Measurement Assurance Subcommittee, National Conference of Standards Laboratories.

J. Levine, Chairman, Electronic Shops

J. Levine, Computing Allocation Committee, Colorado University

J. Levine, National Academy of Sciences, Committee on Geodesy

J. Levine, Board of Review of Science Institute

J. Levine, NBS Computer Users Committee

D. B. Sullivan, member, Commission A International Radio Scientific Union.

D. J. Wineland, Committee for NBS Precision Measurements Grants

D. J. Wineland, Program Committee of the Division of Electron and Atomic Physics, American Physical Society

QUANTUM PHYSICS DIVISION

SUMMARY OF ACTIVITIES

FISCAL YEAR 1985

OVERVIEW

The Joint Institute for Laboratory Astrophysics[1] (JILA) has had another exciting and productive year:

- David Norcross' energetic term as Chairman of JILA came to an end on December 31; Carl Lineberger graciously agreed to succeed him and will be serving as Chairman until 1987.

- After eight years as Chief of Quantum Physics Division, Gordon Dunn has been liberated from his bureaucratic responsibilities and allowed to return full time to more rewarding pursuits in his laboratory. He is succeeded as Division Chief by Katharine Gebbie.

- David Hummer has spent the past year at the Institute of Astronomy and Astrophysics, University of Munich, as the recipient of a Senior U.S. Scientist Award from the Alexander von Humboldt Foundation.

- Stephen Leone received the Department of Commerce Gold Medal Award for his contributions to the field of chemical dynamics.

- David Nesbitt received a Dreyfus Fellowship: This prestigious award, of which only ten are given annually, is designed to help launch the research programs of young scientists in all areas of chemistry.

- The Visiting Fellows Program continues to thrive. In 1985 JILA had 13 Visiting Fellows and 1 Research Fellow for Teachers; as part of the same program, Arthur Phelps spent six months in Gaithersburg as the JILA/NBS Exchange Fellow. In 1986 there will be 12 Visiting Fellows, 1 Research Fellow for Teachers, and 1 JILA/NBS Exchange Fellow.

- The University's plans for an addition to the JILA building are progressing famously: the current schedule calls for construction to begin late in the second quarter of 1986. This will provide an additional 15,000 square feet of desperately needed office and laboratory space.

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[1] Quantum Physics is the division through which NBS participates in the Joint Institute for Laboratory Astrophysics, a cooperative enterprise between the NBS and the University of Colorado. More background on the Institute in included as the last section in this report.

- JILA's computing capability has been substantially increased with the installation in August of a VAX/8600 with color graphics and hardwired communication to offices and laboratories. In addition, hardware will soon be installed to allow communication, both interactively and in batch mode, with the Cyber 205 in Gaithersburg.

- During the past year, Quantum Physics Division scientists:

  - Obtained high resolution infrared spectra of a weakly bound Van der Waals molecule in a planar supersonic jet.

  - Contributed to an international comparison of absolute gravity meters at the BIPM in Paris.

  - Developed a powerful technique to stabilize the laser frequency of any cw laser with transducers located external to the laser.

  - Demonstrated experimentally that extrinsic electric fields can have a profound effect in enhancing dielectronic recombination of electrons and ions.

  - Found that the expected energy density of gravitational radiation from binaries is about 10^{-3} of the energy density of light in the Universe.

  - Developed an equation of state for moderately dense plasmas that exhibits dramatically improved agreement with experiment.

  - Made the first measurements of the magnetic fields of dwarf flare stars.

  - Carried out for HCN the first reliable calculations of electron collisions with a triatomic polar molecule.

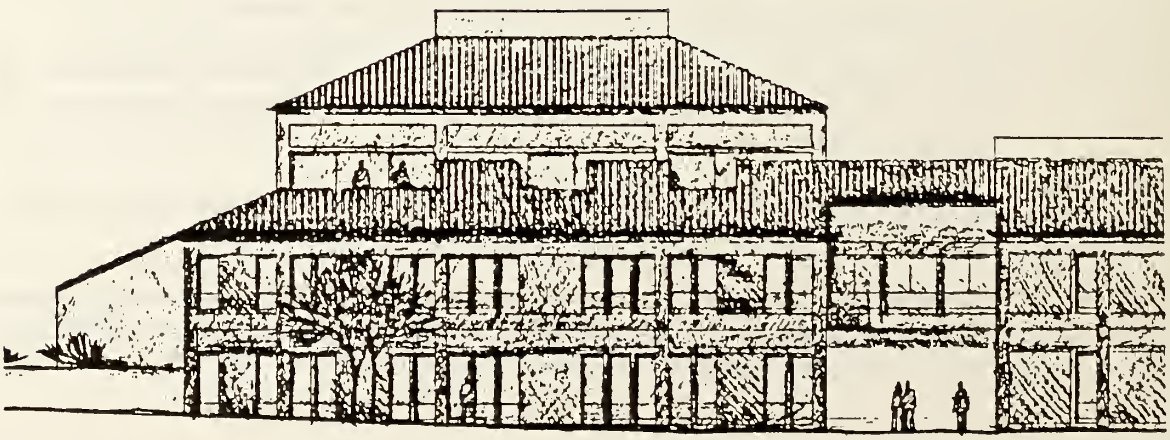
  - Demonstrated that heavy silanes and radicals produced by silane discharges (used to produce photovoltaics) are made by surface reactions.

  - Determined that the $N^+ + O_2$ ion reaction can contribute substantially to the red emission of the Aurora Borealis.

  - Provided theoretical understanding of the anomalously large measured probabilities in the multiple ionization of atoms by ultra-intense laser pulses.

- Demonstrated that in the competition between two decay channels from highly excited atomic states, the Raman process becomes competitive with direct photoionization at high laser power densities.

- Measured the very rapid collisional quenching of a rotational level of the $H_2(c^3\Pi_u)$ metastable state by thermal-energy H_2 molecules.



FUNDAMENTAL AND PRECISE MEASUREMENTS

Laser Stabilization and Stopped Atoms - J. L. Hall

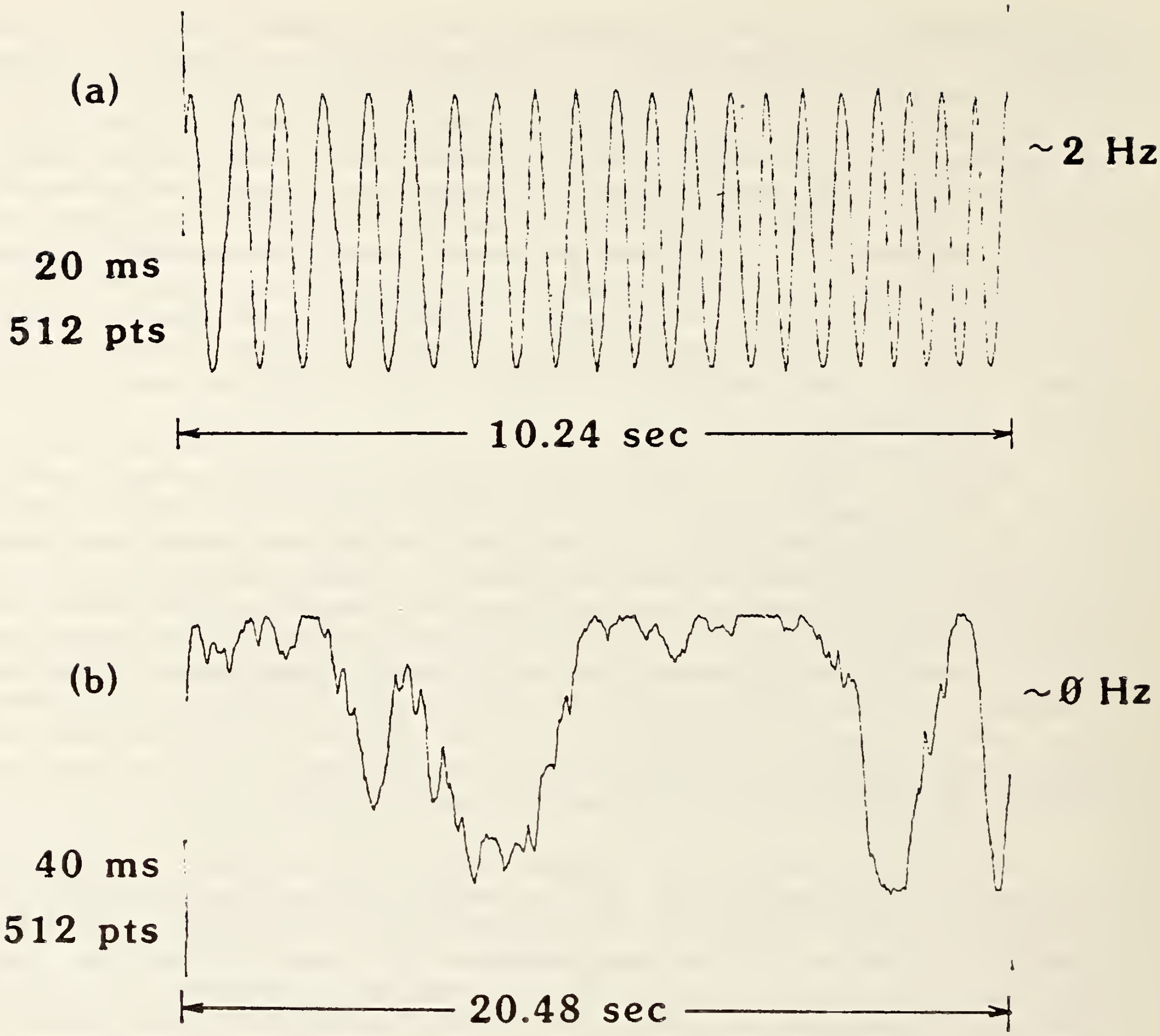
The application of stable laser techniques to fundamental spectroscopic problems requires the availability of stable -- but widely tunable -- cw dye lasers. The apriori incompatibility of high stability with wide tunability (not to mention with the rapidly-flowing intracavity free dye stream) has greatly prolonged the development of such lasers. Industry is also interested in these problems. At present there are something like 550 commercially produced, actively-stabilized, cw dye laser systems in service worldwide, all based on a fundamental stabilization technique published and developed by Hall's group. With linewidths of about 1 or 2 MHz, these commercial lasers are in part responsible for the explosion of tunable-laser spectroscopic techniques over the past five years. Dramatically higher levels of dye laser frequency stability have now been demonstrated in Hall's laboratories, variously 50 kHz, 1 kHz and 200 Hz. A high power dye laser has even been phase-locked to a stable low-power He-Ne source. Now that sufficient transducer bandwidth can be obtained to suppress intrinsic laser instability using feedback techniques, the next major challenge is to develop refined methods of tuning/guiding/offsetting the laser's frequency and of controlling it to an appropriate reference in order to enhance the mid- and long-term stability. Hall's group is now developing an interferometric scan technique for wide scans ($\Delta\nu/\nu \leq 10\%$) and moderate accuracy (< 1 MHz). The accurate tuning problem has been addressed for modest scans (± 3.5 GHz) by the development here of a broadband traveling wave electro-optic phase modulator (based on a miniature $LiTaO_3$ crystal), which produces a tunable optical sideband with the full sub-Hz accuracy of the rf source and with the full 34% efficiency available in the phase modulation process. Using this system, augmented by computer control, Hall has recently studied isotope shifts and hyperfine structure in Hg with an accuracy in the 20 kHz range, limited principally by the 24 MHz natural linewidth of the transition.

Another interesting application of the tunable sideband technique is the conversion of an atomic beam to a static gas sample at millikelvin equivalent temperature. The velocity deceleration of the atomic beam is provided by the directed momentum transfer from the laser to the counter-running atomic beam, about 30,000 absorption/random-emission events being required to suppress the initial thermal velocity and stop a beam of sodium atoms dead in their tracks. During this process, the changing velocity-induced Doppler shift sweeps through about 100 resolvable natural linewidths. The availability of the inertia-free sideband frequency sweeping capability (using a swept frequency oscillator to feed the broadband electro-optic modulator) has been fundamentally useful in this work, enormously simplifying the interpretation of these atom-cooling experiments. Hall's group has obtained a three-dimensional residual velocity distribution of 3 m/s RMS, equivalent to a kinetic temperature of about 8 mK, which is in quantitative agreement with the fundamental limit imposed by the natural linewidth. Hall is now preparing to follow this stage with a period of post-cooling, pumping a 20-fold weaker line (which happens to be in the uv for Na). This work will open qualitatively new regimes of "atomic beam" physics, including gravity-effects as a first-order consideration, atom bouncing, and atom aggregation with "atom mirrors" formed by pulsed, reversing curved wavefronts. One of the most exciting prospects for spectroscopy implicit in this work is the availability of long perturbation-free coherent interaction times, certainly 10's to 100's of milliseconds. Hall's computer simulations suggest that an average atom may spend a few 10's of seconds in this bounce trap. Thus, a high density buildup factor may be expected given the typical 2 ms "recharging" cycle repetition rate. Strong optical cooperative effects (super radiant emission and soliton modes) are expected, while high density collisional effects (such as Bose condensation) may be accessible with a suitably chosen atomic system and/or still stronger cooling. The immediate payoff of this stable-laser and cold-atom technology will be for the laser stabilization problem itself -- to provide a super-narrow (in view of the increased interaction time) transition for the laser frequency reference.

As an adjunct to this work, Hall and his group are pressing the limits of laser stabilization to a passive material optical reference cavity. Lowering the noise and drift rate of such a locked source will allow slower servo loops in guiding on to an atomic resonance. The lower bandwidth there will thus lead to lower frequency noise of the system. In addition, the cavity locking techniques are interesting in their own right because of possible application in inertial guidance (passive laser-driven ring resonator gyroscopes), local oscillator stabilization for space satellite communication, and as the optical reference source for gravity wave detectors based on interferometry. The dye laser experiments up to now have used servo bandwidths of a few (≤ 5) MHz. If the frequency servo bandwidths can be pushed into the 30-40 MHz domain, it will be possible to lock the exciting -- and now widely available -- single frequency solid state laser diode to produce kilohertz linewidths or perhaps less. Hall's preliminary experiments in this direction are very promising. On the other side, driving toward the ultimate stability/lock accuracy limit with conventional gas laser sources is also very exciting. While the increase in space and improved environmental control planned for the new JILA addition will certainly help the laser stability experiments described above, these cavity stabilization experiments will require drastic improvements in environmental stability if they are to begin to reach their full potential. In the meantime, the scientists in Hall's group are investing considerable effort and occasional cleverness in overcoming the thermal changes, acoustic noise level, floor-borne vibrational noise level, 60 Hz magnetic fields, elevator-induced changes in the Earth's magnetic field, tilting of the laboratory floor driven by wind forces on the JILA tower, etc. At present they have generated and measured beat stability of two independent lasers well below the 100 mHz level (see Figure 1), which would correspond to laser linewidths of the same value if the cavity used for the locking were equivalently stable. Unfortunately, it is easy to demonstrate by heterodyne techniques with a laser stabilized on an I_2 reference line that the previous reference cavity was profoundly influenced by temperature rates of change, barometric changes, and floor-tilt effects. A new cavity support/isolation structure should help such problems, but to work effectively in the mHz domain of interest for laser gyros, and ultimately for laser cooled ion spectroscopy, a laboratory with isolated piers reaching bedrock is essential. Modern control systems for temperature and electric service will also be required in these labs.

At various stages in these developments, techniques have been in hand to allow precision measurements of high physical interest. Representative experiments include the measurement of the relativistic Doppler shift, observation of Ramsey fringes, an improved test of the isotropy of space, measurement of Rydberg atom levels using a traveling-carriage Lambdameter, development of optical sideband techniques for high precision and ultra-sensitive spectroscopy, measurements of state-dependent hyperfine coupling in HF, observation of Rydberg energy level shifts due to thermal radiation, and the stopped atom work described above. In addition to the 100-plus publications, the program has developed four patents -- two issued and two pending.

A description of the JILA stable laser program would be seriously incomplete without mention of the collaborative experiments undertaken jointly with other labs. One collaboration with S. Chu and A. P. Mills of Bell Labs led to precise measurement of the 1S-2S transition frequency of triplet positronium. Such a precise measurement is of great interest as a definitive input to the QED testing business, since no limits are imposed by nuclear form factor corrections. On the other hand, since both leptons e^- and e^+ have the same mass, additional theoretical effort is required to obtain the equivalent Dirac energy levels without access to the central potential approximation. Further, a great deal more effort is required to calculate all the QED terms in positronium than in the hydrogen. Hall's contributions to the positronium experiment were mainly in frequency stabilization and wavelength metrology. Much the same ingredients are present in the JILA-Stanford collaboration (Professor T. W. Hänsch) on the precision measurements in hydrogen. Hydrogen transitions are to be measured at Stanford relative to reference transitions -- for example in Te_2 -- that will ultimately be measured with extreme accuracy at JILA using advanced interferometric techniques now under development. Another by-product of this cooperation with Stanford is the development of a novel and universal laser stabilization technique. The method can work with the output of any cw laser since the active transducer is located outside the laser cavity. The technique uses both an electro-optic phase modulator and an acousto-optic frequency shifter. In addition to frequency correction, the



PHASE STABILITY OF LASER BEAT

Figure 1. Two commercial HeNe lasers intended for the supermarket scanner market have been modified to have effective tuning capability. To evaluate the accuracy of the locking techniques, both lasers have been locked to a single optical reference Fabry Perot Cavity. Independence of the locks is assured by a plurality of optical isolators, acousto-optic frequency shifters etc, so that the inter-laser beat frquency will give pure information about the precision of the two locks. In the upper plot (Fig. 1a), the beat frequency of the two lasers ($\nu_{beat} = c/2L_{ref\text{-}cav} = 124$ MHz) has been further heterodyned down to 2 Hz using a stable rf frequency synthesizer. A further shift of 2 Hz (Fig. 1b) brings the beat essentially to zero. Any momentary phase jump of either source ($\nu = 473 \times 10^{12}$ Hz) would appear directly in this doubly heterodyned optical phase picture. Thus the laser phase is stable over about eight seconds, representing a drastically sub-Hz optical linewidth!

system provides optical isolation against optical feedback to the laser source and can be configured to provide effective intensity control as well. There is strong commercial interest in this device, and a patent application has been filed jointly with Stanford.

Laser Gravitational-Wave Observations in Space - P. L. Bender and J. E. Faller

Work has continued on determining the practicality of a laser experiment to detect gravitation waves in space with periods of about 0.1 seconds or longer. The basic concept for the experiment has been described in earlier annual reports: Laser heterodyne techniques are to be used to measure variations in the roughly million-kilometer separations of three masses in Earth-like orbits around the Sun.

D. Hils, Bender and R. F. Webbink (JILA Visiting Fellow) have made major progress this year in understanding the sources of the continuous gravitational radiation that can be observed in space. Mironovskii had shown in 1966 that WUMa binary stars, for which the Roche lobes of the two stars touch, would give a strong but narrow peak of gravitational waves at about 10^{-4} Hz frequency. The peak strain spectral amplitude expected is about $10^{-17}/\mathrm{Hz}^{1/2}$, made up of contributions from the roughly 10^7 to 10^8 WUMa binaries in the Galaxy. Then in 1984, Iben and Smarr estimated that there should be several hundred close white dwarf binaries giving strain amplitudes at the Earth of 10^{-21} or greater.

Hils, Bender and Webbink have investigated the expected spectrum of gravitational radiation from the close white-dwarf binaries in much more detail and also determined the probable spectrum of radiation from three other types of binaries in the Galaxy. In each case, they found that the spectrum contains contributions from so many binaries that the signals from individual binaries usually cannot be resolved, even for a year of observations. Exceptions are for very nearby binaries, particularly those at the high-frequency end of the observable spectrum. For the close white-dwarf binaries, the calculated strain spectral amplitude ranges from about $10^{-17}/\mathrm{Hz}^{1/2}$ at 10^{-4} Hz to the expected detection sensitivity limit of about $10^{-19}/\mathrm{Hz}^{1/2}$ at 10^{-2} Hz. Bender and his colleagues showed that the expected energy density in the Universe from such gravitational radiation is about 10^{-9} of the energy density necessary to close the Universe, a result that had not been realized earlier! They also calculated the spectral amplitudes for non-contact classical binaries, neutron-star binaries, and cataclysmic variable binaries. The resulting amplitudes are large enough to be observable, but the shape of the spectrum for neutron-star binaries may not be sifficiently different from that for close white-dwarf binaries to distinguish their contributions.

The gravitational radiation spectrum from binaries is of considerable interest for its own sake, but it also is of major importance in terms of the design of a laser gravitational wave antenna in space. One of the primary objectives of the antenna will be to search for pulses of gravitational radiation due to the formation or interaction of black holes with masses of a few thousand solar masses or more. The detection of such pulses seems reasonably likely if black holes in this mass range played a substantial role in the early history of the galaxies. It now appears that the sensitivity limit at frequencies of about 10^{-4} Hz will be determined more by the binary radiation confusion limit than by the interferometer sensitivity. Bender and Faller will thus consider whether an antenna arm length of about 10^5 km rather than the 10^6 km proposed earlier may be desirable in order to improve the sensitivity at frequencies of up to 1 Hz. The possibility of using higher laser power than the 1 mW assumed previously also will be investigated.

Mercury Orbiter Relativity Subsatellite - P. L. Bender

M. A. Vincent and Bender have investigated the accuracy with which the orbit of a relativity subsatellite around Mercury could be determined from a number of roughly 8-hour periods of high-accuracy tracking data from the Earth. The purpose of this work is to support earlier investigations by N. Ashby, Bender, and J. M. Wahr on how well gravitational theory could be tested in a Mercury Orbiter Mission if the center-of-mass distance between Earth and Mercury were determined within a given systematic error limit over a period of one to eight years. In order to convert the measured distance from the Earth to the subsatellite into the desired center-to-center distance, the component in the direction toward the Earth of the satellite position vector with respect to the center-of-mass of Mercury has to be determined.

The orbit calculations assumed that the relativity subsatellite would be in a high inclination orbit at roughly 2500 km altitude. Doppler tracking data plus range data were assumed to have been taken for 32 8-hour periods covering about a year. The data periods were chosen to correspond to two different orientations of the Earth-Mercury vector with respect to the plane of the satellite orbit for each of 16 different orientations of Mercury with respect to the satellite orbit plane. The gravity field coefficients for Mercury up through degree and order 6, 8, or 10 were then solved for, along with range biases and initial orbit elements for each of the 32 periods. The main errors allowed for were radial and off-axis biases in the calculated solar radiation pressure on the satellite plus uncertainties in the higher degree gravitational field terms that were not solved for. For a Doppler tracking precision of 5×10^{-15} and a ranging accuracy of 3 cm, the apparent uncertainty in the center-to-center distance is about 15 cm.

During the next year, Vincent and Bender plan to improve the modeling of the solar radiation pressure effects. This is expected to improve the accuracy for determining the center-to-center distance. However, even the present 15 cm uncertainty would permit excellent checks on gravitational theory. The possibility of a Mercury Orbiter Mission with a relativity subsatellite now seems considerably higher than during the last five years, since Chen-wan L. Yen at the Jet Propulsion Laboratory has found new trajectories that would permit larger payloads to be put in orbit around Mercury than for previously considered trajectories.

<u>Eötvös Experiment</u> - J. E. Faller

The weak equivalence principle tested by the Eötvös experiment is the hypothesis that all test bodies fall with the same acceleration in the same gravitational field. This principle provides the experimental foundation on which the geometrization of space-time in Einstein's General Theory of Relativity is based. The central position of the principle in Einstein's and other metric theories of gravity emphasizes the importance of testing it to the best possible accuracy. Any failure of the universality of free fall would necessitate a theoretical revolution.

Though in concept this principle is testable by dropping different masses and observing whether or not they fall at the same rate, torsion balances have been used since the experiments of Baron R. von Eötvös and his colleagues in the late 19th and early 20th centuries. Accordingly, since that time, experiments designed to test this equivalence of gravitational and inertial mass have been referred to as Eötvös experiments.

The approach to the experiment that Faller has adopted arises from the observation that in the traditional torsion pendulum, the fiber serves both to support the masses and to determine the torsion coefficient. In Faller's approach, the suspension is provided entirely by a liquid, and the restoring and centering functions of the fiber are achieved by an appropriate electrode array subject to adjustable voltages.

P. Keyser and Faller have moved their new large Eötvös float to the center of the spectroscopy laboratory in order to avoid the dyne-sized gravity gradient forces present in the corner of the laboratory, which were causing millimeter-sized offsets in the centering. They then proceeded to install active temperature control. This proved to be no easy task (given the room's oftentimes ±1 °C per few hours excursions). In order to increase the rate of progress (understanding of these systems) during the latter part of this year, work on the large float (with its several week's response time to any changes made for test purposes) was temporarily halted so that the available manpower energies could be focused on the functionally identical (but easier to make) changes on small gradiometer based floats. In part this was dictated by the need for the graduate student (Keyser) to complete his Ph.D. thesis this year or else be subject to the University statute of limitations requiring that he retake (and pass) the comprehensive examinations again. Therefore Faller and Keyser have temporarily refocused their efforts on this useful, but not necessarily as fundamental, application of fluid-fiber torsion pendulums.

GEOPHYSICAL MEASUREMENT METHODS

Gravity Gradiometer - J. E. Faller

Faller and Keyser are proceeding with the testing of two 0.25-m diameter fluid-supported pendulum apparatus as gradiometers. This development -- in addition to its importance for the Eötvös work -- has application to tunnel and intrusion detection as well as security for nuclear stockpiles. Commercial applications of these devices for sink holes etc. are being explored. During the past year, Faller and Keyser have been testing these two floats under differing temperature control conditions, both near room temperature and at 4 °C. They have also run one of these floats as a "non-gradiometer" (using a cylindrically symmetric mass distribution) in an attempt to separate out gravitational (gradient) noise from instrumental noise. One curious and perplexing thing did occur on *one* occasion. One of the floats "locked" up, and as far as they can tell this lock-up was not related to any surface contaminants, nor was it apparently related to any bulk contaminant. An ordered structuring of the (pure) water has been occasionally suggested in the literature, but to see such a thing (if indeed that is what they saw) on such a macroscopic system, is both suspect and mind boggling. Faller and Keyser are continuing to explore this aspect in an attempt to pin it down, if at all possible.

Absolute Gravimeter (g) - J. E. Faller

Over the past year Faller and T. Niebauer, with assistance from J. Gschwind and A. Joll of the Defense Mapping Agency (both assigned to work in JILA), are completing development of a new absolute gravimeter. The value of g continues to play a significant role in the determination of certain physical constants and standards. With the accuracies obtainable today, its measurement also has broad application to geophysics and geodesy.

The JILA absolute gravimeter is based on the free-fall interferometric method: a freely falling mass that contains a corner cube serves as a mirror in one arm of a Michelson interferometer. The times at which selected interferometric fringes occur are used to calculate the acceleration of the mass by the Earth's gravity. A stabilized laser, used as a light source in the interferometer, provides the standard of length, while an atomic frequency standard provides the standard of time. A new dropping mechanism eliminates several sources of systematic errors, and a long period isolation device greatly decreases the instrument's sensitivity to ground vibrations.

The construction of six such instruments is now almost complete. The which-laser issue has been resolved by going to a commercially available intensity-stabilized laser. Nevertheless, Faller and his colleagues have spent the order of one-half a man-year studying the various error sources inherent in these lasers, some of which were not known to the manufacturer. The particular question of interest is how various error sources affect the accuracy of the lasers and what can be done to minimize and/or eliminate them. The discriminator development during the past year appears to have been successful in meeting the critical experimental requirements. Further, Faller and his colleagues have found a way to perform a self-calibration on their timing electronics. Functionally the overall design that has evolved appears to be an excellent one -- both in terms of convenience and field usability.

A major focus during the past year involved finishing the first of these units so that it could be taken to Paris last June and July to contribute to the Absolute Gravity Meter Campaign held at the International Bureau of Pounds and Measurements (BIPM) June 24 through July 5. Also participating in this intercomparison was a Chinese (Beijing) instrument, an Italian (Torino) instrument, and a Russian (Novosibirsk) instrument. Although Sakuma's new BIPM instrument was not working at that time, it was expected that it would be again shortly. The first of the new JILA instruments was demonstrated to work and to work very well. The only problem of any substance was the spongy (mattresslike) floor at the place the BIPM had designated Gravity Point A_5, where the measurements were made.

Over the next months Faller and his colleagues expect to finish their "production" of absolute gravity instruments. Over the next several years their intention is to see absolute gravity measurements become both usable and used in the field. With the new instruments, they expect to improve on the 6-10 gal (2 cm height sensitivity) accuracy of their earlier prototype instruments. If these instruments are reasonably successful in the field, the last years of this century should see absolute gravity measurement mature both as a new geodetic data type and as a useful geophysical tool.

<u>Water Vapor Calibrator Development</u> - P. L. Bender

The accuracy of a number of geophysical and astronomical studies based on microwave distance measurements is limited mainly by uncertainty in the propagation correction due to water vapor in the atmosphere. Measurements of tectonic plate motions by Very Long Baseline Interferometry are among those affected, as will be the tectonic studies soon to be made with dual-frequency Global Positioning System receivers. Water vapor radiometers that measure radiated power in the

22 GHz water vapor emission line are likely to be used with increasing frequency to measure the integrated water vapor content along the line of sight to the sources of the microwave signals. However the accuracy of these results is currently checked only against radiosonde data.

S. J. Walter and Bender have obtained funds from the Jet Propulsion Laboratory to develop a microwave-optical system to improve the accuracy in the correction to the microwave distance measurements due to the atmospheric water vapor. Since optical distance measurements are affected much less by water vapor, the difference between microwave and optical measurements to an aircraft at about 6,000 meters would serve to determine the microwave distance correction. Such an aircraft would be above about 95% of the atmospheric water vapor, and meteorological measurements at the aircraft would permit correction for the remaining water vapor. The resulting measurements of the total amount of water vapor integrated through the atmosphere would be compared with estimates from a dual frequency water vapor radiometer looking along the same line of sight. Such comparisons are expected to give a valuable calibration of the water vapor radiometers used in geophysical and astronomical applications. The comparisons of results also may aid in improving the algorithms used in analyzing the water vapor radiometer results.

During the past year, Walter and Bender have completed a thorough design review for the transmitter and receiver of the water vapor calibrator and have purchased most of the parts for a ground-to-ground test of the instrument. The various components have been mounted on base plates and are now being prepared for initial laboratory tests. Subsystems that still need to be designed and constructed or purchased include a relative phase measurement system for the two output 15 kHz signals from the microwave and optical channels plus a data recording system. The instrumental sensitivity is 18° in relative phase for each 1 cm of microwave path delay due to the atmospheric water vapor. The required overall measurement accuracy is 0.5 cm or better.

Walter and Bender expect to complete the basic instrument and ground testing during the next year and also to carry out some airborne tests. Comparisons against other sources of information on the atmospheric water vapor content along the ground test path cannot be made because of the difficulty of obtaining the other information with sufficient accuracy. Thus the ground-to-ground tests will be limited to determining the instrument stability over short paths and to checking the reasonableness of the observed variations over longer paths. The same is true for the initial airborne tests, which will be made in the Boulder area.

Sobolev Method with Continuous Absorption - D. G. Hummer

G. B. Rybicki (Center for Astrophysics) and Hummer have generalized the Sobolev method for radiative transfer in spectral lines in flowing gases to include the effects of continuous opacity. They have given the generalization in detail for plane parallel geometry and in outline for general geometry. With a student in Munich, Hummer has also worked out the spherical case in detail. Although this work involves an extremely difficult mathematical analysis, the results are simple and give excellent agreement with accurate numerical calculations requiring powerful computers. These results are required for work on the winds of Wolf-Rayet stars and for modeling absorption lines in quasars.

Winds of Wolf-Rayet Stars - D. G. Hummer

With collaborators J. Puls, A. Pauldrach and R. P. Kudritzki in Munich, Hummer has carried out calculations of radiation-driven stellar winds of Wolf-Rayet stars in which the generalization of the Sobolev method mentioned above plays an important role. They have produced detailed structural models of the atmosphere and wind of the eclipsing Wolf-Rayet binary system V444 Cygni, which reproduce well the empirical model for this object obtained by Cherepashchuk *et al.* from the inversion of light curves covering UV, visual and IR wavelengths. The agreement of their theoretical results with the empirical model provides strong evidence that: 1) The effective temperatures of Wolf-Rayet stars are two to three times larger than currently believed; and 2) The winds are driven by the force of radiation from the underlying star. Hummer has realized for at least five years that the accepted effective temperatures of Wolf-Rayet stars were much too low because they were being inferred by comparing observed spectra with inappropriate models. He has also long suspected that when the correct temperatures were used, the radiation field would be found to carry enough momentum to drive the wind -- contrary to popular opinion.

Determination of Atmospheric Parameters of Hot Stars - D. G. Hummer

The existing methods of determining the effective temperature, surface gravity and helium to hydrogen abundance ratio of hot stars have been analyzed by D. Abbott and Hummer, who find that *all* methods of determining temperature from continuum measures are *in principle* grossly unreliable. In collaboration with B. Bohannan, they have undertaken a program to redetermine stellar parameters for hot stars from observations of line profiles observed with CCD detectors at signal-to-noise ratios of several hundred. By fitting a large number of different line profiles to state-of-the-art stellar models that include the effects of blanketing by stellar winds, they can determine accurate values of the basic parameters. The fact that a large number of lines are fit in detail demonstrates the internal consistency of their models. A systematic redetermination of the stellar parameters for hot stars in the Northern Hemisphere is underway as the thesis project of graduate student S. Voels. Hummer and Kudritzki are working on a similar analysis of stars in the Magellanic Clouds, using observational material obtained in December 1984 at the ESO Observatory by a member of the Munich group. Results for six stars have been presented at IAU Symposium 116 on "Stars and Associations in Galaxies" held in Porto Helu, Greece May 26-31, 1985. Further observations are scheduled for this winter.

In their recent review of Intrinsic Parameters of Hot Blue Stars, Kudritzki and Hummer have shown that their determination of stellar parameters is sufficiently accurate to provide, for the first time, observational tests of stellar evolution theory that can discriminate between various alternative treatments of mass loss and convective overshooting as well as check on other approximations. They have planned a joint Munich-Boulder project to obtain high precision spectra of about twenty O-stars in our Galaxy and in each of the Magellanic Clouds to be analyzed as described above.

Hummer has also proposed a program based on the refined theory of stellar winds of O-stars that he developed in Munich in collaboration with Kudritzki and Puls, using his recent generalization of the Sobolev method. They plan to use the maximum wind velocity as determined from UV line profiles, together with the effective temperature and surface gravity as found from their method of analyzing line profiles, to determine the mass, radius, and luminosity of individual hot stars. This provides in principle a purely spectroscopic method, *without* calibrations, of determining the distances of hot stars. For four stars for which data are available, their distance determinations agree well with those obtained by membership in associations.

<u>Rotational Non-LTE in the Atmospheres of Mars and Venus</u> D. G. Hummer

Three years ago A. Kutepov (University of Leningrad), who spent nine months at JILA, and B. Moore (JILA Visiting Fellow) joined Hummer in carrying out the first calculation of rotational band radiative transfer in which rotational LTE was *not* assumed. They found significant deviations from rotational LTE in the atmospheres of Mars and Venus which, if ignored in the interpretations of the observed CO_2 bands, would lead to major errors in the determination of the temperature structure of the atmospheres of these planets. The near-impossibility of sending manuscripts out of the USSR caused a long delay in completing this paper, which has now been published.

Collisional-Radiative Recombination - D. G. Hummer

For the past several years, P. J. Storey (University College London) and Hummer have been working on improved and extended calculations of radiative recombination line intensities and total recombination rates, taking into account the effects of electron collisions, which become crucial at high densities. They have also extended the theory to two- and three-electron systems and have obtained preliminary results. Hummer has recently shown that the effect of collisional transitions from the ground and first excited states, which are ignored in the classical "Case B" theory, become important for hydrogen at densities of 10^6 cm^{-3} and for He^+ at 10^9 cm^{-3}, thus invalidating the theory for these cases. He and Storey have developed an "Extended Case B" that accounts for these collisions, and they are calculating the appropriate recombination data in this approximation. One important conclusion already apparent is that collisions from the n=2 levels at higher densities quickly force the upper levels into LTE, which will probably explain the puzzling results obtained recently by M. J. Barlow (University College London) and Hummer in their analysis of the infrared spectra of Wolf-Rayet stars. The calculations of recombination line intensities for H and He^+ in Case B are now complete. The bulk of the calculations for the Extended Case B covering a higher density range are in hand, and much of the material on the hydrogenic ions of C, N, and O has also been computed. Much work remains to be done on the two- and three-electron systems, which are important for the interpretation of IR lines in a variety of stellar winds.

Hydrogen Line Spectrum of Accretion Disks - D. G. Hummer

D. Carroll, a graduate student, has been constructing models of the accretion disks of dwarf novae in order to compute the profiles of hydrogen lines formed in disks, using the generalization of escape probability theory to axisymmetric flows developed by Rybicki and Hummer a few years ago. The goal of this work is to determine the energy input in the disk from the dissipation of the circular motion, which causes the material to fall inward towards the white dwarf. They hope to obtain observational constraints on the dissipative mechanism, the nature of which is still not understood and remains a major puzzle. Carroll's Ph.D thesis on this work will be submitted in November 1985.

The Opacity Project - D. G. Hummer

In recent years evidence has accumulated that predictions of the theory of pulsating stars are not in accord either with observation or with the theory of stellar evolution for stars with significant amounts of elements heavier than hydrogen and helium. However for stars with very small abundances of the heavier elements, both theories are in accord with observation, and the theory for stellar evolution itself has generally been in agreement with observation. Evolutionary calculations depend primarily on the opacity of material at very high temperatures and densities, characteristic of the centers of stars, while pulsation calculations involve much lower temperatures and densities because the pulsationally unstable regions of stars are much closer to the visible atmospheres. These circumstances have led Hummer and his colleagues to question the accuracy of the opacities of elements heavier than helium and hydrogen, at moderate temperatures and densities, $3.5 \leq \log T \leq 7.0$ and $-12 \leq \log \rho \leq -2$. An examination of the methods used to calculate opacities in this region discloses that the approximations now in use are quite crude and far inferior in accuracy to what is now possible with the computational techniques of present-day atomic theory. For this reason, D. Mihalas (NCAR), M. J. Seaton (London) and Hummer decided to undertake an entirely new and independent calculation of the stellar opacities for the relevant temperatures and densities (so-called "envelope conditions"). This work is now well underway, with Seaton and P. G. Burke (Belfast) leading the calculation of the atomic cross sections, radiative transition probabilities and line-broadening parameters, and Mihalas and Hummer taking responsibility for the equation of state (i.e. specifying the level populations for each species of atom and ion as a function of temperature and density) and the ultimate processing of the individual atomic cross sections etc. into the total opacity.

The benefits to be expected from this work are considerable. (1) The resulting opacity tables (or rather computer fits to bi-cubic splines) will be of known accuracy. (2) In addition to the standard mean opacities (Rosseland, Planck), a variety of group means, opacity distribution functions, and other representations more fine-grained than the gross mean opacities will be computed, as well as various thermodynamic functions for the gas. All of this material is necessary for the solution of radiative-gas dynamical calculations in a variety of astrophysical and terrestrial applications. (3) A vastly improved and much more detailed theory of stellar pulsation will be possible, including the calculation of spectral line profiles as a function of phase. This should yield a much more accurate relation between stellar luminosity and other observable properties such as period, abundance, line profiles, etc. If this turns out as expected, the old period-luminosity relation, which is only highly approximate, could be replaced by a much more reliable method of determining the cosmic distance scale. (4) As a by-product, this project will yield radiative data accurate to about 10%, and electron excitation cross sections of slightly lower accuracy, for all transitions of interest in all atoms and ions up to and ultimately including iron. (5) The equation of state and resulting thermodynamic functions will be the most accurate yet derived for a range of temperatures and conditions that include those of almost all terrestrial laboratory, fusion and industrial plasmas and electrical discharges.

Equation of State D. G. Hummer

In connection with the opacity project, Hummer has devoted a considerable amount of attention in the past year to the question of an improved equation of state for non-ideal plasmas with densities up to 10^{-2} gm cm^{-3}. The general approach is to derive an expression for the Helmholtz free energy as a function of all atomic populations and then to minimize with respect to these populations. This work is being done in collaboration with Mihalas.

Hummer's particular responsibility is the evaluation of finite atomic partition functions. As has been known for many years, the partition function for an isolated atom diverges, and convergence is obtained by accounting for the perturbations of the atom or ion by the surrounding plasma. In view of the difficulty of this problem and the diversity and lack of agreement of existing theories, Hummer decided to take a simple physical approach aiming for a correct physical picture and accepting that quantitative accuracy was probably not possible at present. In the course of this work, he discovered that a number of accepted models were either partially or completely wrong. For example, much work has been done in which the effect of the plasma on the atom is represented by a screened coulomb potential (SCP). Solutions of Schrödinger's equation with the SCP give only a finite number of bound states, which removes the divergence problem in the partition function. However, Hummer has shown that the SCP is completely inappropriate as an atomic potential and that results obtained in this way are *utterly wrong.* Quite a large number of papers based on this model are now worthless. Similarly, a well-known model developed by Unsöld is also wrong.

Hummer has derived results based on the quantum theory of Stark ionization and detailed plasma microfield distributions, which appear to explain in detail accurate laboratory spectra of hydrogen arcs. He and Mihalas have recently completed the first paper of a series on the improved equation of state. Results for two additional papers (one on numerical results for the equation of state and the other on thermodynamic functions in plasmas) are in hand. Hummer has also completed a paper giving rational approximations permitting the rapid computer evaluation of the Holtzmark distribution, its integral and derivative, which enter the evaluation of the truncated partition function.

Measurements of Magnetic Fields in Cool Dwarf Stars - J. L. Linsky

Linsky and his Ph.D. thesis student, S. Saar, are pursuing a major program to measure surface magnetic fields on stars cooler than the Sun. They have already succeeded in making magnetic field measurements on stars much cooler than was heretofore possible; they have also developed an analysis technique to take into account for the first time the saturation of optically thick absorption lines.

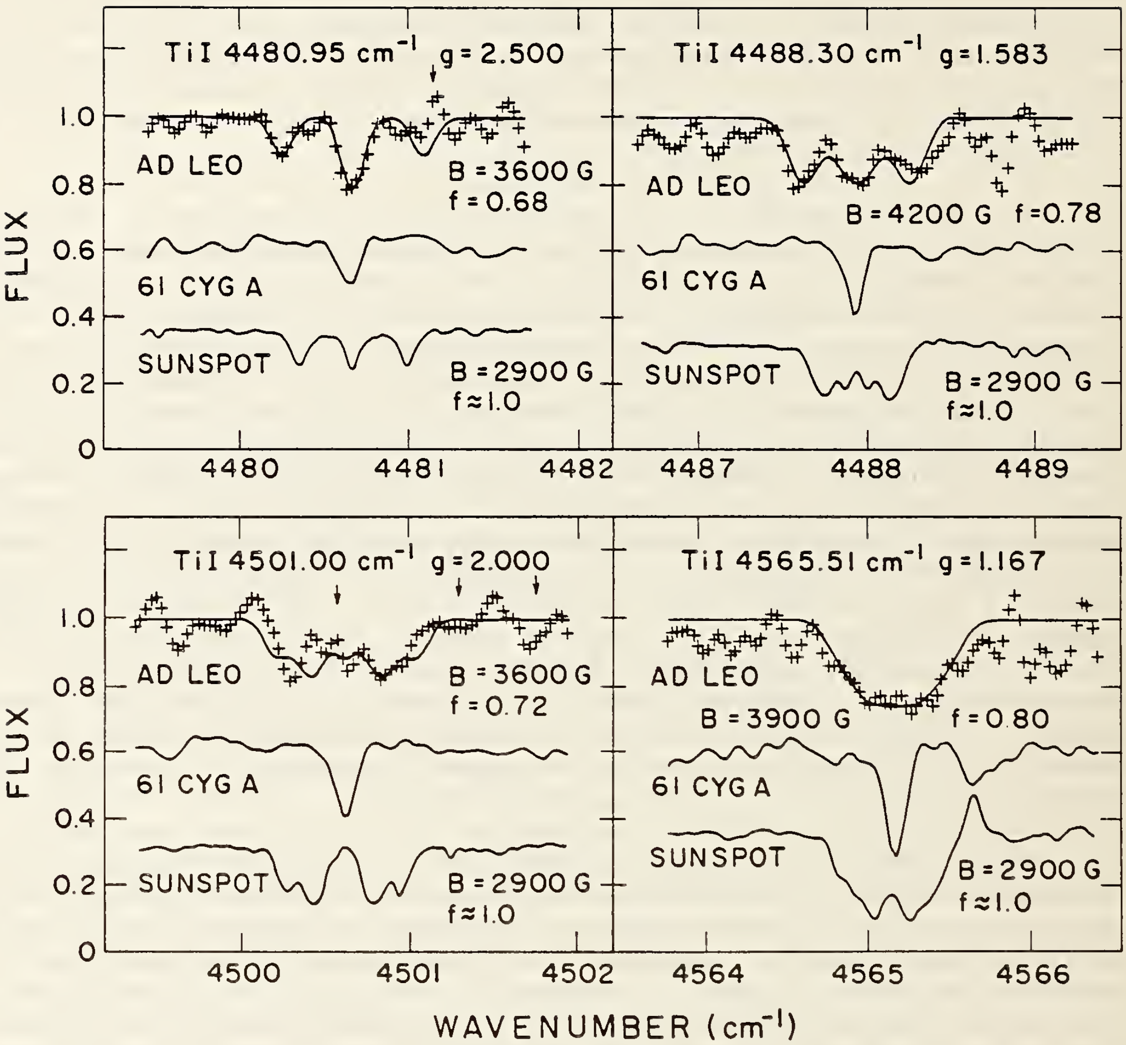


Figure 2. Comparison of apodized 4m FTS spectra of AD Leo (crosses), similar spectra of the dK5 magnetically inactive star 61 Cyg A, and a sunspot umbra/photosphere ratio spectrum from Hall's atlas. (The ratio spectrum removes telluric Lines without affecting Ti I, which is absent at solar photospheric temperatures.) The solid line model fit to the AD Leo data is for the magnetic parameters indicated. All data are on the wavenumber scale of AD Leo. The spectra have been displaced vertically for clarity, and positions where the noise is enhanced because of the approximate removal of strong telluric lines from the AD Leo spectrum are marked with arrows.

Magnetic fields broaden spectral lines by the Zeeman effect. Attempts to measure such fields in cool stars using standard Zeeman analysis techniques with circular polarization optics have been unsuccessful, presumably because highly turbulent and oppositely directed fields cancel the circular polarization signal. To get around this problem, astronomers in the last few years have followed a different approach in which they measure the magnetic field by the increased broadening of unpolarized profiles of absorption lines with large Landé g factors (large Zeeman splitting) compared to lines with small Landé g factors.

Linsky and Saar have extended this work in two important ways. First, they have developed a radiative transfer computer code that simulates the formation of spectral lines in a stellar atmosphere, including Zeeman broadening and saturation due to large opacity at line center. They have then used this code to derive stellar magnetic fields and surface coverage factors by comparing high quality observed line profiles with their computed profiles. Second, they have acquired a large number of high spectral resolution and high signal-to-noise profiles from different observatories. For example, they obtained spectra of the cool flare star EQ Virginis using the Multimirror Telescope and of AD Leo using the Fourier Transfer Spectrometer (FTS) on the Kitt Peak 4 m telescope. They measured fields of 2500 ±300 Gauss covering 80 ±15% of the surface of EQ Virginis and 3800 ±260 Gauss covering 73 ±6% of the surface of AD Leo. These are the first field measurements for any dwarf flare stars. Figure 2 shows the data (pluses) and theoretical fit (solid line) for line profiles of AD Leo and, for comparison, the spectra of a sunspot (2900 Gauss) and the star 61 Cygni A, which is likely to have only a weak field. Linsky and Saar are presently analyzing additional observations from Kitt Peak and the Multimirror Telescope, which indicate fields on about a dozen additional stars.

<u>Planning for Future Space Observatories to Obtain Ultraviolet and X-Ray Astrophysical Data</u> - J. L. Linsky

Linsky is participating in the detailed planning of a number of astronomical missions. The most immediate mission is the Hubble Space Telescope to be launched in 1986/87. Linsky has been a Co-Investigator on the High Resolution Spectrograph (HRS) since 1978 and has participated in the major decisions that have led to the design and construction of this instrument. As a part of the commissioning and calibration of the instrument after launch, the Co-Investigators will be making the first observations of stars with this instrument. The HRS will obtain spectra with resolution up to 10^5 covering the spectral region 110-320 nm. Linsky is also a Co-Investigator on a proposed imaging spectrograph that will hopefully replace the HRS five years after launch. During the last year, Linsky was appointed an Interdisciplinary Scientist and member of the Science Working Group for the proposed Advanced X-Ray Astrophysical Facility (AXAF). This is a proposed

1.2-m grazing incidence telescope that will obtain high resolution X-ray spectra in the mid-1990's. During the next ten years or so, he will advise the AXAF project. His specific interests are high-throughput spectroscopic observations of stars to measure stellar coronal temperatures, densities, and flow velocities.

Linsky is also a member of the Science Working Group that is studying various possible designs for a Far Ultraviolet Spectroscopic Explorer (FUSE) satellite. This will likely be a grazing incidence telescope and spectrograph to cover the 10 - 200 nm spectral range at both low and high spectral resolution. This is a particular change both instrumentally and scientifically because the 10 - 120 nm spectral region is unexplored except for the Sun.

Microwave Measurements of Stellar Mass Loss Rates - **J. L. Linsky**

Linsky and his postdoctoral research associate, S. Drake, have completed a survey of microwave emission from 39 of the closest stars that are more luminous and cooler than the Sun. This survey at 5 and 15 GHz was made using the National Radio Astronomy Observatory Very Large Array (VLA). The purpose of the survey was to measure mass loss rates for a class of stars (giants and supergiants of spectral types G, K, and early M) for which there was very little data heretofore. Microwave emission from these stars is thermal bremsstrahlung from the ionized component of the circumstellar gas that is leaving the star, a phenomena called "mass loss", which is of great interest in astrophysics. In their survey they detected six stars, five of which are wind sources, and one is a hot coronal source (Capella). For these five sources, the microwave spectral indices are consistent with optically thick emission from a stellar wind. The inferred mass loss rates for the ionized components of these winds indicate that the gas is partially ionized (one to five percent) and that the mass loss rates can be used to constrain different theories proposed to explain the acceleration of stellar winds. Drake and Linsky are now writing up their survey of microwave emission from close binary stars. These are all synchrotron sources and show an interesting dependence of microwave luminosity on period and thus on proximity and rotational velocity.

Modeling of Extended, Expanding Stellar Chromospheres - J. L. Linsky

Linsky and Drake, are computing models for the extended outer atmosphere of the prototype cool giant star, Arcturus. To accomplish this, they have written a computer code that solves the radiative transfer equation in spherical geometry including the effects of partial redistribution (PRD) and mass flux conservative outflow. The equations are solved in the co-moving frame of the fluid. PRD means that photons are scattered noncoherently in the line core and nearly coherently in the wings, where the only important noncoherent term is radiation damping.

Using this code, Linsky and Drake have determined a model for Arcturus that predicts an accurate profile of the Mg^+ resonance line and is consistent with the observed microwave flux. This model specifies the mass loss rate and radial dependence of the electron density, total density, expansion velocity, and turbulent velocity.

Linsky and Drake intend to check the validity of the model by using it to predict other line profiles observed in Arcturus and other stars. Linsky has published a detailed review of PRD radiative transfer and its use in computing stellar line profiles.

<u>X-Ray Bright Points on the Quiet Sun</u> - K. B. Gebbie

J. Toomre and Gebbie are conducting two major observational studies as Guest Investigator Programs on the repaired Solar Maximum Mission (SMM) satellite. The first is a program of coordinated observations of X-ray bright points using the Ultraviolet Spectrometer and Polarimeter (UVSP) Instrument and the Soft X-ray Polychrometer (XRP). This work is carried out in collaboration with A. Gabriel of Rutherford Laboratory, J. Gurman of the UVSP team, and L. November and F. Hill of the National Solar Observatory. X-ray bright points, which have so far been seen only in broad-band X-ray images, were one of the significant findings of Skylab. They appear to be formed where small concentrations of magnetic flux emerge through the photosphere. Their discovery has made it possible to follow the emergence of flux on scales much smaller than those of active regions and to identify patterns of behavior quite different from those associated with the normal solar cycle. But apart from Skylab, these results have been derived from a total of only six rocket flights. SMM has not been able to observe X-ray bright points, largely because the X-ray Polychrometer instrument is not sensitive enough to identify them in the usual raster mode.

Fortunately, Toomre's and Gebbie's earlier study of persistent flows in the lower transition region suggests that C IV Doppler observations can be used to provide coordinates for likely sites of X-ray bright points. Near-real-time UVSP data are analyzed to predict coordinates at which to obtain soft X-ray spectral line profiles with XRP during subsequent orbits. Such closely coupled observations with UVSP and XRP may yield the first spectra of X-ray bright points and thus the first quantitative measurements of the plasma producing these soft X-rays.

<u>Rapid UV Brightenings in Active Regions</u> - K. B. Gebbie

As a second Guest Investigator Program on the SMM satellite, Toomre and Gebbie, in collaboration with J. Porter of Marshall Space Flight Center, are pursuing their discovery of rapid changes in the ultraviolet emission from bright sites in active regions. Their recent analysis of

C IV and Si IV line emission observed with high spatial and temporal resolution suggests that heating events of modest amplitude occur almost continually at many sites in active regions. Such heating events suggest that magnetic field reconnection in an active region is proceeding almost stochastically, with modest events occurring far more frequently than those with large amplitudes. This may be evidence in the transition region for the "magnetic burning" or "topological dissipation" advocated by Parker as a means of heating the corona.

Toomre and Gebbie are using the UVSP instrument on SMM to conduct a survey of these brightenings in order to obtain better statistics on their spatial distribution and frequency. This should yield estimates of their contribution to the total energy balance of the transition region and their relation to flare activity

ATOMIC AND MOLECULAR PHYSICS

Electron Collisions with Polar Molecules - D. W. Norcross

A. Jain and Norcross have been carrying out large scale computational studies of rotationally and vibrationally elastic and inelastic scattering of electrons and positrons by a variety of molecules, and developing and extending numerical techniques to treat more complicated molecules and processes. Results will find application in studies of many practical and fundamental processes (e.g. laser modeling, physics of the interstellar medium) and in studies of chemical reaction dynamics (e.g. flow of energy from electron kinetic energy to molecular dissociation via excitation of molecular nuclear motion).

Recent progress includes detailed calculations of cross sections for vibrationally elastic scattering by (linear) HCN, HF, and CO, and for vibrational excitation of HF, and a study of resonance (autoionizing) states of HCN^- as a function of internuclear distance. HCN is of particular interest for several reasons: It is a prototypical triatomic polar molecule with the simplicity of linearity in the ground electronic state; it shares characteristics in electron scattering with nonpolar N_2 (a prominent Pi resonance) and polar HCl (a diffuse Sigma resonance); it exists in diffuse interstellar clouds and in CN laser systems; and it has been considered a candidate for a gaseous high-power switch. Code development leading to a capability for full vibrational close-coupling calculations with an exact treatment of the electron-electron exchange interaction has been outlined and initiated (work to date uses an approximate treatment of nuclear dynamics that necessarily fails near vibrational excitation thresholds). Work is also underway to extend the code to calculate negative ion states of molecules, a novel application of scattering theory.

Future work will include application of the vibrational close-coupling code to previously studied molecules (HF and HCl) in order to provide the first, definitive, near-threshold results; extension of the work to vibrational excitation of CO; and production of accurate results for the lowest bound states of HCl^-, HF^-, and HCN^-. This latter work will be the first to provide a systematic connection between negative ion resonances and true bound states in these molecules as a function of nuclear geometry. S. V. ONeil, P. Rosmus (JILA ex-Visiting Fellow), and Norcross plan to complete an elaborate calculation of the lowest bound states of HCl^- using Rosmus' molecular structure code for comparison with results to be obtained from the scattering code -- there are very large and unexplained differences between previous molecular structure results, none of which seems to be consistent with the resonance results.

Electron Impact Excitation of Atoms and Atomic Ions - D. W. Norcross

Norcross' group is pursuing several fundamental and applied problems in the theory and computational physics of this process. F. Parpia has nearly completed a new attack on one of the most perplexing discrepancies in electron-ion collisions work -- the difference between measurements (by Dunn and coworkers) and calculations (by Norcross, coworkers, and others) for excitation of the resonance line in the simple "one-electron" ion Be^+. A. K. Pradhan is making systematic progress towards completing the work on excitation of Mg-like ions, for application to fusion diagnostics and plasma modeling, and in application of the theory of dielectronic recombination (DR) in practical calculations incorporating field effects. D. A. Harmin is developing an extension of the quantum-defect theory of DR to include the influence of arbitrary electric fields. F. de Paixão is working on an elaborate seven-state close-coupling calculation of electron scattering by the ground and excited states of sodium, looking towards analysis of a variety of experiments using mixtures of laser oriented atoms in excited states and spin polarized electron projectiles.

Results for the excitation cross section of Be^+ differ surprisingly little from those of the earlier calculations, even though much more attention was paid to effects arising from virtual excitation of the core of the ion. Calculations of the polarization of the resonance line radiation excited by electron impact are in progress; this is a much easier quantity to measure, and a serious discrepancy with theory was also observed. The calculations for Fe XV were the first for excitation of the Mg-like ions.to be completed; the important $3s^2$-$3s3p\ ^3P_1$ transition was found to be subject to large resonance enhancement. Progress has been made in the development of a general program for calculating DR cross sections for any ion, in intermediate coupling, and including external field effects in the Stark broadening formulation developed by Harmin. Preliminary results for 3s - 3d and 3p - 3d excitation in Na are in excellent agreement with the measurements of Stumpf and Gallagher; they identify the resonances responsible for the puzzling sharp threshold onset of these cross sections.

The detailed studies of electron impact excitation of singly charged ions will be extended to the first ions of the Na, K, and Mg isoelectronic sequences. The production-mode calculations of the Mg-like ions will continue with work on S V, Ar VII, Ca IX, Cr XIII, and Ni XVII. A new program of calculations on little understood metastable states of atomic negative ions will begin with an attempt to identify an observed long-lived state of Ca^-. The Na calculations will be extended to produce results with higher resolution (e.g. angular distributions) and for more transitions (3s - 4s, 3s - 4p, and 3p - 4s). The first application of the new formalism and program for field effects in DR will be to the case of Mg^+ currently being measured by Dunn's group.

Electron-Atom and Atom-Atom Collision Processes - A. C. Gallagher

The electric breakdown and conduction of a gas and the radiation from the resultant plasma are of importance in lasers and area lighting, in switching and power generation, and in the diagnostics of man-made and astrophysical plasmas. The radiative and electrical properties of these hot gases depend on electron-atom and atom-atom collision processes, which couple the kinetic energies of the particles into radiative transitions and visa versa. During this year Gallagher, in collaboration with postdoctoral research associate J. Kelly and graduate students X. Hahn, M. O'Callaghan, and G. Schinn, has been studying several kinds of collision processes that occur in these hot gases. As it is neither practical nor economical to investigate all specific species and processes of current or potential interest, these investigations are designed to obtain highly detailed diagnostics of a few specific processes, thereby guiding and testing basic understanding applicable to all similar processes. Specifically, Gallagher and his colleagues are carrying out the following experiments.

An experiment to measure fully differential electron excitation of Na atoms from the 3S to 3P state has been constructed and tested. This experiment will use a completely new approach, the detection of differential cross sections by recoil Doppler shift to allow measurements that are fully differential in M_ℓ, M_s and θ. This experiment will test theories in the critical threshold region with orders of magnitude more detail than has previously been available.

Inelastic atom-atom collisions are also being measured differentially using the recoil Doppler shift. Here Na atoms are excited to the $3P_{3/2}$ state with a single velocity in the laser direction (v_z), and a small fraction of these atoms are inelastically transferred to the $3P_{1/2}$ state by collision with an inert gas atom. The v_z distribution of these post-collision atoms is then measured from the laser induced fluorescence (LIF) spectrum of the $3P_{1/2} \rightarrow 4D$ transition. The results of this gas-cell experiment involve a collisional velocity average that somewhat dilutes its diagnostic power. A crossed atomic beam apparatus has therefore been constructed to remove this averaging and allow direct measurement of differential (in angle) inelastic atom-atom collision cross sections and very precisely delineate the theoretical understanding of the interactions and the energy transfer process. Initial experiments in the atomic beam apparatus will study collisions between equivalent and dissimilar alkali atoms in the excited state.

The pair of atoms undergoing a collision can absorb and emit radiation at wavelengths far from the atomic transitions. The spectrum of this continuum radiation provides a powerful diagnostic of the interaction energies of the collision complex. The spectrum has been studied in this and other laboratories for many years to study collisional interactions. These studies have been restricted to radiative transitions between isolated electronic states of the collision complex, or in other words to elastic collisions. This year in collaboration with T. Holstein, Gallagher's group has extended the lineshape theory to include inelastic collisions and particularly the absorption and emission of radiation in the voided level-crossing region responsible for most inelastic atom-atom energy transfer. This theoretical result is now published, and experiments have been designed to use and test this theory in the laboratory.

A new experiment has been started this year to study collisional and stimulated radiation processes in Sr and Sr-alkali vapor mixtures. Fluorescence transients following pulsed radiative excitation of Sr are being diagnosed to establish radiative and collisional pathways and cross sections in this highly excited vapor.

<u>Silane Neutral Chemistry</u> - A. C. Gallagher

The quality and utility of hydrogenated amorphous silicon (a-Si:H) film photovoltaics has increased every year since their initial production in 1976. Efficiencies of 8-10% are now routinely achieved compared with crystal silicon cell efficiencies that are now 14-18%. Because a-Si:H can be deposited inexpensively from a discharge as a thin layer on large areas, it is a leading contender for solar power generating systems. In spite of this impressive progress, major improvements in deposition rate, large-area reliability, stability, and efficiency are still feasible.

Since 1979 Gallagher and his group have been studying the discharge and surface processes that lead to the film production in order to assist this progress with improved understanding of the microscopic processes. During the last year, they have concentrated on understanding the neutral radical gas chemistry, using their unique and sensitive radical detector (based on threshold ionization mass spectrometry). They were able to measure the mixture of mono and disilane radicals, which are primarily responsible for film deposition, and have modeled the sources of these radicals. By analyzing their data, they have shown that much of the discharged neutral chemistry occurs on surfaces, and they have delineated several of the dominant surface processes using measurements and diagnosis of silane surface pyrolysis. With this increased understanding of the surface processes, they are now devising experimental tests of their models for the surface process of greatest interest; the silicon incorporation and film growth. During the last year, R. Robertson has completed his thesis under this project.

Dielectronic Recombination - G. H. Dunn

In 1964 dielectronic recombination (DR) was hypothesized to be the dominant recombination process in very hot plasmas. On the basis of its success in rationalizing a discrepancy in temperature measurements of the Sun, the mechanism has since been routinely incorporated into models of astrophysical, fusion, and other hot plasmas. Nevertheless, it was not until 1983 that experimental breakthroughs in JILA and three other laboratories resulted in the first successful laboratory measurements of the cross section for this process. *All* the experiments gave cross sections significantly greater than theoretically predicted. To explain the discrepancies, the hypothesis was advanced that extrinsic fields of modest size in the collision region mix angular momentum states, increasing the number of states through which DR can occur. The extrinsic field thus becomes a "knob" by which the cross section can be turned up or down. The next step was obviously to test this bizarre but important concept under controlled conditions.

The experiments at JILA were performed using crossed beams of ions and electrons to study the process $e + Mg(3s)^+ \rightarrow Mg(3p,n\ell)^{**} \rightarrow Mg(3s,n\ell)^* + h\nu$. In the 1983 experiments, the stabilizing photon and product Rydberg atom were detected in coincidence and the total cross section measured. In the more recent measurements, the Rydberg atoms were detected and cross sections measured both as a function of the principal quantum number of the final Rydberg atom ($Mg(3p,n\ell)$) for fixed electron energy and as a function of electron energy for fixed principal quantum number. For this work, Dunn and his collaborators developed a novel and versatile new Rydberg state analyzer/detector, which uses a wedge field and position sensitive detector. Figure 3 illustrates results obtained by Dunn, A. Müller (JILA Visiting Fellow), D. Belić, B. DePaola, N. Djurić, D. Mueller, and C. Timmer for σ_{nf} versus n_f for three values of electric field in the collision region. Recent theoretical work by groups in Connecticut, Oak Ridge, and JILA are in qualitative agreement with these results, though some work remains to be done.

It is predicted that DR involving ions with transitions $\Delta n=1$ and larger radiative stabilization rates will be less subject to the observed field effects. Work is underway to make measurements on the helium-like ion Li^+ using the Rydberg state detection method.

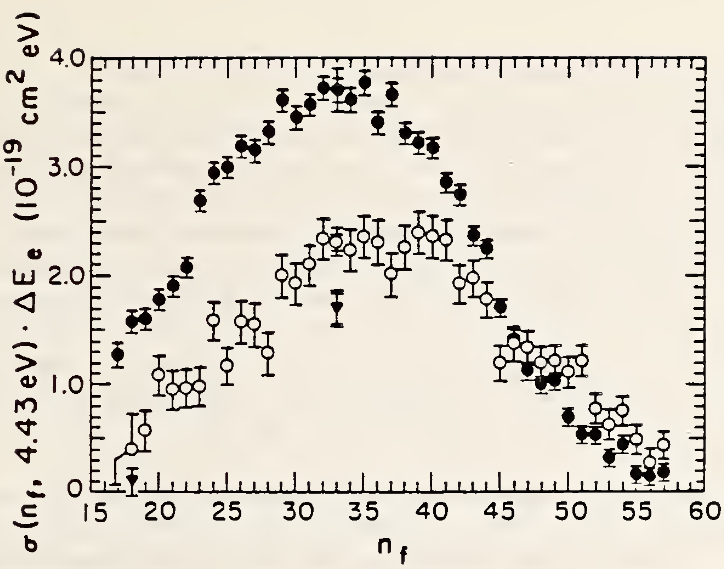


Figure 3. Cross section × width ΔE_e of electron energy distribution versus field ionization quantum number n_f. Solid circles, E_c = 23.5 V cm^{-1}; open circles, E_c = 7.24 V cm^{-1}; triangles, E_c = 3.62 cm^{-1}. Uncertainties are one statistical standard deviation. For n_f = 33, the relative uncertainties are also indicated. Absolute uncertainties at n_f = 33 are within 10%.

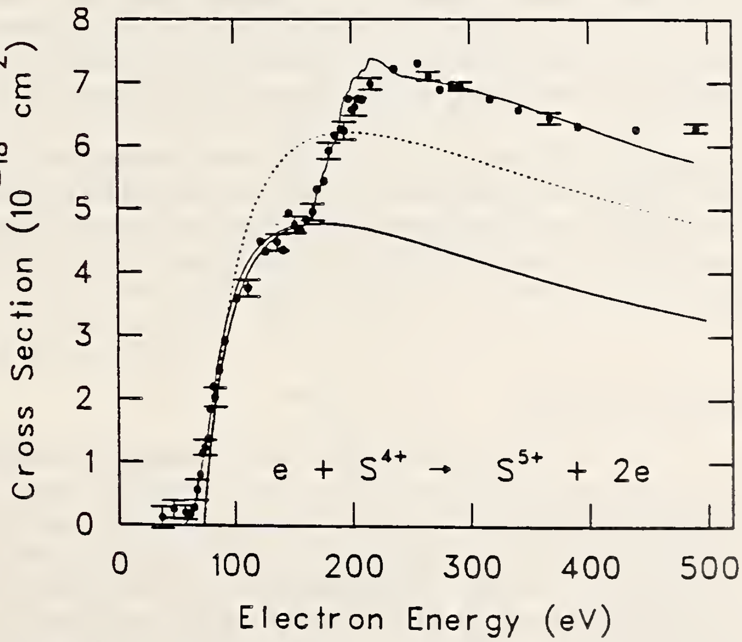


Figure 4. Measurements on electron-impact ionization of S^{4+}. The excitation-autoionization feature beginning around 170 eV is clear. The solid curve through the points is a theoretical calculation that agrees well with the data.

Electron-Impact Ionization of Ions - G. H. Dunn

Dunn and his colleagues have found during the past few years that electron-impact ionization of ions is affected to varying degrees by "secondary" processes such as excitation-autoionization and dielectronic-capture double autoionization. Indeed, these indirect mechanisms may dominate the ionization process by more than an order of magnitude. Since these cross sections are important for modeling fusion, astrophysical, and high-power laser plasmas, Dunn and his colleagues have been trying to gain a systematic understanding so that the cross sections can be predicted and incorporated into modeling codes.

Using the electron-cyclotron-resonance (ECR) ion source at Oak Ridge National Laboratory (ORNL) for the first time, A. Howald, D. Gregory, F. Meyer, R. Phaneux, Müller, Djurić and Dunn made measurements on electron-impact ionization of Mg-like ions, S^{4+}, $C\ell^{5+}$, and Ar^{6+}, where excitation of a 2p electron followed by autoionization plays an important role. Figure 4 shows results for S^{4+}, where the excitation-autoionization feature beginning around 170 eV is clear. The solid curve through the points is a theoretical calculation that agrees with the data. The X-ray laser breakthrough at Livermore using Ne-like selenium is beset with an anomaly that 2p - 3p excitations are apparently not as large as theoretically predicted. Dunn's previous data on excitation-autoionization of Na-like ions also shows this same anomaly, but the data on Mg-like ions agrees with theory. Repeat measurements were also made on O^{5+}, which had previously shown an anomalously high excitation-autoionization cross section compared with other Li-like ions. The new experiment is in line with others and with theory.

The ECR source at ORNL is prolific in producing multiply-charged ions. Charge states of ions not previously available (e.g., iron ions up to Fe^{9+}) permit measurements on species and charge states of particular importance to the fusion program. These measurements are being pursued.

Merged Electron-Ion Beams - G. H. Dunn

Dunn and his colleagues have, for more than ten years, been involved in making measurements on electron-impact excitation of ions. The approach has been to use crossed beams of ions and electrons and to observe and measure the fluorescence in the third orthogonal direction. Using this approach, they measured excitation of Be^+, C^{3+}, N^{4+} (Li-likes), Mg^+, Al^{2+} (Na-likes), Ca^+, Ba^+, Hg^+, Li^+, Zn^+ and Ga^+. With a few exceptions, this constitutes the extent of cross section measurements for electron-ion excitation. For most (but not all) of the above cases, $\Delta n=0$ and $\Delta\ell=1$ for the excitation. A few years ago, it became clear that the fluorescence technique would not yield good measurements for many of the most important cases (e.g., high-z ions, $\Delta n\neq0$, $\Delta\ell\neq1$).

To cope with this, Dunn and his colleagues are developing an entirely new measurement concept to obtain electron-ion excitation cross sections. The method involves merged beams of electrons and ions and the detection of the inelastically scattered electrons with trochoidal analyzers fore and aft. The profound advantage is that the collection efficiency is 100% compared with 10^{-4} or so for the fluorescence and other methods of detecting inelastically scattered electrons. The method overcomes *all* the limitations mentioned above and can yield good measurements for high z, $\Delta n \neq 0$ and $\Delta \ell \neq 1$.

Timmer, DePaola, and Dunn have been designing and building the equipment necessary to realize these concepts. This new apparatus will soon be together, and they plan to be doing first experiments with it this coming year. At JILA they will make measurements on singly charged ions, since their ion source is limited. This will shake down the methodology as well as yield some interesting measurements. They will then take the apparatus to the ECR ion source at ORNL for measurements using multiply-charged ions. Some of the first measurements will undoubtedly involve looking at excitations of the type 2p - 3p in Ne-like ions, since there appears to be such an anomaly involving these excitations in the X-ray laser work at Livermore.

Low Temperature Ion-Molecule Reactions - G. H. Dunn

Dunn and his colleagues have developed the Penning ion-trap as a tool for investigating ion-molecule reactions in a heretofore inaccessible temperature range (4 K - 30 K). A number of reactions have been studied, including the first observations and measurements of radiative association involving small nonpolar molecules. In all cases, the reactant neutral molecule has been H_2 (or D_2), and conditions are such that there is (probably) a normal mix (3:1) of ortho/parahydrogen. To gain a more complete understanding of these mechanisms and to obtain data more directly applicable to the modeling of molecule formation in the interstellar medium, the measurements should be done with pure parahydrogen. M. Schauer, S. Jefferts, and Dunn are modifying the apparatus to make these experiments possible.

Dielectronic Recombination - S. Geltman

At high temperatures, dielectronic recombination becomes the most important electron-ion recombination process in a plasma. It dominates over one-electron radiative recombination because there are many doubly-excited Rydberg states into which the free electron may resonantly enter. Geltman has been working with a group at the Lawrence Livermore National Laboratory in the preparation of a computer package for dielectronic recombination to be incorporated into their dense-plasma modeling codes. The needed branching rates between radiative decay and autoionization are being calculated in a hydrogenic approximation for arbitrary Z, which is determined by the instantaneous plasma conditions. Programs for the needed rates have been prepared, and they are in the process of being tested in the Livermore codes.

<u>Multiple Ionization by Intense Laser Pulses</u> - S. Geltman

A number of experiments have been done in recent years in which high states of ionization have been seen when atoms are irradiated by intense laser pulses. Typically these measurements are done on rare gases with photons from Nd:YAG (1.17 eV) and ArF (6.42 eV) lasers, the pulse lengths are in the picosecond range, and intensities are $\approx 10^{12}$ - 10^{17} W/cm^2. The general process may be represented as $X + N_q h\nu \rightarrow X^{q+} + qe$, where ions have been detected for N_q and q values as large as 99 and 10, respectively. It has not been possible to obtain a correlation between the numbers of multiply charged ions produced at intensity I and the expected theoretical form, I^{N_q}.

Geltman has been re-examining the theory on the basis of a Hartree atom model in which the outer shell electrons are independent of one another and interact only with an effective central field. The one-electron ejection probability p may be computed in the normal quantum perturbation theory manner and has the expected I^{N_1} where N_1 is a photon number much smaller than N_q. Geltman has been able to construct products of these (with appropriate statistical factors) to represent $P^{(q)}$, the approximate probability for multiple electron ejection. His results for the relative abundance of charge states Xe^{q+} give much improved agreement with the data of Rhodes et al. than was possible to obtain with the I^{N_q} form. For low-intensities, his new theory gives the dependence I^{qN_1} and a time-dependence of t^q, rather than t. There is also good general agreement of the theory with multiple ionization measurements using CO_2 laser pulses, which of course involve much higher photon numbers.

Geltman is planning to apply the present theory to other measurements as they become available and also to extend it to cases where multiphoton ionizations may occur via autoionizing states, such as in Sr. The latter processes are highly resonant and pair correlations become important.

<u>Model Study of Above-Threshold Ionization</u> - S. Geltman

In analyzing the energy spectrum of electrons that are ejected in a multiphoton ionization process, it has been found that not only is there a peak at the expected $E_1 = N_1 h\nu$ - IP, but at sufficiently high laser intensities additional peaks appear at $E_2 = E_1 + 2h\nu$, $E_3 = E_1 + 2h\nu$, etc. Thus electrons are absorbing more photons than the minimum required for ionization. A number of approximate theories have had varying degrees of success in explaining these measurements.

Geltman has started an investigation of this process using very simple atomic and field models, so that an exact solution of the time-dependent Schrödinger equation can be found. He has taken the model in which the atomic potential is a one-dimensional δ-function and the laser field is an oscillating square wave. The fact that this model laser field is a constant between alternations of direction allows one to use the well-known mathematics of the d.c. Stark effect, i.e., to express exact wave functions in terms of Airy functions. This should allow the development of a step-by-step exact numerical solution, from which one has the population of all continuum states, i.e., the ejected electron distribution. Geltman plans to examine the electron energy peak structure under various conditions of frequency, intensity, and pulse length.

Stark Effects in Laser Isotope Separation - S. Geltman

Geltman has been continuing his cooperation with T. Lucatorto and J. Snyder of NBS/Gaithersburg in their program of using sharply tuned lasers in multiphoton ionization to obtain highly efficient isotope separations. The prototype system of separating the rare isotopic ^{90}Sr from the common one ^{88}Sr has been treated by means of a system of two cw lasers tuned to 460.8 and 428.3 nm, which pump the ground state Sr to the 5s13d state via the 5s5p intermediate resonance. It is then photoionized by an intense CO_2 laser. The Stark shifts in this two-step excitation are critical in optimizing the efficiency of the isotope separation. These shifts and the needed photoionization cross section were calculated as a function of laser intensities. This led to a resulting sensitivity of the overall scheme of better than 10^{-15} with a throughput of 10^{13} atoms/sec. The next phase of this project will involve the Kr isotopes of atomic weights 81 and 84, which are very important in the analysis of ground water for radioactive traces. In addition to Stark shift theory, this project will involve calculating charge transfer cross sections. The cooperation between Boulder and Gaithersburg on this work will continue.

Kinetics of Metastable H_2 - A. V. Phelps

Phelps and his colleagues are making measurements of the collisional process responsible for the production and loss of $H_2(c^3\Pi_u)$ metastable molecules in electrical discharges in H_2. Such discharges are important in devices such as hydrogen thyatrons and negative ion sources.

The present phase of this work is concerned with the measurement of the rate coefficients for collisional destruction of the metastables. H. Tischer (CU) and Phelps have published a letter describing these measurements for the N=1 rotational level and the v=2 vibrational level of the $c^3\Pi_u$ state of H_2. A. B. Wedding (CU) and Phelps are extending the measurements to other rotational and vibrational levels of the metastable state. The experimental technique involves the measurement of the transient absorption of a cw dye laser by the metastables following perturbation of the metastable population by a pulsed dye laser.

After completing the measurements of the H_2 metastable destruction, Phelps and his colleagues plan a brief look at D_2 metastables. They then plan to determine experimental rate coefficients for the excitation of these metastables by electron impact from ground state H_2.

Nonequilibrium Electron Experiment and Theory - A. V. Phelps

Phelps and his colleagues are making experimental tests of models of the behavior of electrons in gases at very high electric fields and low gas densities. The current experiment yields absolute values of the emission of radiation as a function of position from a low pressure, high voltage discharge in a spatially uniform electric field. Comparison of these results with the predictions of theory provides tests of the accuracy of various approximate theories. The data and theories derived from this study are important for the modeling of plasma reactors, charged particle beam propagation and high power switches.

In collaboration with B. Jelenković (CU), Phelps has made a number of measurements of the spatial distribution of emitted light from these low current discharges for a variety of gases, electrode materials, and electric-field-to-gas-density (E/n) ratios. The measurements are made absolute by comparison with previous experiment and theory at low E/n. At present, the agreement with theoretical calculations made in collaboration with L. C. Pitchford (GTE Laboratories) is poor, and an explanation is being sought.

The future of this project is uncertain because of the difficulties in getting other agency funding. The immediate plan is to pulse the current through the discharge on a time scale that will separate electron and ion induced emission. After this, Phelps and his colleagues propose to make energy analyses of the electrons and to compare theory and experiment for nonuniform electric fields.

JILA-NBS/Gaithersburg Exchange - A. V. Phelps

During the second half of FY-85, Phelps participated in the NBS program to exchange scientists between JILA and NBS/Gaithersburg. While in Gaithersburg, he worked with the Applied Electrical Measurements Group of the Electrosystems Division of the National Engineering Laboratory. The research project was to model electron behavior in the corona discharges being studied experimentally by R. J. Van Brunt. Initially, it involved developing a set of collision cross sections for electrons and SF_6. They then used these data in their recently developed electron Boltzmann code for gases for which electron attachment is important and applied them to SF_6 and SF_6 mixed with other gases to predict SF_6 dissociation rate coefficients for modeling the measured decomposition rates. This collaboration is expected to continue as the need arises in Van Brunt's research and may be part of a proposed project on computer modeling of plasma-chemical reactors used for processing of materials.

Angular Distributions of Photoelectrons from High Excited Atomic States - S. J. Smith

The (angular momentum) properties of highly excited aligned states reached by stepwise excitation with polarized pulsed laser beams can be studied by measuring and analyzing angular distributions of photoelectrons, since these are determined in part by the angular part of the excited state wave function. Smith and G. Leuchs (Max Planck Institute for Quantum Optics, Munich) have used this method in the past to study Rydberg series in barium, a system with two valence electrons in which the single electron Rydberg series is perturbed by the presence of states in which both valence electrons are simultaneously excited. During FY-85, Smith and Leuchs completed a study of the 6sns $^1S_0$ Rydberg series in barium in the energy range around a 5d7d (J=0) doubly excited state. The results were particularly interesting for two reasons: (1) The interaction with the 5d7d (J=0) state is a pure quadrupole interaction with direct uncomplicated interpretation, and (2) This type of measurement was shown to be unique among measurements of series perturbations in that it contains information about the sign of the interaction.

Smith and Leuchs continued or initiated two additional studies during FY-85. One was a study of the competition between two decay channels from highly excited states: (1) Direct photoionization, and (2) A Raman redistribution to nearby states. The effect of the latter process appears in the angular distribution from a subsequent photoionization process, which then differs from that of (1). These studies show that the Raman process, negligible at low power densities of the photoionizing laser, becomes competitive with direct photoionization at high laser power densities. This is in direct contradiction to the commonly accepted view of theoreticians that the first order (direct photoionization) process should always dominate over the second order (Raman redistribution process). Revised theories of this competition have been worked out by K. Rzazewski (JILA Visiting Fellow) and by G. Alber.

Of continuing interest is the possibility of observing some manifestation of the limits of validity of dipole selection rules in photoionization of electrons from Rydberg atoms, since the phase of the optical field may vary appreciably from one side of the atomic system to the other. A departure from the dipole selection rule would appear in the photoelectron angular distribution as the introduction of a higher spherical harmonic in the distribution. More specifically, one could expect a front-to-back asymmetry with respect to a plane transverse to the laser beam. An exhaustive study of the photoelectron flux from the 13 $^2D_{3/2}$ state of sodium by Nd:YAG second harmonic radiation at 55° forward and backward with respect to the plane shows four percent asymmetry to about four standard deviations. The effect is an order of magnitude larger than the estimate based on a classical picture of the electron orbit. The experimental result for the ratio of electric quadrupole and electric dipole matrix elements, Q=0.035(8), is a good check on the bound-free matrix element of r^2, not available in other experiments.

Further measurements in two-electron perturbed systems are being planned with a view to obtaining more quantitative (accurate) measurements of perturbations and to exploiting the photoelectron angular distribution method as an unique spectroscopic tool.

<u>The Role of Fluctuations in Non-Linear Optical Absorption in Atoms</u> - S. J. Smith

D. S. Elliott, M. Hamilton, K. Arnett and Smith have developed a system based on the use of fast frequency and phase modulators for imposing statistically well characterized fluctuations with a bandwidth of about ±1 GHz onto the external beam of a highly stabilized ring laser. Furthermore, by driving the system with Gaussian (random, statistically stationary) noise, they can achieve prescribed laser lineshapes ranging from Lorentzian to Gaussian. They are fully characterized statistically by the laser lineshape and linewidth, both of which can be measured directly. The objective is to study experimentally and fully quantitatively the effect of different laser lineshapes and linewidths on a variety of nonlinear optical absorption processes in atoms.

The results of the first studies, addressed to one of the conceptually simplest nonlinear processes, unsaturated Doppler-free two-photon absorption (3S-5S transition in atomic sodium), were completed in FY-85. The results clearly demonstrate the limitations of intuition, and/or experience with monochromatic lasers, in dealing with nonlinear effects.

During FY-85 a major effort was made to study effects associated sodium). The double-optical-resonance technique was used. A weak probe laser sampled the structure of the $3P_{3/2}$ level, which is split and shifted in an intense laser field, by coupling it (by scanning) to the $4D_{5/2}$ level. Figure 5 shows examples of probe scans (a) with a nearly monochromatic laser, and (b) with a wideband laser of measured power spectrum (c). The most dramatic feature in the results of this work is the behavior of the symmetry of the double-peaked probe scan. The asymmetry can take different signs with different laser lineshapes and linewidths. This phenomenon provides a strong handle on the role of fluctuations in a nonlinear process and is of great interest to the theoreticians (such as former JILA Visiting Fellows P. Lambropoulos (USC) and J. Eberly (Rochester)).

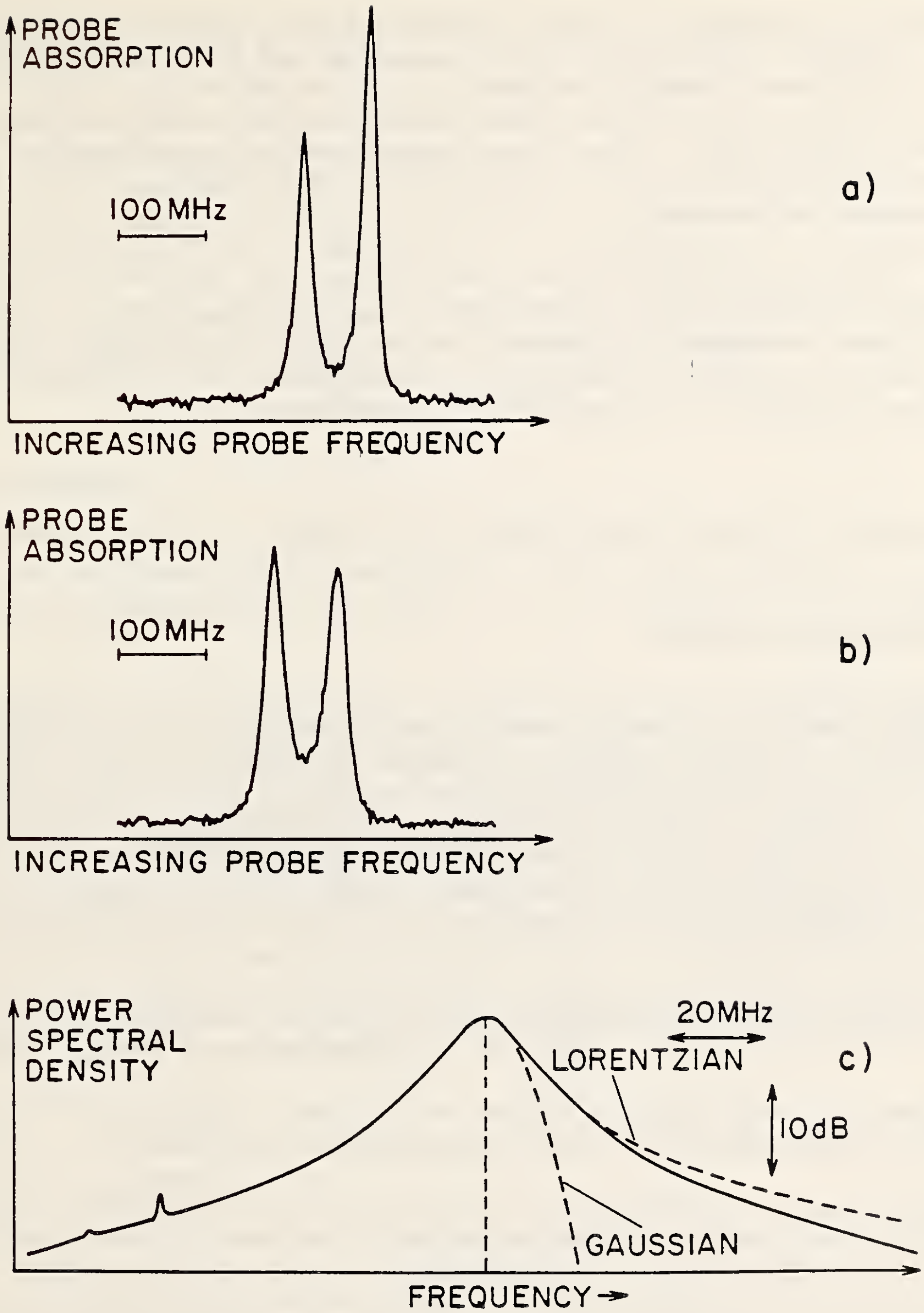


Figure 5. The probe laser absorption spectrum for (a) a "monochromatic" saturating laser and (b) a saturating laser with a nearly Lorentzian shaped power spectrum (c) with HWHM of 7 MHz. In (c) the subsidiary peaks on the left are frequency components on the local oscillator beam used in the heterodyne detection of this spectrum. Thus they can be ignored. Note that the vertical scale is logarithmic. The Lorentzian and Gaussian curves drawn for comparison also have HWHM of 7 MHz.2

Finally, during FY-85 Smith started a study of the effect of lineshape, linewidth, and intensity on the so-called Hanle effect (zero magnetic field level crossing resonances), in collaboration with H. Metcalf and T. Bergmann (both of SUNY Stony Brook) and J. Brandenberger (Lawrence University). The object is to provide a quantitative check of theoretical predictions of P. Avan and C. Cohen-Tannoudji, which depend on lineshape properties.

A thesis project (K. Arnett) will continue this effort as well as initiating studies using amplitude noise on the laser. Preliminary efforts have been made to observe the resonance fluorescence spectrum in sodium using optical heterodyne techniques (a collaboration with D. Elliott, Purdue). This effort will continue.

JILA ATOMIC COLLISION CROSS SECTION DATA CENTER - J. W. Gallagher

FY 1985 Accomplishments

The JILA Data Center under the direction of J. Gallagher has carried on an active program to compile and evaluate data in the areas of electron and photon collisions with atoms, ions, and simple molecules. Several projects entailed collaboration with Data Center visitors who participated in the review and evaluation of data in their fields of expertise. The following projects were completed in FY 1985; journal references may be found in the list of QPD publications elsewhere in this report.

- *Charge transfer of hydrogen atoms and ions in metal vapors.*
  T. J. Morgan, R. E. Olsen, A. S. Schlachter, and J. W. Gallagher

- *Electron production in proton collisions: Total Cross Sections.*
  M. E. Rudd, Y.-K. Kim, D. Madison and J. W. Gallagher

- *Anisotropic scattering of electrons by N_2 and its effects on electron transport: Tabulations of cross section and results.*
  A. V. Phelps and L. C. Pitchford

- *Tabulations of collision cross sections and calculated transport and reaction coefficients for electrons in H_2 and D_2.*
  S. J. Buckman and A. V. Phelps

- *Tabulations of collision cross sections and calculated transport and reaction coefficients for electron collisions with O_2.*
  A. V. Phelps

- *An evaluated compilation of data for electron-impact excitation of atomic ions.* J. W. Gallagher and A. K. Pradhan

- *Atomic data for electron-impact excitation of ions.* A. K. Pradhan and J. W. Gallagher

- *Alignment and orientation of collision processes - What we have learned so far.* N. A. Anderson, J. W. Gallagher, I. V. Hertel

- *Analysis of orientation and alignment in electron impact excitation of heavy rare gases.* The Ar 4s ^1P and ^3P Case. N. Anderson, J. W. Gallagher, I. V. Hertel, and F. J. da Paixão

Work in Progress

Collisional Alignment and Orientation of Atomic Outer Shells. I. Direct Excitation by Electron and Ion Impact. N. O. Andersen, J. W. Gallagher, and I. V. Hertel

To describe these processes, the authors have determined new parameters that have more physical meaning than those usually published and which can be derived from published data in most cases. Data have been collected and reformatted from approximately two hundred papers on alignment and orientation in electron collisions with H, He Ne, Ar, Kr, Xe, Li, and Na. Measured and calculated data for each incident energy and final target state are being compared to evaluate the quality of the work and identify the influence of competing physical processes such as radiation trapping in experimental work and the accuracy of theoretical descriptions. A manuscript describing this work is being prepared for submission to "Physics Reports" and an Information Center Report will give a comprehensive presentation of the data.

A Review of Measured Electron Impact Excitation of Atoms and Atomic Ions. D. W. O. Heddle

Professor Heddle of Royal Holloway College, University of London, spent a month at JILA in the summer of 1985 continuing work on this review. Last year he reviewed data on the alkalis, alkaline earths, cadmium and zinc. This year he concentrated on helium, a substantial topic in itself, and a detailed analysis of the associated data. The data on the other rare gases were also collected and reviewed. Heddle will continue to work on the review at his home institution and plans to complete a first draft of the manuscript for "Reviews of Modern Physics" in 1986.

Absolute Partial Cross Sections for Molecular Photoionization Processes. J. W. Gallagher, C. E. Brion, P. W. Langhoff and J. A. R. Samson

The authors had collected and compared all data on total photoionization, partial channel photoionization, and dissociative ionization of twenty-one common small molecules by the fall of 1984. Preparation of the manuscript lagged, however, and virtually no progress has been made on the project during FY-85. Efforts are currently being renewed to complete this project and to submit a manuscript to the "Journal of Physical and Chemical Reference Data" in 1986.

The Atomic Collisions Data Base.

In addition to the Data Center's bibliographic collection, approximately nine hundred numerical data files have been entered into the Data Base. These are being used to prepare figures supporting the Center's review activities. Programs have been developed to produce listings and indices of the material in the Data Base. Work is currently ongoing to provide on-line enquiry capability.

The Digital Equipment Pro 380 data-capture system was acquired to replace the outdated Tektronix 4051 and peripherals. Purchased software is being studied and tailored to meet specific needs of the Data Center.

FY 1986 Plans

Gallagher and her colleagues will be making a major effort to complete the three reviews currently underway. In addition, they will continue the modification and improvement of procedures through full incorporation of the Atomic Collisions Data Base and the DEC Pro 380.

Work will begin on "Atomic Data for Fusion, Volume II. Collisions of Electrons with Atoms and Molecules", which is part of the five-volume series to be published by the Controlled Fusion Atomic Data Center of Oak Ridge National Laboratory.

A second new project, a review of properties and reaction rates of atmospheric ozone, will be started with J. I. Steinfeld of M.I.T.

State-Resolved Dynamics via Laser Absorption Spectroscopy - D. Nesbitt

Nesbitt is pursuing four new areas of research into molecular spectra and dynamics using ultrahigh sensitivity infrared absorption techniques: (1) Spectroscopy, intramolecular energy transfer, and vibrational predissociation of weakly bound clusters in a supersonic molecular beam, by direct absorption of a tunable difference frequency laser, (2) Gas-solid interactions by monitoring the nascent quantum state distributions of sublimation from simple molecular solids into a vacuum, (3) Molecular properties (such as dipole moments) of vibrationally excited species by coherent transients, (4) Spectra of ultracold radicals in a supersonic jet excited by a weak Corona discharge.

Although Nesbitt joined the Division only a year ago, he and C. Lovejoy and M. Schuder have already obtained high quality spectra of small Van der Waals and hydrogen bonded molecules. Study of these prototypic, weakly bound species provides new information on the nature of bonding, collisional energy transfer in the gas phase, and the extremely important issue of the time scale for intramolecular vibrational relaxation. Their novel technique uses time resolved, direct infrared absorption of a high resolution tunable difference-frequency laser in a supersonic jet expansion. This source of tunable laser light (2.2μ - 4.2μ) covers a strategically rich portion of the spectrum where -OH, -CH, -NH, -SH, -PH, XH (X=halogen) stretches and their deuterated analogs occur. By dynamically subtracting laser amplitude noise, Nesbitt, Lovejoy and Schuder obtain absorption sensitivities near the shot noise limit of $10^{-6}/Hz^{1/2}$ with 10 μW of laser power. This powerful combination of high sensitivity and tuning range permits high resolution study of a wide range of molecular systems completely inaccessible by previous laser techniques.

Using these techniques, Nesbitt, Lovejoy and Schuder have obtained the first infrared observation of Ar-HF in both the fundamental (ν_1) and combination band ($\nu_1 + \nu_3$). They observe considerable shifts in the molecular geometry upon vibrational excitation. It is particularly interesting that although the excitation energy exceeds the Van der Waals bond strength by forty fold, the exceedingly narrow line widths of both the ν_{21} and $\nu_1 + \nu_3$ spectra indicate vibrational predissociation lifetimes greater than 2.4 million vibrational periods. Two groups (Klemperer at Harvard and Saykally at Berkeley) are presently searching for the low frequency modes of Ar-HF based on the above spectra. Spectra of the HF dimer have also been observed in the cooled jet (T < 10 K); the absence of spectral congestion at these temperatures permits measurement of the predissociation lifetimes for the two HF stretch modes.

Present efforts in this area of research are heading in several complementary directions. 1) A search for combination bands in

Ar-HF based on the symmetric Van der Waals stretch is underway and will complete the identification of all three vibrational modes. 2) The corresponding He-HF, Ne-HF, and Xe-HF will be pursued in order to establish the systematic trends as a function of inert gas polarizability, size, etc. 3) Similar studies on DF complexes are planned. The isotopic dependence of vibrational frequency, rotational constants, etc. provides important additional tests of the potential surface. 4) Predissociation dynamics of HF dimer will be investigated by linewidth studies as a function of initial rotational state and tunnelling component.

Nesbitt is also pursuing three other projects using state-of-the-art infrared generation and detection capabilities. With Schuder, he is investigating the quantum state dynamics of sublimation phenomena. Their approach relies on ultra sensitive detection of molecules that have freshly sublimated into a vacuum, before collisions can scramble the nascent quantum states. Such information provides insight into the nature of solid-gas interactions at the interface, as well as determining by detailed balancing the sticking coefficients for collisional deposition as a function of internal quantum state.

Nesbitt is developing new methods for probing molecular properties such as dipole moments of vibrationally excited species by coherent transients. The approach uses the capability to saturate an infrared transition in the presence of a uniform electric field. The heterodyne quantum beats that are generated on the laser as the external fields are collapsed correspond to the tuning of the molecular m_J levels in the presence of the field. By appropriate choice of molecular symmetry, these quantum beats can provide very precise, direct measurement of vibrationally induced changes in the dipole moment.

P. Engelking (JILA Visiting Fellow, 1985-86) and Nesbitt are pursuing the study of ultracold radical spectroscopy in a supersonic jet excited by a weak Corona discharge. Engelking has pioneered the development of these Corona discharge methods to generate copious quantities of radicals under cooled beam conditions. Combining these methods with the infrared capability available in Nesbitt's laboratory, he and Nesbitt plan to study the vibrational spectroscopy of these highly reactive species.

Energy Transfer - S. R. Leone

The study of energy transfer processes is important for making high powered lasers more efficient, for accurately describing the collisional excitation processes and emission processes in the upper atmosphere and interstellar media, and for interpreting a wide variety of chemical reaction dynamics problems such as occur in combustion. In addition, energy transfer processes are one area for which accurate theoretical interpretation of the results is possible.

D. Neuschafer and Leone are studying electronic energy transfer processes in atomic calcium vapor as a function of the orbital "alignment" of the calcium excited state in the collision. Using linearly polarized laser light for the excitation and an atomic beam apparatus to define the relative velocity direction, they can align the p-orbital of the excited calcium either parallel or perpendicular to the collision direction. The rates of electronic energy transfer processes are then studied as a function of this alignment. Dramatic dependences on the orbital alignment are observed with a variety of rare gas collision partners for the transfer from the Ca 5 $^1P_1$ state to the Ca 5 ^3P_J state. For He and Ne the perpendicular configuration is more efficient than the parallel alignment by 40% and 70% respectively, whereas for Xe the parallel alignment is more efficient by 25%. No preferential alignment effect occurs for Kr. The results are interpreted with reasonable success in terms of curve crossing models. Work in the future will investigate the effect of alignment on an elementary chemical reaction, such as $Ca^* + H_2$ with specific probing of the CaH product alignment. R. Schwenz (NSF Summer Faculty Fellow) is exploring new processes in Sr atoms for implementing similar alignment techniques.

D. J. Donaldson and Leone have developed a successful method to study the rates of vibrational deactivation of vibrationally excited methyl radicals. A molecule such as acetone is photolyzed with the 193 nm output of a rare gas halide excimer laser to produce methyl radicals in selected vibrational states. The deactivation processes are followed by time-resolved infrared emission. With this method some of the first rates for state-selected vibrational deactivation of the free radical have been obtained with a variety of collision partners. The amount of data on free radical deactivation is extremely limited, and thus the value in this new method of measurement. The observed rates are uniformly more rapid than measured rates for similar "closed-shell" molecules, indicative of the strong attractive interaction of the free radical species with other molecules. These rates are important in basic combustion processes.

In separate experiments L. Cousins and Leone are studying the vibrational excitation and reaction processes of energetic H and D atoms, also produced by photolysis techniques. Preliminary results have been obtained on the vibrational excitation of HF and DF by collisions of 2 eV H atoms with these molecules. A new apparatus is being developed to carry out these fast atom experiments under crossed beam conditions, so that single collision results are achieved. In addition new sources of fast atoms will be developed, such as from laser ablation or desorption from surface films.

C. Hamilton, V. Bierbaum, and Leone have obtained some of the first rates for vibrational deactivation of an ion, CO^+, with several collision partners under well-characterized conditions. They obtained these rates by direct optical monitoring of the ion vibrational states by laser-induced fluorescence. The only previous method of obtaining ion deactivation rates relies on a chemical monitoring method whereby the vibrationally excited ion reacts with another reagent, but the vibrationally cold ion does not. The optical probe method promises to obtain significant new details about ion vibrational deactivation with greater state specificity, such as in the capability to study a whole series of vibrational states. As a first demonstration of the concept, the vibrational deactivations of CO^+ in a low vibrational state, v=1, and in a much higher vibrational state, v=4, were studied with CO. The rates were found to be identical (5×10^{-10} cm^3 $molecule^{-1}$ s^{-1}). From quantitative measurements of the disappearance and appearance of various vibrational states, it was determined that the vibrational deactivation occurs primarily through charge transfer of the CO^+ with CO (i.e. transfer of the charge to the other molecule that is not vibrationally excited). This work will continue to explore other vibrational states and collision partners in order to elucidate the mechanisms and underlying dynamics of ion vibrational deactivation.

<u>Ion-Molecule Collision Dynamics</u> - S. R. Leone

Ions are important in all kinds of media such as plasmas, lasers, and the upper atmosphere. This program is designed to push the state-of-the-art in measurement capability in ion reaction dynamics and other ion collision processes. The results included here are in many cases the only determinations of product state distributions for elementary ion-molecule reactions at thermal energies.

Hamilton, Bierbaum, G.-H. Lin, J. Maier, C. Chee and Leone in two separate experimental apparatuses have completed an extensive series of investigations on the thermal energy charge transfer reactions between N^+ + CO, Ar^+ + CO, and Ar^+ + N_2. They have carried out experiments to obtain both the vibrational and rotational distributions under single collision (crossed beam) conditions. They find that some channels in the ion-molecule reactions behave strictly according to a Franck-Condon mechanism, thus forming vibrational and rotational product states according to vertical transitions. Other channels are formed by more intimate collision complexes in which high vibrational and rotational excitation is imparted to the products. A marked difference is observed in the rotational distributions of the v=0 and v=1 vibrational levels of CO^+ produced in the N^+ + CO reaction. The v=0 state rotational levels can be characterized as cold, only 400 K, whereas the v=1 state rotations are non-Boltzmann and over 2000 K. This is dramatic evidence that two very different mechanisms participate in the formation of the two vibrational levels in the charge transfer. In addition, a major change in the branching ratio between the two channels is observed with varying kinetic energy. These effects are being explored in more detail with simple models and by further experiments to vary the kinetic energy over a wider range.

A. Langford, Bierbaum, and Leone have completed a new set-up to probe ion velocity distributions under well characterized electric field drift conditions using a single mode ring dye laser to measure the Doppler profile in laser-induced fluorescence. These experiments, if successful, will be the first optical measurements of ion velocity distributions under well-defined conditions, and thus available theoretical analyses will be applicable. The first experiments will be carried out on either Ba^+ or a metastable transition in Ar^+. Thus far, Doppler profiles under conditions of zero field have been observed for N_2^+, and clean sources of Ba^+ ions are being prepared so that experiments can proceed in the upcoming months.

Photofragmentation and Neutral Reaction Dynamics - S. R. Leone

Photofragmentation processes are of special interest to chemists because they represent the latter "half" of chemical reactions. The initial state preparation is more well-defined in a photoexcitation, however, and thus these processes are more amenable to theoretical treatment. In addition, photofragmentation can be used to prepare a wide variety of reactive radicals and atoms for basic studies of reaction dynamics.

Photofragmentation of IBr has been used by H. Haugen, E. Weitz (JILA Visiting Fellow) and Leone to probe the difference in reactivity of the two spin-orbit states of the atomic Br atoms. Spin-orbit reactivity is a subject of accelerating interest. It is the symmetry of the reactive potential energy surfaces, and often not the energy, which determines how reactive these different atomic states will be. The researchers find that Br ground state atoms are forty times more reactive with IBr to form Br_2 + I than the low-lying excited spin-orbit state (Br^*, 0.5 eV). The results explain a number of important features of the IBr solar photodissociation laser and have immediate consequences for the interpretation of the reactive potential surfaces. In this case, there is a strict adherence to the original potential symmetries in the reactive encounter, and the Br^* reactive surface has a high barrier to both reaction and quenching processes.

In last year's report, Leone presented a new method to obtain highly accurate quantum yields and branching fractions of electronically excited atoms. The method involves a time-resolved, laser gain-versus-absorption measurement, which samples the initial yield and compares it to a total atom yield at a slightly later time. The crucial point is the probing of the "coupled" pair of states with the same laser beam. The method achieved yields of Br and Br^* that were accurate to a few percent with relatively little effort. During this year, the same method has been applied with a sensitive diode laser probe system at 1315 nm in the near infrared to study the yields of spin-orbit states in I atoms. This work was carried out by Haugen, W. Hess, S. Kohler (NSF Visiting Faculty Fellowship for Women), and Leone. A commercially available InGaAsP communications diode laser was tuned to the I atom transitions, stabilized to the transition of interest, and transient gain and absorption signals were observed upon photolysis of C_3F_7I and CH_3I. Accurate yields were obtained, clearing up a many year-old controversy concerning the absolute yields of I^* from these compounds. This general class of molecules is of interest for solar-pumped laser systems, and future work will investigate novel compounds synthesized by C. Shiner of the CU Chemistry Department for use in these lasers. In addition, the tuning of these diode lasers for use in spectroscopy will be explored by insertion of antireflection coated diodes into an external resonator. The impact of the ready availability of these diode laser probes for important laser species such as I^* for laser diagnostics should also be apparent.

J. Smedley and Leone are investigating a long-standing problem dubbed "collisional release". In this process, a molecule of Br_2 is excited very near to its dissociation limit, and then collisions are allowed to dissociate the molecule upwards in energy. The researchers have obtained the first quantitative measurements of the rates of such processes. They use a high resolution pulsed dye laser along with single isotopes of bromine to excite a single state selectively up near the dissociation limit. A lengthy series of measurements is necessary to quantify the yield of the excited atoms, which is the indicator of the collisional release process. The researchers find that as a collision partner bromine is seven times more efficient than Xe in dissociating a Br_2 molecule that is excited to 3 kT below the dissociation limit. This difference is attributed to the possible formation of a Br_3 species, which enhances the collisional release probability due to favorable thermochemistry. Further work will elucidate the collisional release probability as a function of energy below the dissociation limit, with other collision partners where a chemical affinity exists to form weak Van der Waals molecules that may enhance the rate (e.g., Cl_2, HBr, I_2) and as a function of rotational angular momentum.

Donaldson and Leone are setting up a time-resolved Fourier Transform Infrared (FTIR) emission experiment to study photofragmentation of large polyatomic molecules. A high repetition rate excimer laser will be used to pulse dissociate molecules that produce vibrationally and rotationally excited free radical species. The firing of the excimer laser is timed to the mirror sweep of the FTIR in such a way as to obtain a laser pulse ten microseconds before the sampling of the infrared detector. This time will be short enough so that at low pressures in a jet, there will be no collisions. Sophisticated background limited detectors will be used to sample the weak emission. As a preliminary experiment to test out the method without yet using the FTIR, Donaldson and Leone have taken low resolution spectra of the emitting CO and CH_3 fragments upon photodissociation of acetone. From these spectra they can tell that the CO fragments are highly excited rotationally. Crude vibrational distributions are observed for both the CO and the methyl radicals. With the FTIR technique, it will be possible to quantify the extent of both vibrational and rotational excitation under high resolution in the fragmentation of many complex molecules. The FTIR has just been installed and is fully operational; Donaldson and Leone await the arrival of the high repetition rate excimer laser to begin these experiments.

<u>Surface Scattering Dynamics</u> - S. R. Leone

K. Carleton and Leone have started a new program to study the scattering and sticking properties of Ga atoms on metal surfaces from a basic point of view, but with an emphasis on semiconductor growth technology. A pulsed tunable dye laser is used to detect the Ga atom spin-orbit states as they scatter or desorb from a metal surface. Thus far, the beam of Ga atoms has been detected with high signal-to-noise, and the ultrahigh vacuum system with complete surface diagnostics has been tested and is working properly. The first experiments will involve measuring the different sticking probabilities of the two spin-orbit states on a clean platinum surface and on a surface already covered with many Ga adlayers. Future experiments will involve measurements of angular desorption and co-deposition of Ga with other semiconductor-relevant materials.

PUBLICATIONS

Quantum Physics Division (525)

(P. M. Williams, A. J. Longmore, K. A. van der Hucht, A. Talavera, W. M. Wamsteker), D. C. Abbott and (C. M. Telesco), "Condensation of dust around the WC7 star HD 192641 (WR 137)," Monthly Notices Roy. Astron. Soc. 215, 23P-29P (1985).

D. C. Abbott, "Current problems of line formation in early-type stars," in Progress in Stellar Spectral Line Formation Theory (J. E. Beckman and L. Crivelli, Eds., Reidel, Dordrecht, 1985), pp. 279-304.

D. C. Abbott and (L. B. Lucy), "Multiline transfer and the dynamics of stellar winds," Astrophys. J. 288, 679-693 (1985).

*G. S. Agarwal, "Finite boundary effects in quantum electrodynamics," in Quantum Electrodynamics and Quantum Optics (A. O. Barut, Ed., Plenum, New York, 1984), pp. 1-13.

*N. Andersen, (T. Andersen, L. Jepsen and J. Macek), "Electron detachment processes in keV H^-, Li^-, Na^-, K^- - rare-gas collisions," J. Phys. B: Atom. Molec. Phys. 17, 2281-2294 (1984).

*N. Andersen, I. V. Hertel and (H. Kleinpoppen), "Shape and dynamics of states excited in electron-atom collisions: Comment on orientation and aligment parameters by consideration of attractive and repulsive forces," J. Phys. B: Atom. Molec. Phys. 17, L901-908 (1984).

*N. Andersen, (T. Andersen, H.-P. Neitzke and E. H. Pedersen), "A coherence study of $2p\sigma - 2p\pi$ rotational coupling: $Li(2^2P)$ and $He(2^1P)$ orientation and alignment in 1-25 keV Li^+-He collisions," J. Phys. B: Atom. Molec. Phys. 18, 2247-2269 (1985).

*W. J. Alford, N. Andersen, K. Burnett and J. Cooper, "Collisional redistribution of light: Far-wing line shapes and polarizations for the Ba-(Ar,Xe) systems," Phys. Rev. A 30, 2366-2380 (1984).

*W. J. Alford, N. Andersen, M. Belslev, J. Cooper, D. M. Warrington and K. Burnett, "Collisional redistribution of circularly polarized light in barium perturbed by argon," Phys. Rev. A 31, 3012-3016 (1985).

NOTE: Names in parentheses are authors who are not connected with JILA-NBS or CU. List does not include JILA publications by JILA CU Fellows and their associates.

*Entries with stars are those resulting from the work of JILA Visiting Fellows.

PUBLICATIONS

Quantum Physics Division (525)

*D. M. Neumark, K. R. Lykke, T. Andersen and W. C. Lineberger, "Laser photodetachment measurement of the electron affinity of atomic oxygen," Phys. Rev. A 32, 1890-1892 (1985).

*(A. C. Raga) and K.-H. Böhm, "Predicted long-slit, high-resolution emission-line profiles from interstellar bow shocks," Astrophys. J. Suppl. 58, 201-224 (1985).

*(E. W. Brugel), K. H. Böhm, J. M. Shull and E. Böhm-Vitense, "The unexpected ultraviolet variability of Herbig-Haro object 1," Astrophys. J. (Letters) 292, L75-78 (1985).

P. L. Bornmann, "A new method for determining temperature and emission measure during solar flares from light curves of soft X-ray line fluxes," Astrophys. J. 293, 595-608 (1985).

A. Brown, "Outer atmospheres of giant and supergiant stars," in Cool Stars, Stellar Systems, and the Sun, Proceedings, Cambridge (USA) 1983 (S. L. Baliunas and L. Hartmann, Eds., Springer-Verlag, Berlin, 1984), pp. 282-295.

K. G. Carpenter, (R. F. Wing) and R. E. Stencel, "Line identifications, line strengths, and continuum flux measurements in the ultraviolet spectrum of Arcturus," Astrophys. J. Suppl. 57, 405-422 (1985).

K. G. Carpenter, A. Brown and R. E. Stencel, "The geometric extent of C II (UV 0.01) emitting regions around luminous, late-type stars," Astrophys. J. 289, 676-680 (1985).

K. G. Carpenter, "Characteristics of the Fe II and C II emission in high-resolution IUE spectra (2300-3000 Å) of Alpha Orionis," Astrophys. J. 285, 181-189 (1984).

A. Brown and K. Carpenter, "The temperature of C II emission line formation regions in cool stars," Astrophys. J. (Letters) 287, L43-46 (1984).

K. G. Carpenter, "Chromospheric emission lines in high-resolution LWR spectra (2200-3000 Å) of Gamma Cru (M3 III) and Alpha Ori (M2 Iab),) in Future in Ultraviolet Astronomy Based on Six Years of IUE Research, NASA Conference Publ. 2349 (1984), pp. 450-453.

K. G. Carpenter, "The structures and spectra of magnetic, line-blanketed model atmospheres," Astrophys. J. 289, 660-668 (1985).

PUBLICATIONS

Quantum Physics Division (525)

*S. Chapman, "Nonadiabatic molecular collisions. II. A further trajectory-surface-hopping study of the ArH_2^+ system," J. Chem. Phys. 82, 4033-4043 (1985).

*(T.-S. Ho, C. Laughlin) and S.-I Chu, "Laser-assisted charge-transfer reactions - Li^{+3} + H: Coupled dressed-quasimolecular-states approach," Phys. Rev. A 32, 122-133 (1985).

*(S. K. Bhattacharya) and S.-I Chu, "The resonant photoionization of hydrogen atom in intense magnetic fields," J. Phys. B: Atom. Molec. Phys. 18, L275-280 (1985).

*R. M. Crutcher, "Optical and radio study of the Taurus molecular cloud toward HD 29647," Astrophys. J. 288, 604-617 (1985).

S. A. Drake, "Modeling lines formed in the expanding chromospheres of red giants," in Progress in Stellar Spectral Line Formation (J. E. Beckman and L. Crivelli, Eds., Reidel, Dordrecht, 1985), pp. 351-359.

(M. S. Pindzola, D. C. Griffin, C. Bottcher, D. C. Gregory, A. M. Howald, R. A. Phaneuf, D. H. Crandall), G. H. Dunn, D. W. Mueller and T. J. Morgan, "Survey of experimental and theoretical electron-impact ionization cross sections for transition metal ions in low stages of ionization," Oak Ridge National Laboratory Tech. Memo 9436 (March 1985).

(T. D. Mark) and G. H. Dunn, Eds., Electron Impact Ionization (Springer-Verlag, Wien, New York, 1985).

(D. C. Gregory, D. H. Crandall, R. A. Phaneuf, A. M. Howald), G. H. Dunn, R. A. Falk, D. W. Mueller and T. J. Morgan, "Electron impact ionization of multicharged ions of ORNL: 1980-1984," Oak Ridge National Laboratory Tech. Memo 9501 (May 1985).

D. W. Mueller, T. J. Morgan, G. H. Dunn, (D. C. Gregory and D. H. Crandall), "Absolute cross-section measurements for electron-impact ionization of doubly charged ions Ti^{2+}, Fe^{2+}, Ar^{2+}, Cl^{2+} and F^{2+}," Phys. Rev. A 31, 2905-2913 (1985).

G. H. Dunn, D. S. Belic, N. Djuric and D. W. Mueller, "Dielectronic recombination," in Atomic Physics 9 (R. S. Van Dyck, Jr. and E. N. Fortner, Eds., World Scientific, Singapore, 1984), pp. 505-522.

G. H. Dunn, "Electron-ion ionization," in Electron Impact Ionization (T. D. Mark and G. H. Dunn, Eds., Springer-Verlag, Wien, New York, 1985), pp. 277-319.

PUBLICATIONS

Quantum Physics Division (525)

D. S. Elliott and (J. F. Ward), "Vibrational mode contributions to molecular third-order polarizabilities," Mol. Phys. 51, 45-63 (1984).

*G. Alber, J. Cooper and P. Ewart, "Theory of resonant degenerate four-wave mixing with broad-bandwidth lasers," Phys. Rev. A 31, 2344-2352 (1985).

*P. Ewart and (S. V. O'Leary), "Absorption and saturation effects on degenerate four-wave mixing in excited states formed during collisions," J. Phys. B: Atom. Molec. Phys. 17, 4595-4608 (1984).

*(A. Charlton) and P. Ewart, "A simple, high power, nanosecond pulse Nd:YAG laser," Opt. Commun. 50, 241-244 (1984).

*P. Ewart and (S. V. O'Leary), "Measurement of relative, extreme-wing absorption coefficients by excited-state degenerate four-wave mixing," J. Phys. B: Atom. Molec. Phys. 17, 4609-4616 (1984).

(T. Marson) and J. E. Faller, "High precision gravity measurements," in Proceedings of the Conference on High Precision Geodetic Measurements (Universita di Bologna, Italy, 1985), pp. 314-328.

M. A. Zumberge, J. E. Faller and R. L. Rinker, "A new, portable, absolute gravimeter," in Precision Measurement and Fundamental Constants II (B. N. Taylor and W. D. Phillips, Eds., NBS Spec. Publ. 617, 1984), pp. 405-409.

(A. J. F. Metherell, C. C. Speake, Y. T. Chen) and J. E. Faller, "Optimizing the shape of the attracting mass in precision measurements of G," in Precision Measurement and Fundamental Constants II (B. N. Taylor and W. D. Phillips, Eds., NBS Spec. Publ. 617, 1984), pp. 581-585.

R. L. Rinker and J. E. Faller, "'Super Spring' -- A long period vibration isolator," in Precision Measurement and Fundamental Constants II (B. N. Taylor and W. D. Phillips, Eds., NBS Spec. Publ. 617, 1984), pp. 411-417.

P. T. Keyser, J. E. Faller and K. H. McLagen, "New laboratory test of the equivalence principle," in Precision Measurement and Fundamental Constants II (B. N. Taylor and W. D. Phillips, Eds., NBS Spec. Publ. 617, 1984), pp. 639-641.

J. E. Faller and P. L. Bender, "A possible laser gravitational wave experiment in space," in Precision Measurement and Fundamental Constants II, (B. N. Taylor and W. D. Phillips, Eds., NBS Spec. Publ. 617, 1984), pp. 689-690.

PUBLICATIONS

Quantum Physics Division (525)

J. E. Faller, J. K. Hoskins, P. T. Keyser and T. M. Niebauer, "Fluid-fiber gradiometers: Their promise for tunnel detection -- A status report," in Tunnel Detection, Proceedings, 2nd Technical Symposium (Colorado School of Mines, Golden, CO, 1984).

H. Chatham, D. Hils, R. Robertson and A. Gallagher, "Total and partial electron collisional ionizatin cross sections for CH_4, C_2H_6, SiH_4 and Si_2H_6," J. Chem. Phys. 81, 1770-1777 (1984).

R. K. Janev and J. W. Gallagher, "Evaluated theoretical cross section data for charge exchange of multiply charged ions with atoms III: Non-hydrogenic target atoms," J. Phys. Chem. Ref. Data 13, 1199-1247 (1984).

(F. Hill), J. Toomre, (L. J. November) and K. B. Gebbie, "On the determination of the lifetime of vertical velocity patterns in mesogranulation," in Small-Scale Dynamical Processes in Quiet Stellar Atmospheres (S. Keil, Ed., National Solar Observatory, Sac. Peak, NM, 1984), pp. 160-172.

J. G. Porter, J. Toomre and K. B. Gebbie, "Frequent ultraviolet brightenings observed in a solar active region with solar maximum mission," Astrophys. J. 283, 879-886 (1984).

S. Geltman and (R. K. Nesbet), "High-energy forward elastic scattering of electrons: Born amplitudes for a pseudostate model of atomic hydrogen," Phys. Rev. A 30, 1636-1642.

S. Geltman, "Multiple ionization of a Hartree atom by intense laser pulses," Phys. Rev. Lett. 54, 1909-1912 (1985).

S. Geltman and G. Leuchs, "Intensity-dependent electron angular distributions in resonant multiphoton ionization," Phys. Rev. A 31, 1463-1469 (1985).

S. Geltman, "Dielectronic recombination as a direct free-bound radiative process," J. Phys. B: Atom. Molec. Phys 18, 1425-1442 (1985)

*D. M. Gibson, "Radio observations of active stars: Direct evidence for polarity reversals?" in Cool Stars, Stellar Systems, and the Sun, Proceedings, Cambridge (USA) 1983 (S. L. Baliunas and L. Hartmann, Eds., Springer-Verlag, Berlin, 1984), pp. 197-201.

PUBLICATIONS

Quantum Physics Division (525)

*E. B. Gliner, "Combined effect of potential and nonpotential magnetic fields on equilibrium in stellar atmospheres," Astrophys. J. 283, 363-372 (1984).

L. Hollberg and J. L. Hall, "Measurement of the shift of Rydberg energy levels induced by blackbody radiation," Phys. Rev. Lett. 53, 230-233 (1984).

W. Ertmer, R. Blatt, J. L. Hall and M. Zhu, "Laser manipulation of atomic beam velocities: Demonstration of stopped atoms and velocity reversal," Phys. Rev. Lett. 54, 996-999 (1985).

P. Nachman, M. D. Rayman and J. L. Hall, "Relativistic time dilation: A latter-day Ives-Stillwell experiment," in Precision Measurement and Fundamental Constants II (B. N. Taylor and W. D. Phillips, Eds., NBS Spec. Publ. 617, 1984), pp. 671-673.

J. L. Hall and (T. W. Hansch), "External dye-laser frequency stabilizer," Opt. Letters 9, 502-504 (1984).

M. W. Hamilton and (W. J. Sandle), "Polarization switching with sodium vapor in a Fabry Perot," in Optical Bistability 2, (C. M. Bowden, H. M. Gibbs and S. L. McCall, Eds., Plenum, New York, 1984), pp. 39-44.

*(A. Bahring), I. V. Hertel, (E. Meyer, W. Meyer, N. Spiess and H. Schmidt), "Excitation of laser state-prepared $Na^*(3p)$ to $Na^*(3d)$ in low-energy collisions with Na^+: Experiment and calculations of the potential curves of Na_2^+," J. Phys. B: Atom. Molec. Phys. 17, 2859-2873 (1984).

*I. V. Hertel and (H. Schmidt), "Comment on 'A theoretical study of coherence effects in charge transfer collisions: Application to Na + Li^+'," J. Chem. Phys. 81, 3361-3362 (1984).

*I. V. Hertel, "Collisions in the presence of a laser field and the laser as a tool for state selective preparation of molecular states in collisions," in Proceedings of the Colloquium on Atomic and Molecular Collisions in a Laser Field," J. Phys. (Paris) 46, C1-37 - C1-41 (1985).

(A. Pauldrach, J. Puls), D. G. Hummer and (R. P. Kudritzki), "A radiation driven stellar wind model atmosphere for the Wolf-Rayet binary V444 Cygni," Astron. Astrophys. (Letters) 148, L1-4 (1985).

D. G. Hummer and (G. B. Rybicki), "The Sobolev approximation for line formation with continuous opacity," Astrophys. J. 293, 258-267 (1985).

PUBLICATIONS

Quantum Physics Division (525)

D. C. Abbott and D. G. Hummer, "Photospheres of hot stars. I. Wind-blanketed model atmospheres," Astrophys. J. 294, 286-302 (1985).

A. Jain and (D. G. Thompson), "Rotational excitation of CH_4 molecules by low-energy positrons," Phys. Rev. A 30, 1098-1100 (1984).

A. Jain and (D. G. Thompson), "EROTVIB, a general program to calculate rotationally and/or vibrationally elastic and inelastic cross sections for electron (positron) scattering by spherical, symmetric and asymmetric top molecules," Computer Phys. Commun. 32, 367-383 (1984).

A. O. Langford and (C. B. Moore), "Reaction and relaxation of vibrationally excited formyl radicals," J. Chem. Phys. 80, 4204-4210 (1984).

A. O. Langford and (C. B. Moore), "Collision complex formation in the reactions of formyl radicals with nitric oxide and oxygen," J. Chem. Phys. 80, 4211-4221 (1984).

H. K. Haugen, E. Weitz and S. R. Leone, "Effect of spin-orbit excitation on chemical reactivity: Laser treatment absorption spectroscopy of $Br(^2P_{1/2}, ^2P_{3/2})$ + IBr reactive dynamics," Chem. Phys. Lett. 119, 75 (1985).

C. A. Wight, D. J. Donaldson and S. R. Leone, "A two-laser pulse-and-probe study of T-R,V energy transfer collisions of H + NO at 0.95 and 2.2 eV," J. Chem. Phys. 83, 660-667 (1985).

G.-H. Lin, J. Maier and S. R. Leone, "Nascent vibrational and rotational distributions from the charge transfer reaction $Ar^+ + CO \rightarrow CO^+ + Ar$ at near thermal energy," J. Chem. Phys. 82, 2 527-5535 (1985).

C. A. Wight, D. J. Donaldson and S. R. Leone, "A two-laser pulse-and-probe study of T-R,V energy transfer collisions of H + NO at 0.95 and 2.2 eV," J. Chem. Phys. 83, 660-667 (1985).

C. E. Hamilton, V. M. Bierbaum and S. R. Leone, "Product vibrational state distributions of thermal energy charge transfer reactions determined by laser-induced fluorescence: $N^+ + CO \rightarrow CO^+$ (v=0-2) + N," J. Chem. Phys. 83, 601-610 (1985).

C. E. Hamilton, V. M. Bierbaum and S. R. Leone, "Product vibrational state distribution of thermal energy charge transfer reactions determined by laser-induced fluorescence in a flowing afterglow: $Ar^+ + CO \rightarrow CO^+$ (v=0-6) + Ar," J. Chem. Phys. 83, 2284-2292 (1985).

PUBLICATIONS

Quantum Physics Division (525)

C. E. Hamilton and S. R. Leone, "Nascent product vibrational state distributions of thermal ion-molecule reactions determined by infrared chemiluminescence," in Gas Phase Chemiluminescence and Chemi-ionization (A. Fontijn, Ed., Elsevier Science Publishers, 1985), pp. 139-156.

K. L. Carleton, K. H. Welge and S. R. Leone, "Detection of nitrogen rotational distributions by resonant 2+2 multiphoton ionization through the $a^1\Pi_g$ state," Chem. Phys. Lett. 115, 492-495 (1985).

S. R. Leone, "State-resolved molecular reaction dynamics," Ann. Rev. Phys. Chem. 35, 109-135 (1984).

L. Hüwell, D. R. Guyer, G.-H. Lin and S. R. Leone, "Laser-induced fluorescence measurement of nascent vibrational and rotational product state distributions in the charge transfer of $Ar^+ + N_2 \rightarrow Ar + N_2^+$ (v=0,1) at 0.2 eV," J. Chem. Phys. 81, 3520-3535 (1984).

C. A. Wight, F. Magnotta and S. R. Leone, "Vibrational energy disposal in reactive and inelastic collisions of H(D) + HCℓ(DCℓ) at 1-3 eV," J. Chem. Phys. 81, 3951-3957 (1984).

S. R. Leone, "Laser probing of chemical reaction dynamics," Science 227, 889-895 (1985).

M. O. Hale and S. R. Leone, "Laser studies of near-resonant state-changing collisions of calcium (4s6s $^1S_0$) with the rare gases," Phys. Rev. A 31, 103-112 (1985).

M. O. Hale, I. V. Hertel and S. R. Leone, "Effects of orbital alignment on inelastic collsions of Ca(4s5p $^1P_1$) with helium," Phys. Rev. Lett. 53, 2296-2299 (1984).

*W. Lichten and (A. Robatino), "A new mechanism for positron production in heavy ion collisions," Phys. Rev. Lett. 54, 781-784 (1985).

J. L. Linsky, A. Brown, M. C. Marstad, (M. Rodono, A. D. Andrews, C. J. Butler and P. B. Byrne), "Models for the active and quiescent regions on the RS CVn-type system II Pegasi (HD 224085)," in Proceedings, Fourth European IUE Conference, 15-18 May 1984, Rome, Italy, ESA SP-218 (July, 1984), pp. 351-354.

PUBLICATIONS

Quantum Physics Division (525)

(P. B. Byrne, J. G. Doyle, A. D. Andrews, C. J. Butler), N. Marstad, J. L. Linsky, T. Simon, (M. Rodono, S. Catalano, C. Blanco, E. Marilli and V. Pazzani), "Rotational modulation of spots and plages on RS CVn stars," in Proceedings, Fourth European IUE Conference, 15-18 May 1984, Rome, Italy, ESA SP-218 (July, 1984), pp. 343-349.

(C. J. Butler, J. G. Doyle, A. D. Andrews, P. B. Byrne), J. L. Linsky, T. Simon, N. Marstad, (M. Rodono, V. Pazzani and G. Cutispoto), "IUE observations of BY Draconis," in Proceedings, Fourth European IUE Conference, 15-18 May 1984, Rome, Italy, ESA SP-218 (July, 1984), pp. 243-246.

(R. Hammer) and J. L. Linsky, "Corona models tested with IUE and Einstein observations," in Proceedings, Fourth European IUE Conference, 15-18 May 1984, Rome, Italy, ESA SP-218 (July, 1984), pp. 25-32.

(M. Rodono, G. Cutispoto, S. Catalano), J. L. Linsky, D. M. Gibson, A. Brown, (B. M. Haisch, C. J. Butler, P. B. Byrne, A. D. Andrews, J. G. Doyle, D. E. Gary, G. W. Henry, G. Russo, A. Vittone, F. Scaltriti and B. Foing), "Coordinated IUE and ground-based observations of active stars: Flare events on YZ CMi, V 1005 Ori, AD Leo and AR Lac," in Proceedings, Fourth European IUE Conference, 15-18 May 1984, Rome, Italy, ESA SP-218 (July, 1984), pp 247-252.

S. A. Drake, A. Brown and J. L. Linsky, "The origin of low-velocity absorption components in the Mg II resonance lines of hybrid-chromosphere stars," Astrophys. J. 284, 774-783 (1984).

J. L. Linsky, "RS CVn binary systems," in Cool Stars, Stellar Systems, and the Sun, Proceedings, Cambridge (USA) 1983 (S. L. Baliunas and L. Hartmann, Eds., Springer-Verlag, Berlin, 1984), pp. 244-258.

S. A. Drake and J. L. Linsky, "Better determinations of mass loss rates for red giants and supergiants," in Cool Stars, Stellar Systems, and the Sun, Procedings, Cambridge (USA) 1983 (S. L. Baliunas and L. Hartmann, Eds., Springer-Verlag, Berlin, 1984), pp. 350-352.

F. M. Walter, J. L. Linsky, (T. Simon, L. Golub and G. S. Vaiana), "Stellar chromospheres and coronae in the Ursa Major cluster stars," Astrophys. J. 281, 815-825 (1984).

(W. B. Landsman, R. C. Henry, H. W. Moos) and J. L. Linsky, "Observations of hydrogen and deuterium toward Alpha Centauri A," Astrophys. J. 285, 801-807 (1984).

PUBLICATIONS

Quantum Physics Division (525)

A. Brown, (C. Jordan), R. E. Stencel, J. L. Linsky and (T. R. Ayres), "High-resolution, far-ultraviolet study of Beta Draconis (G2 Ib-II): Transition region structure and energy balance," Astrophys. J. 283, 731-744 (1984).

A. Brown, (M. V. Penston, R. Johnstone, C. Jordan, N. P. M. Kuin, M. T. V. T. Lago, B. Gross) and J. L. Linsky, "Atmospheric properties of RU Lupi derived from high- and low-resolution IUE spectra," in Future of Ultraviolet Astronomy Based on Six Years of IUE Research, NASA Conference Publ. 2349 (1984), pp. 472-475.

S. A. Drake, A. Brown and J. L. Linsky, "Ultraviolet, radio and X-ray observations of hybrid stars," in Future of Ultraviolet Astronomy Based on Six Years of IUE Research, NASA Conference Publ. 2349 (1984), pp. 472-475.

J. L. Linsky, (T. R. Ayres), A. Brown, K. Carpenter, (C. Jordan, P. Judge, B. Gustafsson, K. Eriksson, M. Saxner, O. Engvold, E. Jensen, O. K. Moe and T. Simon), "A progress report on the analysis of long exposure SWP high resolution spectra of cool stars," in Future of Ultraviolet Astronomy Based on Six Years of IUE Research, NASA Conference Publ. 2349 (1984), pp. 445-449.

(T. R. Ayres, O. Engvold, O. K. Moe, T. Simon, C. Jordan, P. Judge), A. Brown and J. L. Linsky, "Precise measurements of radial velocities of emission lines in the far-ultraviolet spectra of late-type stars," in Future of Ultraviolet Astronomy Based on Six Years of IUE Research, NASA Conference Publ. 2349 (1984), pp. 468-471.

*I. R. Little-Marenin and S. J. Little, "The $^{12}C/^{13}C$ ratio of the carbon star V460 Cygni revisited," Astrophys. J. 283, 188-191 (1984).

*I. Little-Marenin, (T. R. Ayres and T. Simon), "Three short-period binaries as seen at high dispersion: UX Ari, Iota Tri and HR 5110," in Future of Ultraviolet Astronomy Based on Six Years of IUE Research, NASA Conference Publ. 2349 (1984), pp. 404-407.

R. B. Christensen and D. W. Norcross, "Electron-impact excitation of Li II: A model study of wave-function and collisional approximations, and of resonance effects," Phys. Rev. A 31, 142-151 (1985).

A. Jain and D. W. Norcross, "Ab initio calculations of low-energy electron scattering by HCN molecules," Phys. Rev. A 32, 134-143 (1985).

PUBLICATIONS

Quantum Physics Division (525)

R. B. Christensen, D. W. Norcross and A. K. Pradhan, "Electron impact excitation of ions in the magnesium sequence: Fe XV," Phys. Rev. A 32, 93-104 (1985).

(G. D. Meneses), F. J. da Paixao and (N. T. Padial), "Electron impact excitation of krypton," Phys. Rev. A 32, 156-165 (1985).

F. J. da Paixão, N. T. Padial and (G. Czanak), "Electron-photon coincidence parameters for the $4s'[1/2]_1^0(^1P_1)$ and $4s[3/2]_1^0(^3P_1)$ states of argon," Phys. Rev. A 30, 1697-1713 (1984).

H. Tischer and A. V. Phelps, "Rapid collisional quenching of the n = 1, v = 2 level of the $H_2(c^3\Pi_u)$ metastable state by H_2," Chem. Phys. Lett. 117, 550-554 (1985).

A. V. Phelps, "Ionization in gas discharges: Experiment and modeling," in Electron Impact Ionization (T. D. Mark and G. H. Dunn, Eds., Springer-Verlag, Wien, New York, 1985), pp. 335-343.

A. V. Phelps and L. C. Pitchford, "Anisotropic scattering of electrons by N_2 and its effects on electron transport: Tabulations of cross section and results," JILA Information Center Report No. 26 (March 1985).

S. J. Buckman and A. V. Phelps, "Tabulations of collision cross sections and calculated transport and reaction coefficients for electrons in H_2 and D_2," JILA Information Center Report No. 27 (May 1985).

A. V. Phelps and (L. C. Pitchford), "Anisotropic scattering of electrons by N_2 and its effect on electron transport," Phys. Rev. A 31, 2932-2949 (1985).

S. J. Buckman and A. V. Phelps, "Vibrational excitation of D_2 by low energy electrons," J. Chem. Phys. 82, 4999-5011 (1985).

A. K. Pradhan, "Theoretical calculations for dielectronic recombination cross sections," Phys. Rev. A 30, 2141-2144 (1984).

A. K. Pradhan, "Resonance and intermediate-coupling effects in electron scattering with highly charged ions. III. Ca^{18+}," Phys. Rev. A 30, 100-105 (1984).

A. K. Pradhan, "Recombination-cascade X-ray spectra of highly charged helium-like ions," Astrophys. J. 288, 824-830 (1985).

PUBLICATIONS

Quantum Physics Division (525)

A. K. Pradhan and (M. J. Seaton), "Dielectronic recombination. II. Effects on cross sections for inelastic collisions between electrons and atomic ions," J. Phys. B: Atom. Molec. Phys. 18, 1631-1635 (1985).

*A. R. P. Rau, "High excitation of two electrons," in Atomic Physics 9 (R. S. Van Dyck, Jr. and E. N. Fortson, Eds., World Scientific, Singapore, 1984), pp. 491-504.

*A. R. P. Rau, "The electron-electron interaction in doubly-excited states of atoms," Pramana (India) 23, 297-303 (1984).

*G. Alber, J. Cooper and A. R. P. Rau, "Unified treatment of radiative and dielectronic recombination," Phys. Rev. A 30, 2845-2848 (1984).

H. G. Robinson and (C. E. Johnson), "Measured gj-factor ratio of $^4He^+(1^2S_{1/2})$ and $^4He(2^3S_1)$," in Precision Measurement and Fundamental Constants II (B. N. Taylor and W. D. Phillips, Eds., NBS Spec. Publ. 617, 1984), pp. 229-231.

*(P. Botschwina) and P. Rosmus, "An ab initio calculation of spectroscopic properties of SiO and $HOSi^+$," J. Chem. Phys. 82, 1420-1426 (1985).

*K. Rzazewski and R. Grobe, "Saturation of continuum-continuum transitions in multiphoton absorption," Phys. Rev. Lett. 54, 1729 (1985).

*(M. Trippenbach) and K. Rzazewski, "Linear versus nonlinear regime in macroscopic quantum fluctuations of Stokes pulses," Phys. Rev. A 31, 1932-1935 (1985).

*(M. Florjanczyk), K. Rzazewski and (J. Zakrzewski), "Resonance scattering of a short laser pulse on a two-level system: Time-dependent approach," Phys. Rev. A 31, 1558-1562 (1985).

*J. Smak, "Eruptive binaries. XI. Disk-radius variations in U Gem," Acta Astron. 34, 93-96 (1984).

*J. Smak, "Accretion in cataclysmic binaries. IV. Accretion disks in dwarf novae," Acta Astron. 34, 161-189 (1984).

*(J. R. Thorstensen), J. Smak and (F. V. Hessman), "The two periods of TT Arietis," Publ. Astron. Soc. Pacific 97, 437-445 (1985).

D. S. Elliott, M. W. Hamilton, K. Arnett and S. J. Smith, "Correlation effects of a phase-diffusing field on two-photon absorption," Phys. Rev. A 32, 887-895 (1985).

PUBLICATIONS

Quantum Physics Division (525)

D. S. Elliott, M. W. Hamilton, K. Arnett and S. J. Smith, "Two-photon absorption from a phase-diffusing laser field," Phys. Rev. Lett. 53, 439-441 (1984).

P. Zoller, E. Matthias and S. J. Smith, "Configuration interaction in multiphoton ionization," in Quantum Electrodynamics and Quantum Optics (A. O. Barut, Ed., Plenum, New York, 1984), pp. 313-321.

(P. Lambropoulos) and S. J. Smith, Eds., Multiphoton Processes, Proceedings of the 3rd International Conference, Iraklion, Crete, Greece, September 5-12 (Springer-Verlag, 1984).

G. Leuchs and S. J. Smith, "Excited electron correlations in resonant multiphoton ionization via barium Rydberg states," Phys. Rev. A 31, 2283-2290 (1985).

(W. Hagen) and R. E. Stencel, "On the rarity of RX Com stars," Astron. J. 90, 120-122 (1985).

T. Tsubokawa, "A fringe singnal processing method for absolute gravimeter," Metrologia 20, 107-113 (1984).

(C. J. Schrijver, R. Mewe) and F. M. Walter, "Coronal activity in F-, G- and K-type stars II. Coronal structure and rotation," Astron. Astrophys. 138, 258-266 (1984).

F. M. Walter, "Post-T Tauri stars in T associations," in Cool Stars, Stellar Systems, and the Sun, Proceedings, Cambridge (USA) 1983 (S. L. Baliunas and L. Hartmann, Eds., Springer-Verlag, Berlin, 1984), pp. 75-77.

F. M. Walter, J. E. Neff, (B. W. Bopp and R. E. Stencel), "Rotational modulation and high speed streams in FK Comae Berenices: Evidence for a massive, highly-evolved binary system," in Cool Stars, Stellar Systems, and the Sun, Proceedings, Cambridge (USA) 1983 (S. L. Baliunas and L. Hartmann, Eds., Springer-Verlag, Berlin, 1984), pp. 279-281.

F. M. Walter and (L. V. Kuhi), "X-ray photometry and spectroscopy of T Tauri stars," Astrophys. J. 284, 194-201 (1984).

(C. J. Schrijver, R. Mewe) and F. M. Walter, "Coronal structure and rotation in late-type stars," in Cool Stars, Stellar Systems, and the Sun, Proceedings, Cambridge (USA) 1983 (S. L. Baliunas and L. Hartman, Eds., Springer-Verlag, Berlin, 1984), pp. 166-168.

PUBLICATIONS

Quantum Physics Division (525)

*(M. M. Shara, A. F. J. Moffat) and R. F. Webbink, "Unravelling the oldest and faintest recovered nova: CK Vulpeculae (1670)," Astrophys. J. 294, 271-285 (1985).

*R. F. Webbink, "Structure parameters of galactic globular clusters," in Dynamics of Star Clusters, IAU Symposium 113 (J. Goodman and P. Hut, Eds., Reidel, Dordrecht, 1985), pp. 541-577.

*R. F. Webbink, "Eighth North American Workshop on Cataclysmic Variables and Related Systems (Louisiana State University, Baton Rouge, Louisiana, February 27-March 1, 1984)," Comm. Astrophys. 10, 189-198 (1985).

*(J. T. Knudtson) and E. Weitz, "Infrared spectra and bandstrengths of the fundamental and first overtone of HCl and DCl in liquid xenon solutions," J. Chem. Phys. 83, 927-933 (1985).

*(D. R. Burgess, Jr., I. Hussla, P. C. Stair, R. Viswanathan) and E. Weitz, "Pulsed laser induced thermal desorption from surfaces: Instrumentation and procedures," Rev. Sci. Instr. 55, 1771-1776 (1984).

(V. A. Apkarian, J. M. Lindquist) and E. Weitz, "Vibrational energy transfer pathways of CH_3F under weak and strong excitation conditions: A comparison," Chem. Phys. Lett. 112, 328-334 (1984).

*K. H. Welge and (H. Rottke), "Resonant two-photon ionization and dissociation of the hydrogen atom and molecule," in Multiphoton Processes, Proceedings of the 3rd International Conference, Iraklion, Crete, Greece, September 5-12 (P. Lambropoulos and S. J. Smith, Eds., Springer-Verlag, 1984), pp. 151-163.

*(H. Rottke) and K. Welge, "State-selective photoionization and photodissociation spectroscopy of the H_2 molecule from excited states," in Proceedings of the Colloquium on Atomic and Molecular Collisions in a Laser Field, J. Phys. (Paris) 46, C1-127 - C1-134 (1985).

C. A. Wight and (J. L. Beauchamp), "Infrared laser photodetachment of electrons from vibrationally excited allyl anions," J. Phys. Chem. 88, 4426-4430 (1984).

(J. Mlynek, C. Tamm, E. Buhr) and N. C. Wong, "Amplitude- and frequency-modulation Raman heterodyne detection of optical double resonance," J. Opt. Soc. Am. 1, 492-493 (1984).

PUBLICATIONS

Quantum Physics Division (525)

(J. Mlynek, C. Tamm, E. Buhr) and N. C. Wong, "Raman heterodyne detection of radio-frequency resonances in SM vapor: Effects of velocity-changing collisions," Phys. Rev. Lett. 53, 1814-1817 (1984).

(Publications in press)

D. C. Abbott, (J. H. Bieging and E. Churchwell), "Observations of non-thermal emission from early-type stars," in Proceedings, Radio Stars Workshop, Boulder, Colorado, June, 1984 (R. Hjellming and D. Gibson, Eds., Reidel, Dordrecht, in press).

D. C. Abbott, "Wolf-Rayet star atmospheres," (Report for IAU Commission 36) in Reports on Astronomy (in press).

D. C. Abbott, "Thermal radio emission from the winds of single stars," in Proceedings, Radio Stars Workshop, Boulder, Colorado, June, 1984 (R. Hjellming and D. Gibson, Eds., Reidel, Dordrecht, in press).

D. C. Abbott, "The theory of radiation-driven winds from early-type stars," in Proceedings, III Trieste Workshop at Sacramento Peak Observatory (in press).

*N. Andersen, J. W. Gallagher and I. V. Hertel, "Alignment and orientation of atomic outer shells induced by electron and ion ipact: Some recent developments and reamining problems," in Proceedings, Seventh International Conference on Laser Spectroscopy (in press).

*T. Andersen and (S. Mannervik), "Multiply-excited three-electron systems studied by optical emission spectroscopy," Comments At. Mol. Phys. (in press).

*K. R. Lykke, D. M. Neumark, T. Andersen, V. J. Trapa and W. C. Lineberger, "Photodetachment spectroscopy of $^{-}CH_2CN$," in Proc., Seventh International Conference on Laser Spectroscopy (Springer-Verlag, in press).

*T. Andersen, K. R. Lykke, D. M. Neumark and W. C. Lineberger, "Photodetachment spectroscopy of FeO^-," in Invited Papers of the XIVth International Conference on the Physics of Electronic and Atomic Collisions (D. C. Lorents, W. E. Meyerhof and J. R. Petersen, Eds., North-Holland, in press).

PUBLICATIONS

Quantum Physics Division (525)

(in press)

P. L. Bender and (D. R. Larden), "GPS carrier phase ambiguity resolution over long baselines," in Proceedings, First International Symposium on Precise Positioning with the Global Positioning System (in press).

*R. Bilham and (P. Williams), "Sawtooth segmentation and deformation processes on the southern San Andreas fault, California," Geophys. Res. Lett. (in press).

*R. Bilham, "Southern San Andreas fault geometry and fault-zone deformation: Implications for earthquake prediction in the Coachella Valley, California," presented at the National Earthquake Prediction and Evaluation Council, to appear in U. S. Geological Survey Report.

*E. Böhm-Vitense and (C. Proffitt), "Blue companions of Cepheids," Astrophys. J. (in press).

*E. Böhm-Vitense, "Cepheid distances from blue main-sequence companions," Astrophys. J. (in press).

P. L. Bornmann, "Further analysis of temperature and emission measure during the decay phase of solar flares derived from soft X-ray light curves," Solar Phys. (in press).

A. Brown, "Radio continuum emission from T Tauri stars and associated structures," in Proceedings, Cosmical Gas Dynamics Conference (VNU Science Press, in press).

A. Brown, (R. Mundt) and S. A. Drake, "Radio continuum emission from pre-main sequence stars and associated structures," in Proceedings, Radio Stars Workshop, Boulder, Colorado, June, 1984 (R. Hjellming and D. Gibson, Eds., Reidel, Dordrecht, in press).

*S.-I Chu, "Multiphoton processes in intense laser fields," in Proceedings, Workshop on Atomic Spectroscopy and Its Related Dynamical Properties (Instit. of Atomic and Molecular Science and National Tsing-Hua University in Taiwan, R. O. C., June 23-25, 1984, in press).

*S.-I Chu and J. Cooper, "Threshold shift and above threshold multiphoton ionization of atomic hydrogen in intense laser fields," Phys. Rev. A. (in press).

PUBLICATIONS

Quantum Physics Division (525)

(in press)

*S.-I Chu, "Dynamics and symmetries in intense field multiphoton processes: Floquet theoretical approaches," in Advances in Multi-Photon Processes and Spectroscopy (World Scientific, Singapore, in press).

G. H. Dunn, D. S. Belic, B. DePaola, N. Djuric, D. Mueller, A. Müller and C. Timmer, "Field effects on Rydberg product state distribution from dielectronic recombination," in Atomic Excitation and Recombination in External Fields (M. H. Nayfeh and C. W. Clark, Eds., Harwood, in press).

T. M. Niebauer, J. K. Hoskins and J. E. Faller, "Absolute gravity: A reconnaissance tool for studying vertical crustal motions," in Proceedings, Chapman Conference on Vertical Crustal Motions: Measurement and Modeling, J. Geophys. Res. (in press).

J. E. Faller, P. L. Bender, J. L. Hall, D. Hils and M. A. Vincent, "Space antenna for gravitational wave astronomy," in Proceedings, Radio Stars Workshop, Boulder, Colorado, June, 1984 (R. Hjelming and D. Gibson, Eds., Reidel, Dordrecht, in press).

H. Chatham and A. Gallagher, "Ion chemistry in silane dc discharges," J. Appl. Phys. (in press).

A. Gallagher, "Silane discharge gas and surface reactions," in Proceedings, Materials Research Society (in press).

M. O'Callaghan, A. Gallagher and (T. Holstein), "Absorption and emission of radiation in the region of an avoided level crossing," Phys. Rev. A (in press).

B Stumpf and A. Gallagher, "Electron excitation of Na(3S) and Na(3P) atoms to the Na(3D) state," Phys. Rev. A (in press).

A. K. Pradhan and J. W. Gallagher, "Atomic data for electron-impact excitation of ions," in Proceedings, Conference on Low Energy Electron Excitation Data (in press).

(T. J. Morgan, R. E. Olson, A. S. Schlachter) and J. W. Gallagher, "Charge transfer of hydrogen ions and atoms in metal vapors," J. Phys. Chem. Ref. Data (in press).

PUBLICATIONS

Quantum Physics Division (525)

(in press)

*(V. A. Osherovich), E. B. Gliner, (I. Tzur and M. L. Kuhn), "The magnetic and thermodynamic structure of a polar coronal hole," Solar Phys. (in press).

W. C. Wong and J. L. Hall, "Servo control of amplitude modulation in FM spectroscopy: Shot-noise limited measurement of water vapor pressure broadening," in Proceedings, Seventh International Conference on Laser Spectroscopy (in press).

D. A. Harmin, "Hydrogenic treatment of stark effects in Rydberg atoms," in Atomic Excitation and Recombination in External Fields (M. H. Nayfeh and C. W. Clark, Eds., Harwood, in press).

*I. V. Hertel, (H. Schmidt, A. Bahring and E. Meyer), "Angular momentum transfer and charge cloud alignment in atomic collisions: Intuitive concepts, experimental observations and semiclassical models," Rep. Progr. Phys. (in press).

(A. A. Kutepov), D. G. Hummer and (C. B. Moore), "Rotational relaxation of the 00(0)1 level of CO_2 including radiative transfer in the 4.3 micron band of planetary atmospheres," J. Quant. Spectrosc. Radiat. Transfer (in press).

(R. P. Kudritzki) and D. G. Hummer, "Intrinsic parameters of hot blue stars," in Luminous Stars and Associations in Galaxies, IAU Symposium 116 (Reidel, Dordrecht, in press).

(T. Gehren, D. Husfeld, R. P. Kudritski), P. S. Conti and D. G. Hummer, "Non-LTE analysis of massive stars in the Magellanic Clouds," in Luminous Stars and Associations in Galaxies, IAU Symposium 116 (Reidel, Dordrecht, in press).

A. Jain, "Some theoretical aspects of positron and electron scattering by molecules," in Third International Workshop on Positron (Electron) Gas Scattering (in press).

A Jain, "Positron scattering by NH_3 and H_2O molecules below positronium formation threshold," in Third International Workshop on Positron (Electron) Gas Scattering (in press).

PUBLICATIONS

Quantum Physics Division (525)

(in press)

H. K. Haugen, E. Weitz and S. R. Leone, "Accurate quantum yields by laser gain-versus-absorption spectroscopy: Investigation of Br/Br* channels in photofragmentation of Br_2 and IBr," J. Chem. Phys. (in press).

A. O. Langford, V. M. Bierbaum and S. R. Leone, "Auroral implications of recent measurements on $O(^1S)$ and $O(^1D)$ formation in the reaction of N^+ with O_2," Planetary Space Sci. (in press).

A. O. Langford, V. M. Bierbaum and S. R. Leone, "Flowing afterglow infrared chemiluminescence studies of vibrational energy disposal in the ion-molecule reactions $F^- + HBr,DBr \rightarrow HF,DF, + Br^-$," J. Chem. Phys. (in press).

D. Neuschafer, M. O. Hale, I. V. Hertel and S. R. Leone, "Energy transfer processes of aligned excited states of Ca atoms," in Invited Papers of the XIVth International Conference on the Physics of Electronic and Atomic Collisions (D. C. Lorents, W. E. Meyerhof and J. R. Petersen, Eds., North-Holland, in press).

*W. Lichten, "What causes the sharp positron spectrum in heavy atom collisions? The atomic hypothesis," in Proceedings, Atomic Theory Workshop (Am. Inst. Phys., in press).

S. H. Saar and J. L. Linsky, "The magnetic field of the BY Draconis flare star EQ Virginis," Astrophys. J. (in press).

S. A. Drake, (T. Simon) and J. L. Linsky, "A VLA radio continuum survey of active late-type giants in binary systems: Preliminary results," in Proceedings, Radio Stars Workshop, Boulder, Colorado, June, 1984 (R. Hjellming and D. Gibson, Eds., Reidel, Dordrecht, in press).

S. A. Drake, D. C. Abbott, (J. H. Bieging, E. Churchwell) and J. L. Linsky, "VLA observations of A and B stars with kilogauss magnetic fields," in Proceedings, Radio Stars Workshop, Boulder, Colorado, June, 1984 (R. Hjellming and D. Gibson, Eds., Reidel, Dordrecht, in press).

J. L. Linsky, "Definition and empirical structure of the range of stellar chromospheres-coronae across the H-R diagram: Cool stars," in Proceedings, III Trieste Workshop, National Solar Observatory (in press).

PUBLICATIONS

Quantum Physics Division (525)

(in press)

J. L. Linsky, "Observed and computed stellar line profiles: The roles played by partial redistribution, geometrical extent and expansion," in Proceedings, Workshop on Stellar Spectral Line Formation (in press).

J. L. Linsky, "Beyond Lyman Alpha: The new frontier in ultraviolet spectroscopy," Comments Astrophys. (in press).

*T. M. Miller, "Electron affinities," in CRC Handbook of Chemistry and Physics (in press).

*T. M. Miller, "Atomic and molecular polarizabilities," in CRC Handbook of Chemistry and Physics (in press).

A. K. Pradhan, "Review of electron impact excitation data for the helium sequence," in Proceedings, Conference on Low Energy Electron Excitation Data (in press).

A. K. Pradhan, "Improved excitation rate coefficients for the n=2 and n=3 levels of Ca XIX and Fe XXV including fine structure," Astrophys. J. Suppl. (in press).

A. K. Pradhan and J. W. Gallagher, "Atomic data for electron-impact excitation of ions," in Proceedings, Conference on Low Energy Electron Excitation Data (in press).

*(H. J. Werner) and P. Rosmus, "Ab initio calculations of radiative transition probabilities in diatomic molecules," in Comparison of the ab initio Calculations with Experiments -- State of the Art (R. Bartlett, Ed., Reidel, in press).

*(J. Senekowitsch, H.-J. Werner), P. Rosmus and S. V. ONeil, "Ab initio calculations of radiative transition probabilities in SH, SH^+ and SH^-," J. Chem. Phys. (in press).

D. S. Elliott, M. W. Hamilton, K. Arnett and S. J. Smith, "The structure of the thermal modes in pulsating stars," Astrophys. J. (in press).

G. Leuchs, G. Alber and S. J. Smith, "Competition between photoionization and two-photon Raman coupling," in Proceedings, Seventh International Conference on Laser Spectroscopy (in press).

PUBLICATIONS

Quantum Physics Division (525)

(in press)

*R. F. Webbink, "Epsilon Aurigae in an evolutionary context," in _Proceedings, North American Workshop on the Recent Eclipse of Epsilon Aurigae_ (in press).

(Publications submitted)

D. C. Abbott, (J. H. Bieging, E. Churchwell) and A. V. Torres, "Radio emission from galactic Wolf-Rayet stars and the structure of Wolf-Rayet winds," Astrophys. J. (submitted).

D. C. Abbott, (J. H. Bieging, E. Churchwell) and A. V. Torres, "Radio emission from galactic Wolf-Rayet stars and the structure of Wolf-Rayet winds," Astrophys. J. (submitted).

*D. M. Neumark, K. R. Lykke, T. Andersen and W. C. Lineberger, "Infrared spectrum and autodetachment dynamics of NH^-," J. Chem. Phys. (submitted).

*T. Andersen, K. R. Lykke, D. M. Neumark and W. C. Lineberger, "Photodetachment spectroscopy of FeO^- autodetaching resonances," J. Chem. Phys. (submitted).

*(E. Gottwald, A. Mattheus), K. Bergmann and (R. Schinke), "Angularly resolved vibrational excitation in Na_2-He collisions," J. Chem. Phys. (submitted).

*E. Böhm-Vitense, "Theory of transition layers and coronae emission measures," Astrophys. J. (submitted).

*E. Böhm-Vitense, "Analysis of the transition layer and corona of Procyon," Astrophys. J. (submitted).

*E. Böhm-Vitense, "Analysis of the solar transition layer and corona," Astrophys. J. (submitted).

*E. Böhm-Vitense, "The Cepheid mass problem and Cepheid binaries," Astrophys. J. (submitted).

PUBLICATIONS

Quantum Physics Division (525)

(submitted)

*E. Böhm-Vitense, "A simple explanation for the Linsky-Haisch boundary line for transition layers," Astrophys. J. (submitted).

P. L. Bornmann, "Turbulence as a proposed intermediate energy storage mechanism during solar flares," Astrophys. J. (submitted).

*M. Kimura, S. Chapmanand N. F. Lane, "Electron capture in $Ar^{+} + H_2$ collisions in keV energy regime," Phys. Rev. A (submitted).

*(T.-S. Ho) and S.-I Chu, "Floquet-Liouville super-matrix approach for multiphoton processes in polychromatic fields," Phys. Rev. Lett. (submitted).

*T.-S. Ho, K. Wang) and S.-I Chu, "Floquet-Liouville super-matrix approach: Time-development of density matrix operator and multiphoton resonance fluorescence spectra in intense laser fields," Phys. Rev. A (submitted).

*(K. Wang, T.-S. Ho) and S.-I Chu, "Multiphoton dynamics and resonance lineshapes in three-level systems: Many-mode Floquet treatment," J. Phys. B: Atom. Molec. Phys. (submitted).

(D. H. Crandall, R. A. Phaneuf, D. C. Gregory, A. M. Howald), D. W. Mueller, T. J. Morgan, G. H. Dunn and (R. J. W. Henry), "electron impact ionization of B^{2+} and O^{5+}: Excitation-autoionization in Li-like atoms," Phys. Rev. A (submitted).

J. A. Luine and G. H. Dunn, "Ion-molecule reaction probabilities near 10 K," Astrophys. J. (Letters) (submitted).

A. Muller, D. S. Belic, B. D. DePaola, N. Djuric, G. H. Dunn, D. W. Mueller and C. Timmer, "field effects on the Rydberg product state distribution from dielectronic recombination," Phys. Rev. Lett. (submitted.)

S. E. Barlow, J. B. Jeffries, J. Cooper and G. H. Dunn, "Observation and modeling of cylindrically symmetric, cooperative density waves in an ion cloud stored in a hypterbolic penning trap," Phys. Fluids (submitted).

(J. J. Snyder, T. B. Lucatorto, P. H. Debenham) and S. Geltman, "Ultra-sensitive laser isotope analysis in an ion storage ring," J. Opt. Soc. Am. B. (submitted).

PUBLICATIONS

Quantum Physics Division (525)

(submitted)

A. O. Langford, V. M. Bierbaum and S. R. Leone, "Branching ratios for electronically excited oxygen atoms formed in the reaction of N^+ with O_2 at 300 K," J. Chem. Phys. (submitted).

D. J. Donaldson and S. R. Leone, "Absolute rate coefficients for methyl radical reactions by laser photolysis, time-resolved infrared chemiluminescence: $CD_3 + HX \rightarrow DC_3H + X$ (X-Br,I)," J. Chem. Phys. (submitted).

*W. Lichten, "Precise wavelength measurements and optical phase shifts. II. Applications," J. Opt. Soc. Am. (submitted).

J. L. Linsky, "Nonradiative activity across the H-R diagram: Which types of stars are solar-like?" Solar Phys. (submitted).

(W. B. Landsman, J. Murthy, R. C. Henry, H. W. Moos), J. L. Linsky and (J. L. Russell), "IUE observations of interstellar hydrogen and deuterium toward Alpha Cen B," Astrophys. J. (submitted).

S. H. Saar and J. L. Linsky, "The photospheric magnetic field of the DM3.5e flare star AD Leo," Astrophys. J. (Letters) (submitted).

(C. Jordan), A. Brown, F. M. Walter and J. L. Linsky, "The outer atmosphere of Procyon (Alpha CMI F5 IV-V): Evidence of supergranulation or active regions," Monthly Notices Roy. Astron. Soc. (submitted).

S. A. Drake and J. L. Linsky, "Radio continuum emission from winds, chromospheres and coronae of cool giants and supergiants," Astrophys. J. (submitted).

*I. R. Little-Marenin, (T. Simon, T. R. Ayres, N. L. Cohen, P. A. Feldman), J. L. Linsky, (S. J. Little and R. Lyons), "Ultraviolet, optical, infrared, and microwave observations of HR 5110," Astrophys. J. (submitted).

D. W. Muellerand (D. H. Jaecks), "Polarized photon-scattered particle correlation measurements in H^+ + He collisions," Phys. Rev. A (submitted).

A. Müller, "Multiple ionization and the charge state evolution of ions exposed to electron impact," Phys. Letters A. (submitted).

*G. A. Natanson, "Relationship between least-squares and natural collision coordiantes," J. Chem. Phys. (submitted).

PUBLICATIONS

Quantum Physics Division (525)

(submitted)

*T. Uzer, G. Natanson, and (J. T. Hynes), "Coriolis-induced intramolecular vibrational energy flow between anharmonic normal modes," Chem. Phys. Lett. (submitted).

*G. A. Natanson, "Selection rules for rotational excitation of polyatomic molecules by slow electron impact," J. Phys. B: Atom. Molec. Phys. (submitted).

*G. A. Natanson, "Analytical formula for direction cosines of the Eckart frame of a planar molecule," Chem. Phys. Lett. (submitted).

*G. A. Natanson, "Comment on 'Rotational energy surfaces and high-J eigenvalue structure of polyatomic molecules,'" J. Chem. Phys. (submitted).

(P. Lee, A. J. Lieber, R. P. Chase) and A. K. Pradhan, "Helium-like titanium spectra produced by electron-cyclotron-heated tokomak plasmas," Phys. Rev. Lett. (submitted).

*R. Grobe, G. Leuchs and K. Rzazewski, "Migration of population to higher angular momentum Rydberg states through the degenerate Raman coupling," Phys. Rev. A (submitted).

*K. Rzazewski and J. Cooper, "Autoionization in a fluctuating electric field," J. Opt. Soc. Am. B (submitted).

*K. Rzazewski, "Laser induced fluctuations in single photon ionization," Phys. Rev. A (submitted).

*K. Rzazewski and R. Grobe, "Angular momentum distribution of electrons in above threshold ionization," Phys. Rev. Lett. (submitted).

1984-1985 VISITING FELLOWS

Quantum Physics Division (525)

Visiting Fellow	Home Institution	Area of Work
Torkild Andersen	Institute of Physics University of Aarhus Aarhus, Denmark	Dynamics & structure of negative ions; photodissociation or detachment processes of molecular ions by coaxial ion beam techniques.
Klaas Bergmann	Fachbereich Physik der Universität Kaiserslautern Kaiserslautern, West Germany	State-to-state collision dynamics & quantum optics.
Roger Bilham	Lamont Doherty Geological Observatory Columbia University Palisades, NY	The development of improved geodetic measurement capability, including the use of GPS satellites.
Karl-Heinz Böhm	Astronomy Department University of Washington Seattle, WA	Herbig-Haro objects & relatively cool degenerate stars.
Erika Böhm-Vitense	Astronomy Department University of Washington Seattle, WA	Mixing length theory of convection, stellar chromospheres coronae & transition layers.
Shih-I Chu	Department of Chemistry University of Kansas Lawrence, KS	Atomic & molecular collisions, laser physics & molecular astrophysics.
William Lichten	J. W. Gibbs Laboratory Yale University New Haven, CT	Precision laser research.
Thomas M. Miller	Dept. of Physics & Astronomy University of Oklahoma Norman, OK	Laser spectroscopy; atomic & molecular physics.

1984-1985 VISITING FELLOWS

Quantum Physics Division (525)

Visiting Fellow	Home Institution	Area of Work
Alfred Müller	Institut für Kernphysik Universität Giessen Giessen, West Germany	Inelastic electron-ion collisions; formation of intermediate states decaying by electron &/or photon emission.
Grigory A. Natanson	Department of Chemistry The University of Chicago Chicago, IL	Calculations of ro-vibrational energy levels.
Pavel Rosmus	Fachbereich Chemie der J. W. Goethe-Universität Frankfurt am Main West Germany	Quantum chemistry; esp. radiative transition probabilities & potential energy surfaces.
Kazimierz Rzazewski	Institut Fizyki Teoretycznij PAN Warszawa, Poland	Theoretical research in quantum optics; spectra of electrons & photons induced by smooth pulses.
Ronald F. Webbink	Department of Astronomy University of Illinois Urbana, IL	Evolutionary status of symbiotic stars.

1984-1985 RESEARCH FELLOWSHIP FOR TEACHERS

Sally Chapman	Barnard College Columbia University New York, NY	Dynamics of molecular Collisions.

1985-1986 VISITING FELLOWS

Quantum Physics Division (525)

Visiting Fellow	Home Institution	Area of Work
James N. Bardsley	University of Pittsburgh Pittsburgh, PA	Atoms in strong oscillatory fields and non-equilibrium phenomena in ionized gases.
Michael J. Barlow	Department of Physics & Astronomy University College London London, United Kingdom	Properties of hot stars, physical properties of circumstellar and interstellar dust.
Pierre Connes	Service d'Aéronomie du CNRS Verrières-le-Buisson France	High precision spectroscopic techniques and their applications to astronomy and to fundamental physics experiments.
Paul C. Engelking	Department of Chemistry University of Oregon Eugene, OR	Dipole interactions of molecules with electrons.
Ivan Hubeny	Astronomical Institute Czechoslovak Academy of Sciences Ondrejov, Czechoslovakia	Stellar atmospheres. atomic processes, line scattering, numerical simulations.
Francis Perkins, Jr.	Plasma Physics Laboratory Princeton University Princeton, NJ	Magneto-hydrodynamic theory and its applications to solar physics, magnetic fusion and astrophysics.
Weston J. Sandle	University of Otago Dunedin New Zealand	Optical bistability.
Craig L. Sarazin	Leander McCormick Obs. University of Virginia Charlottesville, VA	Cooling flows in clusters of galaxies.

1985-1986 VISITING FELLOWS

Quantum Physics Division (525)

Visiting Fellow	Home Institution	Area of Work
John P. Simons	Department of Chemistry University of Utah Salt Lake City, UT	Electronic structure of negative molecular ions; dynamical behavior of anions.
Sumner G. Starrfield	Department of Physics Arizona State University Tempe, AZ	Study of the nova outburst; evolution of both nova explosions and the hottest known pulsating variable stars.
Peter E. Toschek	I. Institut für Experimentalphysik Universität Hamburg Hamburg, West Germany	Laser spectroscopy; cooling and study of trapped ions.
John Weiner	Department of Chemistry University of Maryland College Park, MD	Inelastic collision dynamics in simple systems.

1985-1986 RESEARCH FELLOWSHIP FOR TEACHERS

Jo Allan Beran	Texas A & I University Kingsville, TX	Environmental chemistry.

1985-1986 NBS/JILA EXCHANGE FELLOW

Daniel E. Kelleher	Atomic &.Plasma Radiation Division Center for Radiation Res. National Bureau of Standards Gaithersburg, MD	Theoretical plasma spectroscopy problems.

SCIENTISTS WORKING AT JILA ON SABBATICAL OR OTHER LEAVE
(Other than Visiting Fellows)

Quantum Physics Division (525)

M. C. Begelman	John Hanley California Institute of Technology Pasadena, CA
P. L. Bender	Feridoun Rabet University of Tabriz, Iran
P. S. Conti	Huib Henrichs Astronomical Institute University of Amsterdam The Netherlands
	H.J.G.L.M. Lamers Space Research Laboratory Utrecht, The Netherlands
J. Cooper	D. M. Warrington University of Otago Dunedin, New Zealand
G. H. Dunn	D. S. Belic Belgrade University Belgrade, Yugoslavia
	Ratko Janev Belgrade Univesity Belgrade, Yugoslavia
J. E. Faller	Igenio Marsson University of Trieste Trieste, Italy
J. W. Gallagher Data Center	T. J. Morgan Department of Physics Weslyan University Middletown, CT
	Nils Andersen H. C. Orsted Institute Copenhagen, Denmark

SCIENTISTS WORKING AT JILA ON SABBATICAL OR OTHER LEAVE
(Other than Visiting Fellows)

Quantum Physics Division (525)

Gallagher (cont.)	Ingolf V. Hertel Institut fur Molekulphysik Freie Universitat Berlin Berlin, West Germany
	Douglas O. Heddle Department of Physics Royal Holloway College University of London, U.K.
	Jeffrey I. Steinfeld Department of Chemistry Massachusetts Institute of Technology Cambridge, MA
S. Geltman	Leonard Rosenberg Department of Physics New York University New York, NY
J. L. Hall	Christian Borde Laboratoire de Spectroscopie Paris, France
	Jean-Marie Chartier Bureau International des Poids et Mesures Sevres, France
	H. Jeff Kimble University of Texas at Austin
	Christophe Salomon University of Paris - Nord France
	Wang Yiqui Peking University People's Republic of China
S. R. Leone	Susan Kohler (NSF Visiting Professorship for Women) Mount Holyoke College South Hadley, MA

SCIENTISTS WORKING AT JILA ON SABBATICAL OR OTHER LEAVE
(Other than Visiting Fellows)

Quantum Physics Division (525)

Leone (cont.)	Richard Schwenz (NSF Summer Faculty Fellowship) University of Northern Colorado Greeley, CO
J. Levine	V. Levshenko U.S.S.R.
	A. Sadovsky U.S.S.R.
W. C. Lineberger	H. Hotop University Kaiserslautern Kaiserslautern, West Germany
	Wolfgang Kamke Free University of Berlin West Germany
J. L. Linsky	Erik Eason University of Washington Seattle, WA
	Ake Nordlund Copenhagen University Copenhagen, Denmark
	Osmi Vilhu University of Helsinki Helsinki, Finland
	Israel Oznovich New Mexico Institute for Mining & Technology
	Hugh Deasy Trinity College Dublin, Northern Ireland
	Varda Bar The Amos De-Shalit Science Teaching Center in Israel The Hebrew University of Jerusalem Jerusalem, Israel

SCIENTISTS WORKING AT JILA ON SABBATICAL OR OTHER LEAVE
(Other than Visiting Fellows)

Quantum Physics Division (525)

R. A. McCray	Timothy Kallman NASA - Goddard Space Flight Center Greenbelt, MD
A. V. Phelps	Sanichiro Yoshida Keio University Yokohama, Japan
S. J. Smith	George Basbas, Editor Physical Review & Physical Review Letters Ridge, NY
	Arnold Russek University of Connecticut Storrs, CT
	Gerd Leuchs Max-Planck Institute West Germany
	Dan Elliott Purdue University Lafayette, IN
	Harold Metcalf SUNY, Stony Brook New York
	Murray Hamilton Universitat Munchen West Germany
J. Toomre	Douglas Gough Institute of Astronomy Cambridge, England
	Joseph Massaguer University of Barcelona Barcelona, Spain

SCIENTISTS WORKING AT JILA ON SABBATICAL OR OTHER LEAVE
(Other than Visiting Fellows)

Quantum Physics Division (525)

Toomre (cont.)	Michael Proctor Department Applied Mathematics & Theoretical Physics University of Cambridge Cambridge, England
	Edgar Knobloch Department of Physics University of California, Berkeley Berkeley, California

CONFERENCES SPONSORED

Quantum Physics Division (525)

Physical Chemistry Workshop - Involved several of the Adjoints and took place largely in JILA, June 24-26, 1985. Drs. D. J. Nesbitt and B. Koel organizers.

SEMINARS AND COLLOQUIA

Quantum Physics Division (525)

Informal Seminars

Ronald F. Webbink (JILA) - Close Binaries as Sources of Gravitational Waves, March 4, 1985.

Mark Levenson (IBM, San Jose) - Brillioun Scattering in Optical Fibers, March 21, 1985.

Des Muller (Griffith University) - Low Energy Collisional Relaxation of Vibrational States in Polyatomic Molecules, July 1, 1985.

Horst Heydtmann (Johann Wolfgang Goethe-Universitat) - Energy Disposal in F Atom Reaction, July 3, 1985.

C. J. Bordé (Universite of Paris Nord) - Gravitational Wave Detection Using Non-Linear Optical Spectroscopy of Atoms, August 7, 1985.

George Basbas (Editor of Physical Review Letters) - How PRL Works, October 1, 1985.

Special JILA Seminars

T. Baer (Spectra Physics) - Femto-Second Pulse Generation Using Nonlinear Effects in Single-Mode Optical Fibers, October 15, 1984.

Howard Taylor (University of Southern California) - New Methods of Spectral Assignment in Atoms and Molecular Systems, November 15, 1984.

A. Adam (University of Waterloo) - Coherent Infrared Laser Stark Spectroscopy of CH_3F in a Molecular Beam, May 10, 1985.

C. H. Kuo (University of Oregon) - Laser Induced Charge Exchange Spectroscopy of N_2^+ and CO^+, May 21, 1985.

A. W. Castelman, Jr. (Pennsylvania State University) - Studies of Ionic Clusters, June 6, 1985.

Bärbel Maessen (University of California, Irvine) - Variational Calculations of Vibrational-Rotational States in Water and Formaldehyde, June 6, 1985.

Arnold Russek (University of Connecticut) - Post Collision Interaction and the Auger Lineshape, June 10, 1985.

Special JILA Seminars (cont.)

Lynn Westling (Institute of Optics, University of Rochester) - Intensity Fluctuations in Multi-Mode Dye Lasers, June 14, 1985.

Philip Arcuni (University of Chicago) - Decay of He^{**} After Fast, Changed-Ion Excitation, June 25, 1985.

Alain Aspec (Institute of Optics, Paris) - Quantum Mechanical Interferometry With Atoms, July 2, 1985.

Ken'ichi Nomoto (University of Tokyo) - White Dwarf Models for Type I Supernovae, July 2, 1985.

Y. Z. Wang (Shanghai Institute of Optics and Fine Mechanics) - Photon Statistics By Atomic Beam Deflection, July 8, 1985.

Fucheng Lin (Shanghai Institute of Optics and Fine Mechanics) - Interactions of Intense Laser Fields With Atoms, July 9, 1985.

H. Takuma (Institute For Laser Science, Tokyo) - Preparation of Pure Excited States By Laser Raman Scattering, July 22, 1985.

JILA Colloquia

Burton Rowe (Laboratoire d'Aerothermique) - Ion-Molecule Reaction Measurements At Very Low Temperatures, October 16, 1984.

Duane H. Jaecks (University of Nebraska) - Excitation and Molecular Dissociation Mechanisms in Diabatic H_3^+/H_2^+-He Collisions, October 23, 1984.

Karl Welge (JILA Visiting Fellow) - VUV Laser Spectroscopy - Photoionization and Photodissociation Processes, October 30, 1984.

JILA Colloquia (cont.)

Hartmut Hotop (University of Kaiserslautern) - Photoionization of Laser-Excited Rare Gas Atoms, November 6, 1984.

Alfred Mueller (JILA Visiting Fellow) - Electron Impact Ionization of Ions, January 29, 1985.

Torkild Anderson (JILA Visiting Fellow) - Fast Beam Spectroscopy of Doubly Excited States in Few Electron Systems, February 12, 1985.

Shih-I Chu (JILA Visiting Fellow, University of Kansas) - Multiphoton Processes In Intense Fields, February 19, 1985.

Grigory Natanson (JILA Visiting Fellow, University of Chicago) - Nontrivial Aspects in the Symmetry Theory of Polyatomic Molecules, February 26, 1985.

Takeshi Oka (University of Chicago) - Infrared Spectroscopic Studies of Molecular Ions, March 12, 1985.

Kazimierz Rzazewski (JILA Visiting Fellow, Instytut Fizyki Teoretycznij PAN) - Spectra of Strong Field Resonance Fluorescence, March 19, 1985.

Theodore Hänsch (Stanford University) - High Resolution Laser Spectroscopy of the Hydrogen Atom, April 9, 1985.

Dieter Meschede (Yale University) - Rydberg Atoms and Radiation Interaction, April 16, 1985.

Aram Mooradian (Lincoln Laboratories, MIT) - Semiconductor Lasers: Spectral Properties and Applications, May 7, 1985.

David E. Pritchard (Lincoln Laboratories, MIT) - State Resolved Studies of Vibration-Rotation Energy Transfer, May 14, 1985

Klaas Bergmann (JILA Visiting Fellow, Universität Kaiserslautern) - Optically Pumped Supersonic Beam Lasers: Concept and Possible Applications, September 10, 1985.

Paul Engelking (JILA Visiting Fellow, University of Oregon) - CH_3O Radical Emission Spectroscopy, September 24, 1985.
Joint JILA/Physics Colloquium

SEMINARS AND COLLOQUIA

Quantum Physics Division (525)

William Lichten (Yale University) - The Rydberg Constant, November 7, 1984.

Joint JILA/Astrophysics, Planetary and Astronomical Sciences Colloquia

Bernard F. Burke (MIT) - Interferometry of All Scales, October 1, 1984.

Douglas O. Gough (University of Cambridge) - Helioseismology: The Rotation and Internal Stratification of the Sun, October 2, 1984.

Marc Aaronson (Steward Observatory, University of Arizona) - A New Distance to the Large Magellanic Cloud by Main Sequence Fitting, October 15, 1984.

Juri Toomre (APAS/JILA) - Solar Five-Minute Oscillations Used to Probe Giant Cells Below the Surface, October 29, 1984.

Richard McCray (APAS/JILA) - Supernovae and Propagating Star Formation, November 5, 1984.

Ron Webbink (JILA Visiting Fellow, University of Illinois) - Old Novae, November 13, 1984

John F. Hawley (Caltech) - Hydrodynamics Around Black Holes: Supercomputer Experiments and a Movie|, November 19, 1984.

Anil Pradhan (JILA) - Atomic Processes in Fusion and Astrophysical Plasmas, November 20, 1984.

George Fuller (University of California, Santa Cruz) - Evolution of Supermassive Stars, November 26, 1984.

George Fuller (University of California, Santa Cruz) - Nuclear Physics of Stellar Collapse, November 27, 1984.

Craig Hogan (Caltech) - Astrophysics of Cosmic Strings, December 3, 1984.

SEMINARS AND COLLOQUIA

Quantum Physics Division (525)

Joint JILA/Astrophysics, Planetary and Astronomical Sciences Colloquia (cont.)

Jack Brandt (Goddard Space Flight Center) - The ICE (International Cometary Explorer) Mission To Comet Giacobini-Zinner: The First Comet Mission, December 10, 1984.

Karl-Heinz Böhm (JILA Visiting Fellow; University of Washington) - Circumstellar Gas Dynamics of Young Stars: High Resolution Studies of Herbig-Haro Objects, February 5, 1985.

Erika Böhm-Vitense (JILA Visiting Fellow, University of Washington) March 1985.

Julian H. Krolik (Johns Hopkins University) - Radiation Pressure-Driven Shocks in Winds from Hot Stars, March 18, 1985.

David Hollenbach (NASA/Ames) April 1, 1985.

Ramesh Narayan (Caltech) - The Stability of Differentially Rotating Disks in Astrophysical Systems, April 22, 1985.

Arieh Konigl (University of Chicago) - MHD Equilibria of Astrophysical Jets, April 30, 1985.

Myron Smith (National Optical Astronomy Observatory) - The Be Stars.

Tim Heckman (University of Maryland, Johns Hopkins) - Optical Line Emission From Cosmic Jets, September 16, 1985.

Len Cowie (Space Telescope Science Institute) - Gas in Clusters of Galaxies, September 30, 1985.

JILA Atomic Physics Seminars

Norbert Bowering (University of Texas at Austin) - Collisional Deactiviation of Two-Photon Excited Xenon Atoms, October 1, 1984.

Farid Parpia (JILA) - Relativistic Time-Dependent Local-Density Approximation, October 2, 1984.

JILA Atomic Physics Seminars (cont.)

Gerd Leuchs (JILA) - The Effect of High Bound State Density on Photoionization, October 9, 1984.

Jeff Kimble (University of Texas at Austin) - Some Thoughts on Squeezed States, October 18, 1984.

Joachim Kessler (NBS, Gaithersburg) - Symmetry, Electron Polarization and Atomic Interactions, November 6, 1984.

Joe Eberly (University of Rochester) - Multiphoton Above-Threshold Ionization -- A Simple Dynamical Theory, December 11, 1984.

R. A. Phaneuf (Oak Ridge National Laboratory) - Merged Beam Studies of Low Energy Collisions of Highly Charged Ions with H Atoms, March 1, 1985.

Herbert Orth (Yale University) - Recent Experiments With Muonic Atoms, March 18, 1985.

Scott Berry (Oak Ridge National Laboratory and University of Tennessee) - Electron Capture and Loss to the Continuum, March 26, 1985.

Chemical Physics Colloquia

Joseph M. Jasinski (IBM, Yorktown Heights) - Laser Diagonistics of SiH_2 radicals, October 5, 1984.

John Hutchinson (Rice University) - Quantum Effects in Molecular Vibrational Dynamics, October 12, 1984.

Peter Rossky (University of Texas) - Molecular Interactions and Solution Structure in Aqueous Systems, October 19, 1984.

Thompson M. Sloane (General Motors Research Laboratory) - Experimental and Computational Studies of Ignition Chemistry in Hydrocarbon-Air Mixtures, October 26, 1984.

SEMINARS AND COLLOQUIA

Quantum Physics Division (525)

Chemical Physics Colloquia (cont.)

Paul Rosmus (JILA and Fachbereich Chemie der Universitat Frankfurt) - Properties of Molecular Ions Calculated from Correlated Wavefunctions, November 2, 1984.

Hartmut Hotop (Universitat Kaiserslautern) - Energy Transfer of Optically Aligned Neon Metastables, November 2, 1984.

Danny L. Yeager (Texas A and M) - Many Electron Wavefunctions, November 9, 1984.

Howard Taylor (University of Southern California) - A New View of Quantum Non-Linear Processes with Applications to Chemistry, November 26, 1984.

Larry Dubois (Bell Labs) - Novel Chemistry and Physics at the Metal-Semiconductor Interface, November 30, 1984.

John P. Maier (Universitat Basel) - Spectroscopic Studies of Polyatomic Cations, December 7, 1984.

William Hinsberg III (IBM, San Jose) - Chemistry of Microlithographic Materials, December 14, 1984.

Charles B. Harris (University of California at Berkeley) - Picosecond Studies of the Chemical Reactivity and Molecular Dynamics of Simple Chemical Reactions in Liquids, January 25, 1985.

Peter B. Armentrout (University of California at Berkeley) - Ion Beam Chemistry: From Triatomics To Transition Metals, February 1, 1985.

Sally Chapman (JILA) - Nonadiabatic Molecular Collisions in the ArH_2^+ System, February 8, 1985.

Mike L. Knotek (Sandia National Laboratory) - Mechanisms of Stimulated Desorption, February 15, 1985.

Michael Trenary (University of Illinois at Chicago) - Reflection-Infrared Studies of Chemisorbed CO, February 22, 1985.

Kenneth C. Janda (California Institute of Technology) - Intramolecular Vibrational Energy Transfer: van der Waals Molecules as Prototypes, March 1, 1985.

Chemical Physics Colloquia (cont.)

Rudolph A. Marcus (California Institute of Technology) - Electron Transfers and the Franck-Condon Principle (The 1985 E. U. Condon Lecture), March 14, 1985.

Mark Passler (Colorado School of Mines) - Low Energy Electron Diffraction (LEED) Studies of NO Adsorbed on Nickel Surfaces, March 15, 1985.

James C. Weisshaar (University of Wisconsin) - Gas Phase Organometallic Ion Chemistry and Spectroscopy, March 22, 1985.

Timothy S. Zwier (Calvin College) - Multiphoton Studies of Clusters, April 5, 1985.

David Smith (University of Birmingham) - Ion-Ion Recombination Studies, April 12, 1985.

Wilson Ho (Cornell University) - Kinetics of Molecular Dissociation at Surfaces, April 19, 1985.

Lional Goodman (Rutgers University) - Potential Surfaces of Molecules and Ions as Revealed by Multiphoton Jet Spectroscopy, April 26, 1985.

Kit H. Bowen (Johns Hopkins University) - Negative Ion Photoelectron Spectroscopy of Negative Cluster Ions, May 10, 1985.

INVITED TALKS

Quantum Physics Division (525)

P. L. Bender, "Laser Doppler Experiment Options for a 200 - 250 Km Altitude Geopotential Research Mission," American Geophysical Union, Baltimore, Maryland, May 28, 1985.

P. L. Bender, "Space Transponders and Gravitational Radiation," The Fourth Marcel Grossmann Meeting on the Development of General Relativity, Rome, Italy, June 21, 1985.

G. H. Dunn, "Ion-Molecule Reactions At Very Low Temperatures and Densities," 37th Annual Gaseous Electronics Conference, University of Colorado, Boulder, Colorado, October 9, 1984.

G. H. Dunn, "Experimental Measurements of the Effect of Extrinsic Fields on Dielectronic Recombination," Workshop on Atomic Spectra and Collisions in External Fields," National Bureau of Standards, Gaithersburg, Maryland, October 23, 1984.

G. H. Dunn, "Experimental Analysis of Field Effects," Workshop on Dielectronic Recombination: Coordination of Experiment and Theory," Rollins College, Winter Park, Florida, January 17, 1985.

G. H. Dunn, "Rydberg States From Dielectronic Recombination," Gordon Research Conference On Atomic Physics, Brewster Academy, Wolfeboro, New Hampshire, July 1, 1985.

G. H. Dunn, "Radiatively Stabilized Collisions: Dielectronic Recombination and Radiative Association," XIV ICEAC Meeting, Stanford University, Stanford, California, July 26, 1985.

J. E. Faller, "Status and Plans For New Gravity Apparatus," Bavarian Academy of Sciences, Munchen, West Germany, October 9, 1984.

J. E. Faller, "The Absolute Measurement of Gravity: A New Geophysical Research Tool," Physics Department, Calvin College, Grand Rapids, Michigan, April 12, 1985.

A. C. Gallagher, "Plasma Processes in Silane Discharge Deposition," Materials Research Society, Boston, Massachusetts, November 20, 1984.

A. C. Gallagher, "Molecular Continuum Radiation," Meeting of the Solar Energy Research Institute on Amorphous Silicon, Washington, D. C., March 22, 1985.

INVITED TALKS

Quantum Physics Division (525)

S. Geltman, "Angular Distribution in Multiphoton Ionization," Center for Basic Standards Colloquium, National Bureau of Standards, Gaithersburg, Maryland, March 20, 1985.

J. L. Hall, "Laser Manipulation of Atoms' Velocity: Chirping the Light Fantastic?!" MIT Quantum Electronics Seminar, Boston, Massachusetts, October 23, 1984.

J. L. Hall, "Advances In Optical Heterodyne Spectroscopy," Optical Society of America, San Diego, California, November 1, 1984.

J. L. Hall, "Laser Manipulation of Atom Velocities: Chirping the Light Fantastic?!" University of Arkansas, Department of Physics, Fayetteville, Arkansas, November 16, 1984.

D. G. Hummer, "The Internal Partition Function," Opacity Project Workshop, London, England, December 17, 1984.

D. G. Hummer, "Models For Atomic Partitions," Seminar, Institute for Astronomy and Astrophysics, University of Munich, January 25, 1985.

D. G. Hummer, "The Effect of Wind Blanketing on Spectra of Hot Stars and on the Determination of Stellar Parameters," Colloquium, Institute for Astronomy, Zurich, Switzerland, April 16, 1985.

D. G. Hummer, "The Effect of Wind Blanketing on Spectra of Hot Stars and on the Determination of Stellar Parameters," Colloquium, NORDITA, Copenhagen, Denmark, May 6, 1985.

D. G. Hummer, "The Internal Partition Function," University of Copenhagen Observatory, Copenhagen, Denmark, May 8, 1985.

D. G. Hummer, "The Effect of Wind Blanketing on Spectra of Hot Stars and on the Determination of Stellar Parameters," Colloquium, Institute for Theoretical Astro Physics, Heidelberg, West Germany, May 14, 1985.

D. G. Hummer, "Intrinsic Parameters of Hot Blue Stars," Invited review with R. P. Kudrutzki, IAU Symposium #116 on "Luminous Stars and Associations in Galaxies," Porto Heli, Greece, May 27, 1985.

D. G. Hummer, "The Effect of Wind Blanketing on Spectra of Hot Stars and on the Determination of Stellar Parameters," Colloquium, Department of Astronomy, University of Leningrad, Leningrad, U.S.S.R., August 29, 1985

INVITED TALKS

Quantum Physics Division (525)

D. G. Hummer, "The Sobolev Method for Line Formation with Continuous Opacity," Theoretical Astrophysics Seminar, Department of Astronomy, University of Leningrad, Leningrad, U.S.S.R., August 30, 1985.

S. R. Leone, "Electronic Energy Transfer in Metal Atoms," Short Wavelength Chemical Laser Workshop, Charleston, South Carolina, November 15, 1984.

S. R. Leone, "Reaction Dynamics of State-Selected Atoms and Radicals," 1984 International Chemical Congress of Pacific Basin Societies, Honolulu, Hawaii, December 19, 1984.

S. R. Leone, "Laser-Excited Chemical Dynamics, Chemistry Department, University of Chicago, Chicago, Illinois, January 7, 1985.

S. R. Leone, "Laser Studies of Chemical Dynamics," Chemistry Department Colloquium, Calvin College, Grand Rapids, Michigan, February 1985.

S. R. Leone, "Laser Studies of Chemical Dynamics," Chemistry Department Colloquium, Michigan State University, East Lansing, Michigan, February 1985.

S. R. Leone, "Laser State-Resolved Collision Dynamics," Chemistry Department Colloquium, The Johns Hopkins University, Baltimore, Maryland, March 1985.

S. R. Leone, "Laser-Excited Chemical Dynamics," ACS Princeton Section Colloquium, Princeton, New Jersey, March 1985.

S. R. Leone, "Lasers and Chemical Dynamics," University of Georgia, Athens, Georgia, April 16, 1985.

S. R. Leone, "Lasers and Chemical Dynamics," Natural Science Division, Tougaloo College, Tougaloo, Mississippi, April 17, 1985.

S. R. Leone, "Energy Transfer Processes of Aligned Excited States of Ca Atoms," XIV ICPEAC, Stanford, California, July 1985.

S. R. Leone, "Laser State-Selection and Detection of Inelastic and Reactive Chemical Dynamics," International Union of Pure and Applied Chemistry Meeting, Manchester, England, September 13, 1985.

J. L. Linsky, "Are Stars Like the Sun?" National Bureau of Standards, Gaithersburg, Maryland, November 9, 1984.

INVITED TALKS

Quantum Physics Division (525)

J. L. **Linsky**, "The Outer Atmospheres and Winds of Cool Stars," Department of Physics and Astronomy, Michigan State University, East Lansing, Michigan, November 14, 1984.

J. L. **Linsky**, "The Goals of Stellar Chromosphere/Corona Research in the Next Decade," Department of Astronomy, University of Wisconsin, Madison, Wisconsin, November 30, 1984.

J. L. **Linsky**, "Outer Atmospheres and Winds of Cool Stars," Max Planck Institute For Astronomy, European Southern Observatory, Munich Observatory, Munchen, West Germany, April 24, 1985.

J. L. **Linsky**, "Modelling of Extended Chromospheres," Dunsink Bicentenary Colloquium, Dunsink Observatory, Dublin, Ireland, September 9, 1985.

D. W. **Norcross**, "Low Energy Electron Scattering From HCN: Rotational Excitation and Resonance Effects," Los Alamos National Laboratories, Los Alamos, New Mexico, October 30, 1984.

D. W. **Norcross**, "Rotational and Vibrational Excitation of Molecules By Low-Energy Electrons," Joint Symposium on Swarm Studies and Inelastic Electron-Molecule Collisions, Granlibakken Resort, Tahoe City, California, July 21, 1985.

A. V. **Phelps**, "Relations Between Electron-Molecule Scattering and Swarm Experiment and Analysis," Joint Symposium on Swarm Studies and Inelastic Electron-Molecule Collisions, Granlibakken Resort, Tahoe City, California, July 20, 1985.

A. V. **Phelps**, "Electron Energy Transfer and Gas Heating During Electrical Discharges in Molecular Gases, General Motors Research Laboratories, Detroit, Michigan, September 12, 1985.

A. V. **Phelps**, "Electron Energy Transfer and Gas Heating During Electrical Discharges," Engineering Physics Colloquium, Polytechnic Institute of New York, Farmingdale, NY, September 16, 1985.

A. V. **Phelps**, "Electrical Discharges in D_2 and N_2 at High Electric Fields and Low Pressure," AT&T Bell Laboratories, Murray Hill, New Jersey, September 17, 1985.

S. J. **Smith**, "Experimental Investigations of the Role of Laser Field Fluctuations in Non-Linear Optical Absorption Processes," Colloquium at Max Planck Institute Für Quantem Optik, Garching, West Germany, September 11, 1985.

INVITED TALKS

Quantum Physics Division (525)

S. J. Smith, "Experimental Investigations of the Role of Laser Field Fluctuations in Non-Linear Optical Absorption Processes," presented at the International School on Coherent Optics, Ustron, Poland, September 19-26, 1985.

TECHNICAL AND PROFESSIONAL COMMITTEE PARTICIPATION AND LEADERSHIP

Quantum Physics Division (525)

P. L. Bender, Member, Fundamental Physics and Chemistry Panel, Space Science Board Study: Major Thrusts in Space Science: 1995-2015.

P. L. Bender, Member, Gravitation and Cosmic Physics Panel, Physics Survey Committee of the National Research Council.

P. L. Bender, Associate Editor, Journal of Geophysical Research.

P. L. Bender, Member, American Geophysical Union Committee on Fellows.

P. L. Bender, Member, Earth Observing System Science Steering Committee, NASA.

P. L. Bender, Member, Working Group 1 on Recent Plate Movements and Deformation, Inter-Union Commission on the Lithosphere.

P. L. Bender, Member, Crustal Dynamics Working Group, NASA.

G. H. Dunn, Member, National Research Council Committee on Atomic and Molecular Science.

G. H. Dunn, Member, Executive Committee, Division of Electron and Atomic Physics, American Physical Society.

G. H. Dunn, Member, Panel on New Instruments and Facilities in Atomic and Molecular Science, CAMS.

G. H. Dunn, Chairman, Nominating Committee, Division of Electron and Atomic Physics, American Physical Society.

G. H. Dunn, Chairman, Ad-hoc Committee on Atomic Data, for CAMS.

G. H. Dunn, Member, Program Committee for Conference on Atomic Processes in High Temperature Plasmas, held at Asilomar, CA. Feb. 1985.

G. H. Dunn, Co-organizer, NATO Advanced Study Institute on Physics of Electron-ion and Ion-Ion Collisions.

G. H. Dunn, Organizer/Chairman, Symposium on Electron-Ion Collisions at Conference on Atomic Processes in Fusion Plasmas, University of California, Santa Cruz, CA, August 1985.

J. E. Faller, Member, Working Group II of the International Gravity Commission.

TECHNICAL AND PROFESSIONAL COMMITTEE PARTICIPATION AND LEADERSHIP

Quantum Physics Division (525)

J. E. Faller, Member, Special Study Group 3.86, "Estimation of Absolute Gravimetric Determinations," of the International Gravity Commission.

J. E. Faller, Member, Special Study Group 3.87, "Development of World-Wide Absolute Gravity Net," of the International Gravity Commis sion.

J. E. Faller, Member, U. S. Interagency Gravity Standards Committee.

J. E. Faller, Member, Management Operations Working Group on Lunar Ranging.

J. E. Faller, Member, Physics Departments' "Geophysics Committee".

J. E. Faller, Member, External Awards Subcommittee of the American Geophysical Society.

A. C. Gallagher, Member, Army Basic Research Steering Committee.

J. L. Hall, Delegate, Consultative Committee for the Definition of the Meter (BIPM), Sevres, France, 1970 - present.

J. L. Hall, Member, International Steering Committee for Conferences on Laser Spectroscopy.

J. L. Hall, Member, NBS Committee for NBS Precision Measurement Grants.

J. L. Hall, Member, Ad hoc Oversight Committee for Air Force Ring Laser Gyro Program.

J. L. Hall, Member, Advisory Committee to the Global Oscillation Group, National Solar Observatory.

D. G. Hummer, Member, Editorial Board, Computer Physics Communications.

D. G. Hummer, Member, Steering Committee of the United Kingdom Collaborative Computational Project on Stellar Atmospheres.

S. R. Leone, Co-Chairman, Gordon Conference on Molecular Energy Transfer for 1985.

S. R. Leone, Editorial Advisory Board, Chemical Reviews, 1982-1985.

S. R. Leone, Associate Editor, Journal of Chemical Physics, 1984-1987.

TECHNICAL AND PROFESSIONAL COMMITTEE PARTICIPATION AND LEADERSHIP

Quantum Physics Division (525)

S. R. Leone, Editorial Advisory Board, Journal of Physical Chemistry, 1984-1987.

S. R. Leone, Member, NRC Committee, Army Research Office Review Board, 1984-1988.

J. L. Linsky, Member, Users' Committee, National Solar Observatory.

J. L. Linsky, Member, Users' Committee, International Ultraviolet Explorer Satellite.

J. L. Linsky, Member, Management and Operations Working Group, Solar and Heliospheric Physics Section, NASA.

J. L. Linsky, Chairman, Management and Operations Working Group, Ultraviolet and Infrared Astronomy Section, NASA.

J. L. Linsky, Chairman, Ultraviolet Astronomy Working Group, American Astronomical Society.

J. L. Linsky, Co-Investigator, High Resolution Spectrograph, Space Telescope.

J. L. Linsky, Member, Far Ultraviolet Spectrograph Explorer Science Working Group.

J. L. Linsky, Member, Scientific Organizing Committee, IAU Symposium No. 122, Circumstellar Matter, Heidelberg, Germany, June 23-27, 1986.

J. L. Linsky, Member, Proposal Review Panel, International Ultraviolet Explorer Satellite.

J. L. Linsky, Member, Editorial Board, Solar Physics.

J. L. Linsky, Member, Committee to Study the Long-Range Scientific Directions of Large-Aperture Ground-Based Solar Astronomy, Association of Universities for Research in Astronomy (AURA).

J. L. Linsky, Member AURA/NSF Study of the Scientific Goals and Priorities of the National Solar Observatory, AURA and NSF.

J. L. Linsky, Interdisciplinary Scientist on the Advanced X-ray Astrophysical Facility (AXAF) and Member of the AXAF Science Working Group, NASA.

TECHNICAL AND PROFESSIONAL COMMITTEE PARTICIPATION AND LEADERSHIP

Quantum Physics Division (525)

J. L. **Linsky**, Member, Astrophysics Council, NASA.

J. L. **Linsky**, Member, IUE Long Range Planning Committee.

J. L. **Linsky**, Member, National Optical Astronomy Observatory (NOAO) Director's Advisory Committee.

J. L. **Linsky**, Member, Committee on Coordinated Ground-Based and Space Observing, NOAO.

D. W. **Norcross**, Member, Panel on Theoretical Atomic and Molecular Sciences of the Committee on Atomic and Molecular Sciences of the National Research Council.

D. W. **Norcross**, Member, Working Group Supervising Collaborative Computational Project 2 (Continuum States of Atoms and Molecules) of the U. K. Science and Engineering Research Council, 1983 - present.

D. W. **Norcross**, Member, Publications Committee, Division of Electron and Atomic Physics of the American Physical Society, 1985-1986.

A. V. Phelps, Member, Review Panel for Tokamak Modeling Program, Plasma Physics Laboratory, Princeton University, 1985.

S. J. **Smith**, Member, Organizing Committee, Tenth International Conference on Atomic Physics, Tokyo, Japan, 1986.

S. J. **Smith**, Co-Chairman, Third International Conference on Multiphoton Processes, Crete, September 5-11, 1984.

S. J. **Smith**, Editorial Board, Metrologia.

S. J. **Smith**, Chairman, Organizing Committee, Fourth International Conference on Multiphoton Processes, Boulder, 1987.

CONSULTING

Quantum Physics Division (525)

P. L. Bender

Dr. Bender is consulting with the University GPS Consortium concerning the accuracy of determining tectonic motions with signals from the Global Positioning System satellites.

S. Geltman

Dr. Geltman is consulting and advising with the Lawrence Livermore National Laboratory on problems related to atomic processes in plasmas.

J. L. Hall

Dr. Hall is consulting with the Theoretical Astrophysics Group at Caltech in the area of laser techniques for gravity wave detection, and informally with colleagues in industry involved with stable laser design and application, and also consults with:

U. S. Air Force Academy - supervision of Graduate Students Working on Laser Stabilization and Laser Ring Gyros,

Ad hoc Oversight Committee for Air Force Ring Laser Gyro Program,

Advisory Committee to the Global Oscillation Network Group, National Solar Laboratory.

D. G. Hummer

Dr. Hummer consults for the X-ray laser project at Livermore and Los Alamos Laboratories.

CONSULTING

Quantum Physics Division (525)

J. L. Linsky

Dr. Linsky consults with NASA concerning (1) future programs in the area of ultraviolet and infrared astronomy, (2) future programs in solar and heliospheric physics, (3) operations and long range planning for the International Ultraviolet Explorer satellite, (4) definition of the proposed Far Ultraviolet Explorer Spectrograph, (5) definition of the proposed Advanced X-ray Astronomical Facility, (6) calibration and initial operations of the Space Telescope High Resolution Spectrograph, and (7) data operations for future missions.

Dr. Linsky consults with the National Optical Astronomy Observatory and the Association of Universities for Research in Astronomy concerning (1) operation of the National Solar Observatory and Sacramento Peak Observatory, (2) planning for coordinated ground-based and space observations, and (3) potential need for a large-aperature ground-based solar telescope.

D. W. Norcross

Dr. Norcross is consulting with the Theoretical Atomic and Molecular Physics Group at the Lawrence Livermore Laboratory on problems related to laser modeling, and is a Visiting Scientist (consultant) to Division T-4 of the Los Alamos Laboratory on problems related to electron collisions with atoms, ions, and molecules.

A. V. Phelps

Dr. Phelps does informal consulting and advising with DoD and DoE laboratories and their industrial and university contractors in the area of atomic and molecular processes in high power switches, laser induced breakdown and charged particle beam propagation. For the Lawrence Livermore National Laboratory this has been formalized by the granting of support for a postdoc.

OTHER AGENCY RESEARCH

Quantum Physics Division (525)

P. L. Bender	NASA	Integrated water vapor calibrator.
P. L. Bender	JPL	Perform integrated water vapor calibration development.
P. L. Bender	NASA	Determination of worldwide tectonic plate motions and large scale intra-plate distortions.
G. H. Dunn	DOE	Determine atomic, molecular, and nuclear data pertinent to the magnetic fusion energy program.
G. H. Dunn	KADE	Support for Max Kade post doctoral fellowship exchange program, with A. Müller.
J. E. Faller	AFGL	Absolute gravity system development.
J. E. Faller	MERADCOM	Fabrication of two gravity gradiometers for subsequent field testing and evaluation.
J. E. Faller	CHINA	Storeroom item purchases for China project
J. E. Faller	DMA-N	Absolute "G" co-op program.
J. E. Faller	CANADA	Construction of an absolute gravity apparatus.
J. E. Faller	HANNOVER	Construction of an absolute gravity apparatus.
J. E. Faller	FINLAND	Construction of an absolute gravity apparatus.
J. E. Faller	AUSTRIA	Construction of an absolute gravity apparatus.
A. C. Gallagher	DOE	Study spectroscopic diagnostics of electron-atom collisions.
A. C. Gallagher	CU/SERI	Diagnostics of a glow discharge used to produce hydrogenated amorphous silicon films, with J. Scott.

OTHER AGENCY RESEARCH

Quantum Physics Division (525)

A. C. Gallagher	AFOSR	Electronic energy transfer processes in the alkali/alkaline earth metal vapors.
J. W. Gallagher & G. H. Dunn	DOE	Cross sections and rates describing electron collisions with atoms and ions.
K. B. Gebbie	NASA	Energy Transport in the Solar Envelope and Atmosphere.
K. B. Gebbie	NASA	X-ray bright points on the quiet sun and rapid UV brightenings in active regions.
K. B. Gebbie	AFGL	Solar Oscillations and Convective Flows as Probes of Structure in the Subphotosphere.
S. Geltman	LLL	Dielectronic theory adaptation.
J. L. Hall	AF ACAD	Stabilization of diode and gas lasers.
J. L. Hall	ONR	Study precision atomic beam spectroscopy using stabilized lasers, with T. Baer
D. G. Hummer	NSF	Theory and observation of expanding atmospheres of early type stars, with D. Abbott and B. Bohannon
S. R. Leone	AF	Diode laser probing of energy transfer in XeF.
S. R. Leone	AFOSR	Electronic energy transfer processes in the alkali/alkaline earth metal vapors.
S. R. Leone	ARO	Eximer laser photolysis studies of translation-to-vibration energy transfer.
S. R. Leone	NASA	Studies of M-1 protypical bonds for potential application to solar-pumped lasers.
S. R. Leone	DOE	Time-resolved free radicals and laser-initiated chain reactions.
S. R. Leone	NSF	State-resolved molecular dynamics.

OTHER AGENCY RESEARCH

Quantum Physics Division (525)

S. R. Leone	ACS	Infrared laser excitation amd fluorescence of intramolecular vibrational relaxation in hydrocarbons.
S. R. Leone	NSF	Energy transfer and reactive exchange in simple molecular systems, with S. Kohler.
S. R. Leone	AFOSR	Argon ion laser/ring dye laser system.
S. R. Leone	AF	State-resolved dynamics of ion-molecule reactions in a flowing afterglow.
J. L. Linsky	NASA	Advanced X-ray astrophysics facility (AXAF).
J. L. Linsky	NASA	X-ray study of Sigma Orionis E and other helium-strong Bp stars, with D. Abbott and A. Brown.
J. L. Linsky	NASA	International ultraviolet experiment studies of astronomical sources, with C. Ambruster, T. Ayers, J. Bookbinder, A. Brown, Caillault, K. Carpenter, S. Drake and F. Walter
J. L. Linsky	NASA	Perform basic research in solar physics, with J. Cooper.
J. L. Linsky	NASA	Search for coronal X-ray emission from the young stars in the Ursa Major cluster and stream, with C. Ambruster.
J. L. Linsky	NASA	High resolution spectroscopy of late K and M supergiants.
J. L. Linsky	NASA	Measurement of the properties of hot astrophysical plasmas, with J. Cooper.
J. L. Linsky	NASA	Measurement of the properties of hot astrophysical plasmas.
J. L. Linsky	NASA	Corona of Procyon, with F. Walter and A. Brown.

OTHER AGENCY RESEARCH

Quantum Physics Division (525)

D. W. Norcross	NSF	Research equipment for computational physics and applied mathematics.
D. W. Norcross	DOE	Basic research involving computational physics and applied physics.
D. W. Norcross	DOE	Atomic and molecular collision processes.
D. W. Norcross	DOE	Atomic data pertinent to the magnetic fusion energy program.
A. V. Phelps	AFOSR	Transient discharges in high pressure gases.
A. V. Phelps	AFWAL	Detection of excited states by laser induced fluorescene.
A. V. Phelps	LLL	Non-equilibrium electrons in gases.
A. V. Phelps	SANDIA	Non-equilibrium electrons and gases.
S. J. Smith	DOE	Near resonant absorption in intense, fluctuating laser fields.

TRIPS SPONSORED BY OTHERS

Quantum Physics Division (525)

P. L. Bender

October 16-19, 1984 - Greenbelt, Maryland.
Attended a meeting of NASA Lunar Ranging Working Group, a meeting concerning Tectonic Measurements with the Global Positioning System, and a meeting of NASA Crustal Dynamics Working Group.
Sponsor: NASA Goddard.

October 30-November 2, 1984 - Chevy Chase, Maryland.
Attended meeting of NASA Earth Observation System Science Committee.
Sponsor: NASA Goddard.

November 3-4, 1984 - Reno, Nevada.
Attended meeting of the U.S. Geodynamics Committee.
Sponsor: National Research Council.

January 10-11, 1985 - Pasadena, California.
Attended meeting of Task Group on Fundamental Physics and Chemistry of the National Research Council Space Science Board study on "Major Directions For Space Sciences: 1995-2015."
Sponsor: National Academy of Sciences.

February 8-12, 1985 - Maui, Hawaii.
Attended a meeting of NASA Lunar Laser Ranging Management/Operations Working Group.
Sponsors: NASA Goddard, University of Hawaii.

May 27-31, 1985 - Baltimore, Maryland.
Attended Spring meeting of the American Geophysical Union and presented an invited talk.
Sponsor: NASA Goddard.

June 17-21, 1985 - Rome, Italy.
Attended the Fourth Marcel Grossmann Meeting on the Recent Development of General Relativity and presented invited talk.
Sponsor: Stanford University.

Bender (cont.)

July 28-August 2, 1985 - Columbus, Ohio; Woods Hole, Massachusetts.
Attended a meeting of the MERIT Working Group (Columbus);
Attended a meeting of the Space Science Board Study, "Major Directions For Space Sciences 1995-2015" (Hyannis).
Sponsors: NASA Goddard, National Academy of Sciences.

G. H. Dunn

October 14-November 9, 1984 - Oak Ridge, Tennessee; Washington, D.C.
Collaborated on experiements of ionization of mutually shared ions (Oak Ridge);
Attended NAS workshop on VUV and X-Ray Sources (Washington, D.C.).
Sponsors: Department of Energy, National Academy of Science.

January 8-15, 1985 - Brussels, Belgium.
Planned and organized summer school on the "Physics of Highly Ionized Ions," to be held in Belgium in the autumn of 1985.
Visited with Professor F. Broulliard of Louvain University and consulted about electron-ion collision experiments and their ECR ion source.
Sponsor: NATO through Louvain University.

January 16-19, 1985 - Winter Park, Florida.
Attended workshop entitled "Dielectronic Recombination: Coordination of Experiment and Theory," held at Rollins College.
Sponsor: Department of Energy.

February 23-28, 1985 - Monterey, California.
Attended American Physics Society Topical Conference on Atomic Processes in High Temperature Plasmas and presented a contributed paper.
Sponsor: Department of Energy.

Dunn (cont.)

April 24-25, 1985 - Washington, D. C.
Attended meeting of the Committee on Atomic and Molecular Science, National Research Council.
Sponsor: National Academy of Sciences.

June 30-July 7, 1985 - Wolfeboro, New Hampshire.
Attended Gordon Conference and presented invited talk.
Sponsor: Gordon Research Conferences.

September 28-October 12, 1985 - Brussels, Belgium.
Co-organizer of North Atlantic Treaty Organization's Institute on Electron-Ion Collisions, present invited lectures on dielectronic recombination.
Sponsor: NATO.

J. E. Faller

October 7-28, 1984 - Munich, Hannover, Braunsweig, Hamburg, West Germany; Paris, Corgese, Corsica, France; Frankfurt, West Germany.
Visited Dr. Boedecker, President of SS-3-87, gave talk at Bavarian Academy of Sciences;
Visited Munich Gravity Wave group at Institute of Astrophysics (Munich);
Visited Drs. Roeder and Schnuell at the Institute for Earth Measurement (Hannover);
Visited Drs. Germen and De Boer at the Physikalisch-Technisched Bundesantalt (Braunsweig);
Visited Dr. Makris at the Institute for Geophysics (Hamburg);
Visited Drs. Sakuma, Speake, and Quinn at the Bureau International des Poids et Measures (Paris);
Attended colloquium on "Kilometric Optical Arrays in Space," and present a paper (Corgese, Corsica, France);
Visited Institute for Applied Geodesy (Frankfurt).
Sponsor: Institute for Earth Measurement.

Faller (cont.)	December 2-7, 1984 - San Francisco, California; Los Angeles, California. Attended the Fall meeting of the American Geophysical Union (San Francisco); Attended a Management Operation Workshop Group for Laser Ranging Advancing (Los Angeles). Sponsor: NASA Goddard.
	December 16-23, 1984 - Maui, Hawaii. Site visit at Lunar Laser Ranging Station; Consulted and did problem solving and observing on several ranging runs. Sponsor: NASA Goddard.
	February 8-12, 1985 - Maui, Hawaii. Attended a Management Operation Group for Lunar Laser Ranging sponsored by the University of Hawaii. Sponsor: NASA Goddard.
	April 11-14, 1985 - Grand Rapids, Michigan. Presented an invited seminar at Calvin College. Sponsor: NASA Goddard.
	May 26-30, 1985 - Baltimore, Maryland. Attended AGU Meeting, participated in MOWG Lunar Laser Working Group, and attended Federal Gravity Commission Meeting. Sponsor: NASA Goddard.
	September 15-20, 1985 - Kahalui, Maui, Hawaii. Attended a Management Operation Group for Lunar Laser Ranging. Sponsor: NASA Goddard.
A. C. Gallagher	November 27-28, 1984 - Boston, Massachusetts. Attended the Materials Research Society Conference and presented a talk. Sponsor: Solar Energy Research Institute.

Gallagher (cont.)

March 18-23, 1985 - Cleveland, Ohio; Washington, D. C.
Visited Dr. John Ingold, General Electric Lamp Division, and gave talk (Cleveland);
Attended Contractor's Meeting of the Solar Energy Research Institute on Amorphous Silicon (Washington, D.C).
Sponsor: Solar Energy Research Institute.

August 29-September 30, 1985 - Madison, Wisconsin.
Collaborated at the University of Wisconsin with C. C. Lin, W. Anderson, and J. Lawler.
Sponsor: University of Wisconsin.

S. Geltman

December 3-7, 1984 - Livermore, California.
Consulted with Dr. Richard More on dielectronic recombination computer package at Lawrence Livermore Labs.
Sponsor: Lawrence Livermore Laboratory.

February 4-8, 1985 - Livermore, California.
Consulted with Dr. Richard More on dielectronic recombination computer package at Lawrence Livermore Labs.
Sponsor: Lawrence Livermore Laboratory.

June 5-7, 1985 - Livermore, California.
Consulted with Dr. Richard More on dielectronic recombination computer package at Lawrence Livermore Labs.
Sponsor: Lawrence Livermore Laboratory.

September 9-11, 1985 - Livermore, California.
Consulted with Dr. Richard More on dielectronic recombination computer package at Lawrence Livermore Labs.
Sponsor: Lawrence Livermore Laboratory.

TRIPS SPONSORED BY OTHERS

Quantum Physics Division (525)

J. L. Hall

October 21-24, 1984 - Boston, Massachusetts.
Presented an invited lecture at MIT Quantum Electronics Seminar entitled "Atom Velocity Manipulation with Lasers: Chirping the Light Fantastic";
Interacted with Professors M. S. Feld, S. Ezekiel, R. Field, and R. Weiss on technical topics of mutual interest.
Sponsor: Massachesetts Institute of Technology.

November 15-17, 1984 - Fayetteville, Arkansas.
Gave an invited lecture "Atomic Velocity Manipulation with Lasers: Chirping the Light Fantastic";
Conducted technical discussions with Professor S. Singh on Photon Counting Problems.
Sponsor: University of Arizona.

January 4-19, 1985 - Sevres, Villetaneuse, Paris, Orsay, and Ecole Normale, France; Hamburg, West Germany.
Visited BIPM (Sevres);
Visited Lab de Physique des lasers (Villetaneuse);
Attended CNRS (Centre Nationale de Recherches Scientifiques) Memorial Symposium in honor of A. Kastler;
Visited University of Paris (Paris);
Visited with the Gravity Wave Antenna group (Orsay and at Ecole Normale);
Discussions with Professor P. E. Toschek and Dr. R. Blatt (Hamburg).
Sponsor: Centre Nationale de Recherches Scientifiques

June 11-14, 1985 - Tucson, Arizona.
Served on an advisory panel concerned with global solar oscillation network.
Sponsor: National Solar Observatory.

TRIPS SPONSORED BY OTHERS

Quantum Physics Division (525)

J. K. Hoskins

October 21-27, 1984 - Harpers Ferry, West Virginia; Bedford, Massachusetts.
Attended Chapman Conference sponsored by the American Geophysical Union (Harpers Ferry);
Consulted with Sgt. Roger Sands at the AF Geophysical Lab on absolute gravity measurements and instruments (Bedford).
Sponsor: Defense Mapping Agency.

D. G. Hummer

October 1, 1984 - September 30, 1985 - University of Munich, West Germany.
Accepted an award from the Alexander von Humboldt Foundation, an independent foundation supported by the Federal Republic of Germany, and used for support of a 1-year foreign training assignment at the Institute of Astronomy and Astrophysics at the University of Munich, West Germany.
Sponsor: Alexander von Humboldt Foundation.

December 10-18, 1984 - London, England.
Opacity Project Workshop: Presented invited review; Worked with collaborators at Univiversity College London.
Sponsor: Science and Engineering Research Council (SERC).

January 6-15, 1985 - Manchester, England.
Collaborative Computational Project on Stellar Atmospheres: 2-day conference and meeting of Steering Committee and Work with collaborators at University College London.
Sponsor: Science and Engineering Research Council (SERC).

March 25-29, 1985 - Frankfurt, Germany.
Attended Bi-annaul Conference of German Astronomical Society: Presented three papers.
Sponsor: von Humboldt Foundation.

TRIPS SPONSORED BY OTHERS

Quantum Physics Division (525)

Hummer (cont.)	April 15-16, 1985 - Zurich, Switzerland. Presented colloquium at the Institute for Astronomy, University of Zurich. Sponsor: University of Zurich.
	May 4-8, 1985 - Copenhagen, Denmark. Presented two Colloquia: NORDITA and University of Copenhagen Observatory. Sponsor: NORDITA.
	May 14, 1985 - Heidelberg, Germany. Presented colloquium at the Institute for Theoretical Astrophysics, University of Heidelberg Sponsor: University of Heidelberg.
	May 26-June 2, 1985 - Porto Heli, Greece. Presented invited review and three contributed papers at the IAU Symposium #116, Stars and Associations in Galaxies. Sponsor: von Humboldt Foundation.
	August 25, 1985-September 5, 1985 - Leningrad, U.S.S.R. Presented two colloquia; Consulted with Professors Yuri Demkov, V. V. Ivanov, A. A. Kutepov, and V. V. Sobolev at the University of Leningrad concerning radiative transfer and spectral line formation. Sponsor: University of Leningrad.
S. R. Leone	January 3-8, 1985 - Chicago, Illinois. Presented departmental colloquium at The University of Chicago. Sponsor: The University of Chicago.

Leone (cont.)

February 12-15, 1985 - Grand Rapids and Lansing, Michigan.
Presented a seminar at Calvin College (Grand Rapids);
Presented a seminar at Michigan State University (Lansing).
Sponsors: Calvin College & Seminary and Michigan State University.

March 18-21, 1985 - Baltimore, Maryland; Princeton, New Jersey.
Presented a seminar at Johns Hopkins University (Baltimore);
Presented a seminar at Princeton University (Princeton).
Sponsors: Johns Hopkins University and Princeton University.

April 15-18, 1985 - Athens, Georgia; Tougaloo, Mississippi.
Visited University of Georgia and presented a seminar (Athens, Georgia);
Visited Tougaloo College and presented a colloquium (Tougaloo).
Sponsors: The University of Georgia and Tougaloo College.

July 6-12, 1985 - Wolfeboro, New Hampshire.
Attended a Gordon Conference on Molecular Energy Transfer;
Chaired and organized Conference along with Professor Paul Houston.
Sponsor: Gordon Research Conferences.

August 27, 1985 - Colorado Springs, Colorado.
Visited Frank J. Seiler's laboratory at the U. S. Air Force Academy to discuss research.
Sponsor: Kirtland Air Force Base.

Leone (cont.)

September 7-14, 1985 - Manchester, England.
Attended and presented invited talk at International Union of Pure and Applied Chemistry meeting.
Sponsor: IUPAC Meeting.

J. L. Linsky

September 30-October 2, 1984 - Greenbelt, Maryland.
Attended meeting of FUSE working group.
Sponsor: ORI, Inc.

November 12-16, 1984 -East Lansing, Michigan; Greenbelt, Maryland.
Gave a colloquium and consulted at the Department of Physics and Astronomy, Michigan State University (East Lansing);
Attended meeting of the IUE Long Range Planning Committee at Goddard Space Flight Center (Greenbelt).
Sponsors: Michigan State University and NASA Goddard.

November 18-20, 1984 - Tucson, Arizona.
Attended meeting of the Director's Advisory Committee of the National Optical Astronomy Observatory (NOAO).
Sponsor: Association of Universities for Research In Astronomy, Inc.

November 26-30, 1984 - Madison, Wisconsin.
Attended meeting of the HRS Investigation Definition Team.
Sponsor: NASA Goddard.

December 10-14, 1984 - Huntsville, Alabama.
Attended meeting of the NASA Solar and Heliospheric Management and Operations Working Group;
Attended Marshall Space Flight Center Neighborhood Symposium and presented a contributed paper.
Sponsor: The University of Alabama.

Linsky (cont.)

December 20-28, 1984 - Washington, D.C.
Made presentation to Dr. Charles Pellerin, Chief of the Astronomy Division at NASA, on the Guest Observer Program of the IUE satellite.
Sponsor: Creative Management Associates, Inc.

January 13-17, 1985 - Tucson, Arizona.
Attended and presented papers at the American Astronomical Society.
Sponsor: NASA Goddard.

January 20-24, 1985 - Tucson, Arizona; Princeton, New Jersey.
Attended meeting of National Solar Observatory Users Committee (Tucson);
Attended meeting of Space Telescope Guaranteed Time Observers to finalize Space Telescope Observing plans (Princeton).
Sponsors: National Solar Observatory and Association of Universities for Research in Astronomy, Inc. and NASA Goddard.

February 19-22, 1985 - Greenbelt, Maryland.
Attended meeting of the NASA Astronomy and Relativity Management and Operations Working Group
Sponsor: NASA Goddard.

March 3-8, 1985 - Greenbelt, Maryland; Austin, Texas.
Attended a meeting of the Space Telescope Imaging Spectrograph Team (Greenbelt);
Attended a meeting of the Space Telescope High Resolution Spectrograph Team (Austin).
Sponsor: NASA Goddard.

Linsky (cont.)

March 13-26, 1985 - Canberra, Australia; Tucson, Arizona; Washington, D.C.
Attended meeting of the NASA-ESA Australian Far Ultraviolet Explorer Science Working Group (Canberra);
Attended the National Optical Astronomy Observatory Directors' Advisory Committee Meeting (Tucson);
Attended meeting of NASA Astrophysics Council (Washington, D.C.).
Sponsors: The University of Virginia, Battelle, and National Optical Astronomy Observatories.

April 2-4, 1985 - Tucson, Arizona.
Attended a meeting of the National Optical Astronomy Observatories Committee on Coordinated Ground-Based and Space Observing.
Sponsor: NASA Goddard.

April 19-May 2, 1985 - Madrid, Spain; Munich, West Germany; Heidelberg, West Germamy; Armagh, Northern Ireland.
Attended a meeting of the IUE (International Ultraviolet Explorer Satellite) NASA-ESA-UK Coordinating Committee;
Visited the Institute for Astronomy and Astrophysics and gave a colloquium;
Attended a meeting of the Scientific Organizing Committee of IAU (International Astronomical Union) Symposium No. 122 (Heidelberg);
Wrote a specific paper with colleagues based on IUE data (Armagh, Northern Ireland).
Sponsors: NASA Goddard, IUE NASA-ESA-UK Coordinating Committee, Institute Astronomy and Astrophysics, and IAU Symposium No. 122.

Linsky (cont.)

May 12-16, 1985 - Tucson, Arizona; Huntsville, Alabama.
Attended a meeting of the National Solar Observatory User's Committee (Tucson);
Attended the AXAF Science Working Group at Marshall Space Flight Center (Huntsville).
Sponsors: National Optical Astronomy Observatories (AURA) and NASA George C. Marshall Space Flight Center.

May 20-22, 1985 - Greenbelt, Maryland.
Attended a meeting of the NASA Astrophysics Council at Goddard Space Flight Center.
Sponsor: Battelle.

June 2-7, 1985 - Charlottesville, Virginia.
Attended the 166th Meeting of the American Astronomical Society and presented contributed papers.
Sponsor: NASA.

June 16-21, 1985 - Tucson, Arizona.
Attended a meeting of the AURA NSF Study of Scientific Goals and Priorities of the National Solar Observatory.
Sponsor: AURA, Inc. Imprest Fund, National Optical Astronomy Observatories.

June 23-25, 1985 - Washington, D. C.
Consulted with Sam Keller (NASA Deputy Assistant Administrator for Science and Technology) and staff members of the House Committee on Science and Technology covering future NASA missions.
Sponsor: NASA Goddard.

July 23-24, 1985 - Washington, D. C.
Attended a meeting of the AXAF Science Working Group.
Sponsor: NASA George C. Marshall Space Flight Center.

Linsky (cont.)

September 1-8, 1985 - Dublin, Ireland.
Attended the Dunsink Bicentenary Colloquium "Circumstellar Material: Late-Type Stars," and presented an invited talk on "Modeling of Extended Chromospheres."
Sponsor: National Science Foundation.

D. J. Nesbitt

July 6-12, 1985 - Wolfeboro, New Hampshire.
Attended Gordon Conference on Molecular Energy Transfer.
Chaired session on "Intramolecular Vibrational Energy Transfer".
Sponsor: Gordon Research Conferences.

D. W. Norcross

October 28-30, 1984 - Los Alamos, New Mexico.
Consulted with groups T4 and T12 at Los Alamos National Laboratories on problems in electron-atom and electron-molecule collisions.
Sponsor: Los Alamos National Laboratory.

December 8-11, 1984 - Washington, D.C.
Attended meeting of the subpanel on Atomic Theory of CAMS of the NSF.
Sponsor: National Academy of Science.

May 12-14, 1985 - Chapel Hill, North Carolina.
Attended a Department of Energy's contractor meeting.
Sponsor: Department of Energy.

May 28-31, 1985 - Norman, Oklahoma.
Attended annual DEAP meeting and reported to membership of DEAP as a member of NRC Panel on AMO theory.
Sponsor: Department of Energy.

Norcross (cont.)	July 19-23, 1985 - Lake Tahoe, Nevada. Attended 4th International Swarm Seminar and Inelastic Electron-Molecule Seminar and presented invited talk. Sponsors: Department of Energy and California Institute of Technology.
A. V. Phelps	November 4-7, 1984 - Waltham, Massachusetts. Participated in symposium on "Radiation in Plasmas," and discussed joint papers and research with Dr. L. C. Pitchford at GTE Laboratories, Inc. Sponsor: GTE Laboratories.
	July 19-23, 1985 - Lake Tahoe, Nevada. Attended 4th International Swarm Seminar and Inelastic Electron-Molecule Seminar and presented invited talk. Sponsors: Department of Energy and California Institute of Technology.
	September 11-12, 1985 - Detroit, Michigan. Visited General Motors Research Laboratories and presented a colloquium and discussed their new research program on the initiation of combustion with electrical discharges. Sponsor: General Motors.
	September 13-18, Farmingdale, New York; Murray Hill, New Jersey. Presented an Engineering Physics Colloquium at Polytechnic Institute of New York (Farmingdale); Visited AT&T Bell Laboratories and presented a seminar on work at JILA with discharges at low pressures and high electric fields. Sponsor: Polytechnic Institute and AT&T.
S. J. Smith	May 12-14, 1985 - Chapel Hill, North Carolina. Attended DoE Contractor's Meeting. Sponsor: Department of Energy.

Smith (cont.)

September 12, 1985 - Garching, West Germany.
Presented an invited colloquium at Max Planck Institute Fur Quantem Optik.
Sponsor: Max Planck Institute.

September 19-26, 1985 - Ustron, Poland.
Presented an invited talk at the International School on Coherent Optics.
Sponsor: National Science Foundation.

UNIVERSITY AND DEPARTMENT COMMITTEE MEMBERSHIPS

Quantum Physics Division (525)

P. L. Bender

Thesis Committees for:

- Z. D. Bergen
  Physics Department, University of Colorado
- P. T. Keyser
  Physics Department, University of Colorado
- M. D. Rayman
  Physics Department, University of Colorado
- B. Shahid-Saless
  Physics Department, University of Colorado
- T. M. Van Dam
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A. C. Gallagher

JILA Space Committee

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- J. Doyle
  Physics Department, University of Colorado
- X. Han
  Physics Department, University of Colorado
- M. O'Callaghan
  Physics Department, University of Colorado

Gallagher (cont.)

R. Robertson
Physics Department, University of Colorado

G. Schinn
Physics Department, University of Colorado

K. B. Gebbie

Thesis Committee for:

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Astrophysical, Planetary and Atmospheric Sciences Department, University of Colorado

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S. Geltman

JILA Rules Committee

JILA Editorial Committee

Teaching Evaluation Committee, University of Colorado

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Physics Department, University of Colorado

J. L. Hall

Chairman, Thesis Committees for:

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Physics Department, University of Colorado

Zhu Miao
Physics Department, University of Colorado

Mike Winters
Physics Department, University of Colorado

UNIVERSITY AND DEPARTMENT COMMITTEE MEMBERSHIPS

Quantum Physics Division (525)

D. G. Hummer

Thesis Committees for:

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Physics Department, University of Colorado

R. Russell
Astrophysical, Planetary, and Atmospheric Sciences Department, University of Colorado

S. Voels
Astrophysical, Planetary, and Atmospheric Sciences Department, University of Colorado

S. McCandless
Astrophysical, Planetary, and Atmospheric Sciences Department, University of Colorado

P. Becker
Astrophysical, Planetary, and Atmospheric Sciences Department, University of Colorado

S. R. Leone

Chairman, Graduate Admissions Committee, Department of Chemistry

Final Ph.D. Defense Committees for:

Bob Robertson
Physics Department, University of Colorado

Charles Hamilton
Chemical Physics Program, University of Colorado

JILA Executive Committee

J. L. Linsky

University Space Science and Policy Task Force

Thesis Committees for:

P. L. Bornmann
Astrophysical, Planetary, and Atmospheric Sciences Department, University of Colorado

Linsky (cont.)

S. Saar
Astrophysical, Planetary, and Atmospheric Sciences Department, University of Colorado

T. Bastian
Astrophysical, Planetary, and Atmospheric Sciences Department, University of Colorado

J. Neff
Astrophysical, Planetary, and Atmospheric Sciences Department, University of Colorado

D. J. Nesbitt

Co-Chairman, JILA Colloquium Committee

JILA Data Center Advisory Committee

Library Committee, Department of Chemistry

Faculty Secretary, Department of Chemistry

Organizing Committee, Physical Chemistry Workshop

D. W. Norcross

Chairman of JILA, January 1983 - December 1984

JILA Computing Committee

Graduate Committee, Department of Physics

Computing Committee, Department of Physics

Member, President's Search Committee for Director, University Office of Space Sciences and Technology

Thesis Committee for:

T. Gorczyca
Physics Department, University of Colorado

A. V. Phelps

Thesis Committees for

J. F. Benage
Physics Department, University of Colorado

Quantum Physics Division (525)

Phelps (cont.)	R. H. Chatham Physics Department, University of Colorado
	R. M. Robertson Physics Department, University of Colorado
	M. O'Callaghan Physics Department, University of Colorado
S. J. Smith	Member, JILA Executive Committee
	Member, Chemical Physics Committee, Department of Physics
	Member, JILA Building Committee

GRADUATE STUDENTS AND POSTDOCTORAL RESEARCH ASSOCIATES SUPERVISED

Quantum Physics Division (525)

	Graduate Students	Postdoctoral Research Associates
P. L. Bender	J. H. Lyou A. Rizzi S. D. Swartz S. J. Walter	M. A. Vincent
G. H. Dunn	S. Jefferts M. Schauer K. Timmer E. Wahlin	B. DePaola N. Djurić
J. E. Faller	P. Keyser T. Niebauer	J. K. Hoskins (NRC)
A. C. Gallagher	S. Davidson J. Doyle X. Han M. O'Callaghan R. Robertson G. Schinn	H. Chatham J. Kelly
S. Geltman	S. Haan	
J. L. Hall	M. Rayman M. Winters N. C. Wong M. Zhu	J. M. Chartier C. Salamon
D. G. Hummer	D. Carroll R. Russell S. Voels	D. C. Abbott
S. R. Leone	K. Carleton (NSF) C. Chee L. Cousins M. Hale C. Hamilton W. Hess G. H. Lin J. Smedley	V. Bierbaum (25%) W. Bussert D. J. Donaldson (NSERC) R. Dressler H. Haugen A. Langford J. Maier (NATO) H. Meyer D. Neuschafer

GRADUATE STUDENTS AND POSTDOCTORAL RESEARCH ASSOCIATES SUPERVISED

Quantum Physics Division (525)

	Graduate Students	Postdoctoral Research Associates
J. L. Linsky	P. Bornman J. Neff S. Saar	C. Armbruster A. Brown J. P. Caillault K. Carpenter S. Drake
D. J. Nesbitt	C. Lovejoy M. Schuder	
D. W. Norcross	T. Gorczyca J. Kelly	S. Alston A. Jain F. da Paixão D. Harmin F. Parpia A. Pradhan
A. V. Phelps		B. Jelenković H. Tischer B. Wedding
S. J. Smith	K. Arnett	M. Hamilton

COURSES TAUGHT AT UNIVERSITY OF COLORADO

Quantum Physics Division (525)

S. Geltman	Independent Study in Atomic Collision Theory (Fall 1985)
J. L. Hall	Laser Stabilization - Physics 696
S. R. Leone	Physical Chemistry Laboratory Course - Development and construction of new experiments
D. J. Nesbitt	Chemistry 558 - Quantum Chemistry (Fall 1985)
D. W. Norcross	Recitation - Physics III (Fall 1985)

BACKGROUND ON JILA

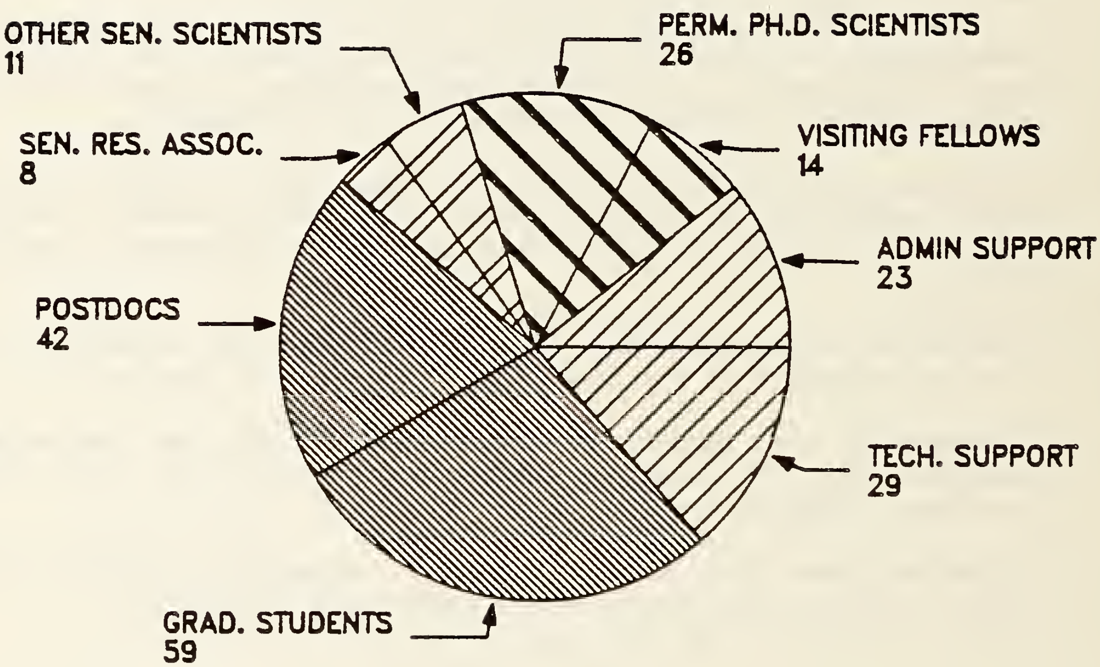
Quantum Physics is the division through which NBS participates in the Joint Institute for Laboratory Astrophysics, a cooperative enterprise between NBS and the University of Colorado. In collaboration with University faculty and visiting scientists, the Division conducts the kind of long-term, high-risk research on which the Bureau's ability to provide standards, measurements, and data ultimately depends. The Division's objectives include:

- Developing the laser as a refined measurement tool and applying it to tests of fundamental laws of physics such as the postulates of special and general and relativity.
- Improving the theory and instrumentation required to measure astrophysical and geophysical quantities such as the cosmic distance scale, the acceleration of the Earth's gravity, and the long distances involved in determining crustal movements.
- Researching new techniques for measuring interactions involving atoms and molecules, to provide data essential in areas such as nuclear fusion, advanced lighting, and laser development.
- Developing and applying measurement techniques to advance fundamental understanding of microscopic molecular processes such as those that occur in combustion and laser-initiated chemical reactions.
- Interacting with University faculty and visiting scientists to maintain expertise at the forefront of research in physics.
- Transferring the results of its research and the technology developed to the Nation's industries, universities and other government agencies.
- Exchanging ideas and skills with other scientists in NBS through visits, seminars and longer-term interchanges of personnel.

A direct outgrowth of the national space program in the early postwar period, JILA was formed in response to a report of the Space Science Board of the National Academy of Sciences. That report pointed to serious gaps in our basic understanding of the behavior of atoms and molecules in terrestrial, planetary, solar and stellar atmospheres. The unifying theme for the Institute therefore became the physics of gaseous atmospheres. Since then, however, JILA has responded to changing national needs and to the requirements of its parent organizations. Thus the Institute has become a world leader not only in atomic and

JILA STAFFING 1985-1986

TOTAL - 212



molecular science and astrophysics but also in precision measurement, laser physics, and certain areas of geophysics.

The permanent Ph.D. scientists or "Fellows if JILA", of which there are currently 22, form a governing body that sets policy, subject to review by the Director of NBS and the President of the University. A Chairman, elected every two years by the Fellows, has much the same role as the chairman of an academic department. Assisted by an executive committee, he is responsible for operating the Institute within the policies set out by the Fellows. Of the 22 Fellows, 8 are fulltime faculty members from the Departments of Physics, Chemistry, and Astrophysical, Planetary and Atmospheric Sciences; 14 are NBS employees, of which 13 are in the Quantum Physics Division and 1 is in the Time and Frequency Division. Although these scientists work side by side, sharing facilities and responsibility for the success of the Institute, each remains officially responsible to his respective employer, NBS and its Director in one case, the University and the academic department in the other.

Through their adjoint faculty appointments, NBS scientists at JILA have both the opportunity and responsibility to teach courses and participate in other faculty activities. This gives them access to graduate and undergraduate students, some of whom become interested in pursuing research directed toward NBS goals. Of 59 graduate students in JILA, 40 are supervised in their research by NBS scientists; of 42 postdoctoral research associates, 33 work with NBS scientists. Some have subsequently joined NBS and now occupy positions of leadership; others are carrying the knowledge and skills acquired at NBS to the Nation's industries, universities and other government agencies. Of over 100 graduate students and research associates supervised by NBS staff at JILA during the past 8 years, 20% are now in industry, 20% in government agencies, and the remainder largely in universities.

Besides the graduate students and postdoctoral research associates, the Visiting Fellows Program is probably the single most important factor in maintaining an atmosphere of change and excitement in JILA. The Program provides partial funding for some ten internationally distinguished scientists a year to spend up to twelve months at JILA collaborating with resident scientists. Since its inception 24 years ago, the Program has become internationally renowned. More than 220 senior scientists from 29 foreign countries as well as the U.S. have participated. The number of applicants exceeds the number of positions typically by a factor of four; in accordance with the Memorandum of Understanding, applicants are chosen according to scholarly achievement, demonstrated interest in the scientific and technical objectives of JILA, and the recommendations of their peers.

For NBS. and University researchers alike, perhaps the greatest attraction of JILA is the large concentration of scientific talent in atomic and molecular physics and closely related areas. Neither institution, with its broad responsibility for measurement in one case and for education in the other, could justify such a large number of senior scientists in a single area. Together these researchers are able to collaborate, exchange ideas and attract visiting scientists in a way that would be impossible for two much smaller groups operating separately.

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☐ Document describes a computer program; SF-185, FIPS Software Summary, is attached.

11. ABSTRACT (*A 200-word or less factual summary of most significant information. If document includes a significant bibliography or literature survey, mention it here*)

This report summarizes the research and technical activities of the Center for Basic Standards during the Fiscal Year 1985. These activities include work in the areas of electricity, temperature and pressure, mass and length, time and frequency, quantum metrology, and quantum physics.

12. KEY WORDS (*Six to twelve entries; alphabetical order; capitalize only proper names; and separate key words by semicolons*)

Astrophysics; atomic and molecular physics; electrical standards; fundamental constant gravity measurements; laser physics; length standards; mass standards; pressure and vacuum standards; temperature standards; time and frequency standards; X-ray and gamma ray wavelength standards

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