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Technical Note 59

MEASUREMENTS AND STANDARDS IN PLASMA-PHYSICS AND ASTROPHYSICS

AT THE NATIONAL BUREAU OF STANDARDS

U. S. DEPARTMENT OF COMMERCE
NATIONAL BUREAU OF STANDARDS

THE NATIONAL BUREAU OF STANDARDS

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Technical Note

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MEASUREMENTS AND STANDARDS IN PLASMA-PHYSICS AND ASTROPHYSICS AT THE NATIONAL BUREAU OF STANDARDS

Edited by

Lewis M. Branscomb, Coordinator

NBS Plasma-Physics and Astrophysics Program

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MEASUREMENTS AND STANDARDS IN PLASMA-PHYSICS AND ASTROPHYSICS

at the National Bureau of Standards

Abstract: The National Bureau of Standards has embarked on a special program to unify and accelerate its research on hot gases. This work will provide data and theory presently required for the quantitative interpretation of astrophysical and geophysical observations and the measurement of properties of plasmas in the laboratory. The data, measurement techniques, and theoretical methods of analysis draw on activities in the fields of atomic and molecular physics, statistical mechanics and thermodynamics, fluid mechanics, and theoretical astrophysics and geophysics. Both the Washington and Boulder laboratories of the NBS are participating. This Note describes the technical objectives of the program and includes in appendices a selected list of papers published at the NBS for the period 1955-1959 and a partial list of Bureau participants.

I. INTRODUCTION

A number of major national programs in applied technology - such as thermonuclear power, space exploration, rocket propulsion, hypersonic aerodynamics, and ionospheric communications - have in common their dependence upon the solution of basic problems in a rapidly growing area of physics: the physics of very hot gases which are often not in a state of local thermodynamic equilibrium. However, progress in understanding the complicated processes in such high-temperature gases has to date been slow and sporadic partly because problems have been attacked independently from separate points of view in a number of different fields.[1]

To alleviate this difficulty, the National Bureau of Standards has initiated efforts to strengthen and unify all its research programs which deal with the properties of hot gases and their accurate measurement. The purpose of this Technical Note is to describe the program which is underway and to list recent significant papers published by the senior scientific staff associated with these activities. From time to time, other Notes may be published to keep the bibliography of publications up to date. Although no central reprint file will be kept, in most cases reprints can be obtained from the authors.

Since the NBS program in this area is intended to meet the needs of astrophysicists, aeronomists, plasma physicists, and others, suggestions on the direction which the program should take will be welcomed.

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[1] For example, gaseous electronics, astrophysics, chemical kinetics, aerodynamics, high temperature physics, atomic spectroscopy and collision theory, and magnetohydrodynamics.

II. BACKGROUND

Engineering and technical applications in the fields mentioned require accurate measurements on the essential material involved: the hot plasma. Because this high-temperature gas is not usually in local thermodynamic equilibrium, the parameters usually invoked to describe gases - temperature, pressure, density, and electrical conductivity - are either ill defined or must be used in restricted senses. It is a general property of such plasmas, for example, that a single temperature parameter cannot be used to characterize the partition of energy over the many states of the system. Thus, a large number of collective and atomic properties of the gas require clear characterization and accurate measurement for scientific progress to be made.

The mission of the National Bureau of Standards is to "provide the central basis for a complete consistent system of physical measurement adequate for the expanding national activity in scientific research." In this case, such a basis can be provided only by making an accurate determination of the important physical parameters. These parameters include transition probabilities, transport properties, the mechanism of radiation propagation through non-equilibrium gases, and the mechanism of energy degradation of radiation. To be fully useful, these precision determinations must be accurately and consistently related to the national standards of physical measurement. Further, any such system of measurement must be completely coupled to the analytical methodology used in interpreting the measurements.

For example, in determining transition probabilities, the first objective will be to find how these probabilities can be measured with maximum accuracy in terms of the basic standards of radiation. This procedure is required to meet the demands of the current program for precise data and to assist other laboratories in making measurements related as closely as possible to the fundamental standards.

To relate the many fields of specialization, a more basic approach is needed, which in essence creates a single broad problem and treats this problem from a systematic and quantitative point of view. The long-range objective is therefore the solution of the "many-body problem" of modern atomic physics in its full generality. Required to accomplish this goal are precision measurements and calculations of the many atomic and collective parameters which govern the behavior of the hot plasma or gas and which provide the diagnostic tools for a description of the state of the gas. Next, a characterization of the behavior of the gas in the correct theoretical framework must be accomplished without introducing drastic simplifying assumptions.

Astronomers were the first to recognize the need for this unified approach, which characterizes the field of astrophysics. Looking at ionized gases which cover enormous ranges of temperature and in which energy is dissipated by shockwaves, radiation, and many types of collisions, the astrophysicists are finding that they are forced by their observations to come to grips with the essential problem and to reduce their reliance on the assumed applicability of equilibrium thermodynamics.

In applying plasma physics to the control of thermonuclear reactions, an astrophysical environment - extremely hot gases with high energy dissipation - is complicated by a highly transitory phenomenon as well. Here accurate spectroscopic parameters, reaction rates, and methods for dealing with this many-body problem are even more desperately needed. Hence, it seems appropriate to take the name "plasma and astrophysics" to characterize this synthesis of specializations dealing with hot gases not in local thermodynamic equilibrium, even though this research area is equally applicable to ionospheric physics, aerodynamics, and the other fields mentioned above.

The appropriateness of undertaking at the National Bureau of Standards a unified approach to the problem of gases in a state of non-LTE[2] is evident from the consequences of replacing the thermodynamic approach (in which energy levels and statistical weights are the only microscopic parameters required) by detailed rate theories (in which transition probabilities and all of the relevant collision cross sections must be known). The demand for basic physical information then becomes enormous, and a corresponding emphasis is placed on accuracy. However, in most cases adequate measurement techniques do not exist. A long-range experimental program to develop new measurement standards is therefore required along with a closely interrelated theoretical program on both the general problem and the specialized fields of application. This theoretical work is also greatly needed for the space sciences to promote full utilization of the enormous amount of new observational material being acquired through the rocket and satellite programs and the new radio and optical telescopes.

The Bureau already has heavy commitments in important aspects of the plasma and astrophysics area through its basic programs on atmospheric, ionospheric, and solar phenomena; the physical properties of atomic systems and high temperature gases; and

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[2] LTE: An abbreviation for "local thermodynamic equilibrium."

propagation of radiofrequency radiation through plasmas. However, the breath taking speed with which the results of modern atomic physics are applied to engineering projects of major national consequence challenges the Bureau to strengthen and coordinate a unified interdivisional and interlaboratory program on measurements and standards in plasma and astrophysics.

The basic motivation behind this entire program is to obtain accurate data and acquire an appropriate understanding of physical behavior which will assist other laboratories and observatories in understanding the properties of non-LTE hot gases as they occur in nature. It is not sufficient, however, to develop measurement standards and methods of analysis without subjecting them to the test of practical application. Indeed, the application of the data to suitable practical situations forms the ultimate test of the scientific method for initially generating reliable and useful data. In addition, the fundamental data and theory are more readily utilized by other scientific laboratories when their value has been demonstrated in application. Through the establishment of collaborative programs with allied scientific institutions such as the High Altitude and Sacremento Peak Observatories, the Diamond Ordnance Fuze Laboratories, and certain universities, the Bureau hopes to see the results of its research utilized most effectively. We also depend strongly on collaboration with similar programs in other countries. Through careful coordination and planning these laboratories and observatories have in many cases divided up the enormous amount of work and cooperatively seek a common objective.

III. DESCRIPTION OF THE PROGRAM AREA

The basic problems in a plasma program are characterizing the gas, which is not in local thermodynamic equilibrium, and providing adequate standards of measurement to describe the gas. In such a gas, net transport of energy across the boundaries is not necessarily negligible compared to the energy stored. Furthermore, this transport generally occurs more rapidly through certain degrees of freedom than in others, so that the different degrees of freedom of the gas are not in equilibrium with one another. While it may be possible to characterize the energy distribution within a given degree of freedom by one temperature parameter, other degrees of freedom which are weakly coupled to the first may be characterized by radically different "temperatures;" in fact, it may not be possible to use the concept of temperature at all, even in this restricted sense. Thus, in the absence of LTE, not only must the energy states of all components of the system and their populations be known, but also the reaction rates and transition probabilities of the most important processes.

The present and the proposed plasma and astrophysics research programs cut across divisional lines of organization and touch very closely other major Bureau programs - for example, high-temperature, microwave, radiometric, wavelength, geophysical, ionospheric, and solar research. It is neither easy nor advantageous to draw a hard line of division; indeed, it is the very close relationship of the plasma and astrophysics research program to these other fundamental standards and observational programs that makes this overall program so challenging and potentially fruitful.

The plasma and astrophysics program is particularly closely related to the interdivisional high-temperature program. The high-temperature program is devoted to the study of the definition and measurement of the properties of high-energy systems in thermodynamic equilibrium. As temperatures rise above the 5- to 10-thousand degree region, all materials are vaporized, and it becomes increasingly difficult to maintain thermodynamic equilibrium because of the problem of containing the hot material. In this very-high-temperature range, thermodynamic equilibrium may only be approached, and then only in a transient state. Here the high-temperature and the plasma- and astrophysics programs become indistinguishable. For convenience, the plasma and astrophysics areas may be arbitrarily separated by the degree of departure from LTE or by at least one degree of freedom in a system with an effective temperature above 10,000°K (1 ev). This temperature will usually result in an appreciable degree of ionization. Many basic programs on atomic parameters are equally important to both areas, particularly atomic energy levels and transition probabilities.

The proposed program separates naturally into the following three parts, which are logically related in a chain but which are nevertheless to be undertaken simultaneously: (A) a study of atomic properties; (B) an investigation of gases under near-equilibrium or idealized conditions; and (C) a study of gases far from thermodynamic equilibrium.

A. Atomic Properties

Atomic properties will be studied to provide all the microscopic parameters required to specify the interaction of individual photons, electrons, atoms, and molecules in the energy region up to 10 kev. Thus, attention is to be focussed on a comprehensive program to provide energy levels; dissociation, ionization, and activation energies; and all interaction cross sections and transition probabilities.

For a long time, the Bureau has carried out a basic program on the atomic properties of high-temperature gases. The results of the atomic energy levels program of the Spectroscopy Section have been effectively applied in astronomical research for decades, but this work has been geared primarily to the traditional requirements of astrophysics. In the past, astrophysics has generally assumed equilibrium conditions, and accordingly has set highest priority on energy level schemes, on wavelength standards, and relative f-values, rather than on absolute transition probabilities and on thermal collision cross sections. The plasma and astrophysics program requires substantial programs in all three of these areas. It is not feasible to wait until the program on energy levels is completed to attack the probability and cross section aspects. Absolute transition probabilities of spectral lines are required if spectroscopic methods are to be used to determine the state of a gas in the absence of LTE. The cross sections for absorption and emission of continuous radiation through photoionization and photodetachment must also be known.

A wide range of information is needed about the absolute cross sections for simple collisional processes - such as a spectral excitation and ionization by electron, ion, and atom impact - as well as about the cross sections for many non-radiative processes - such as elastic scattering, charge transfer, dissociative recombination, and associative detachment. It is particularly important to develop theoretical tools for reliable prediction of these quantities. This ability to predict is an essential goal for physical research, for it permits information to be produced more quickly and completely, and with greater versatility. The theoretical tools can also be applied to situations in astrophysics which cannot be duplicated in the laboratory.

Thus, there must be not only a strong program of experimental research, but also a theoretical program closely correlated with it. Those experiments must be emphasized which are most likely to lead to increased theoretical understanding. While all the elements are relevant to the program, special emphasis should be given to hydrogen, helium, carbon, nitrogen, oxygen, iron, and the light metals because of their abundance and theoretical importance.

The program which is needed, and for which the facilities and interests of the Bureau's Atomic Physics Division and parts of the Heat Division are most appropriate, is outlined below:

1. Atomic and Molecular Energy Levels

a. Analyses of atomic spectra; revision of solar spectrum tables; preparation of new multiplet tables; extensive observations of new rare earth spectra in different states of ionization; investigation of spectra in the vacuum ultraviolet region.

b. Completion of atomic energy levels work on rare earth spectra; investigations of gaps in analyses of other selected spectra; ultraviolet solar spectroscopy; special hyperfine and radiofrequency spectroscopy of astrophysical interest.

c. Analysis and compilation of important molecular electronic spectra.

d. Determination of ionization potentials, which for the most part require more vacuum ultraviolet work under the AEL program and electron affinities.

e. Binding energy calculations.

f. Activation energy determinations for reactions of interest in geophysics, astrophysics, and aerodynamics.

2. Transition Probabilities

a. Measurement of atomic transition probabilities for a broad class of spectra and on an absolute quantitative basis.

b. Determination of natural line shapes and the influence of Zeeman, Stark, and Paschen-Back effects on transition probability and line shape.

c. Measurement of continuous absorption coefficients for photoionization, photodetachment, and free-free absorption; cross sections for the reverse processes.

d. Development of fundamental radiation theory.

3. Collision Cross Sections

a. Studies of the excitation and ionization of atoms and ions by electron impact, especially near threshold.

b. Investigations ot the elastic scattering of electrons by atoms and ions.

c. Heavy-particle collision studies: Collisional recombination; attachment, mutual neutralization, charge transfer, associative detachment, and similar ionic reactions; and excitation and ionization by fast atom impact.

d. Collisional line broadening and frequency shift investigations from the microscopic point of view.

e. Studies of high-temperature chemical reactions and collision cross sections involving neutral atoms, molecules, and surfaces, including ablation, sputtering, and accommodation coefficients.

f. Development of fundamental collision theory.

B. Gases under Near-Equilibrium Conditions, or in Idealized Configurations

Efforts are also underway to achieve greater physical insight into high-temperature phenomena and subsequently to develop methods of characterizing high-temperature gases not in local thermodynamic equilibrium. This work, which will take the equilibrium state as the point of departure, will include studies of spectroscopic and radio-frequency diagnostic methods; determinations of collective atomic parameters which depend on many-body interactions or thermal interaction energies such as line shapes, recombination rate coefficients, and thermodynamic properties at high temperatures; and development of magnetohydrodynamic theory.

This work requires as a basis the values of the atomic parameters for interactions between various energy states. For example, these parameters are essential for the investigation of rate processes characterizing interactions. This investigation in turn makes it possible to specify both the types of ions present in a gas of given chemical composition and the distribution functions giving the occupation numbers of the various energetic states as functions of electron temperature and electron density. As distribution functions are given uniquely by the temperature and density only under conditions of thermodynamic equilibrium, no knowledge of atomic interaction parameters is required. When, however, there exists in the gas a flux of energy, the gas is, in general, not able to "relax" to the LTE configuration, so that the LTE distribution functions are not adequate to describe the gas. If, for example, a flux of non-radiative energy is the energy source, while the dissipation is largely radiative, cyclic processes are established in the gas which retains the non-LTE configuration. Under certain circumstances, groups of energetic states may be strongly coupled among themselves. This permits their relative description by an "effective" temperature, which, however, differs considerably from group to group. Under other circumstances, the relative occupation numbers of each two energy levels require a different "temperature" parameter. Such a variety of situations is encountered in glow discharges in the laboratory, in the ionosphere, in the outer solar atmosphere, and in other gaseous atmospheres encountered in astrophysics. All these processes must be studied theoretically, experimentally, and observationally and the results of the three approaches combined to gain physical insight and make progress.

High-temperature gases and plasmas are studied primarily by optical and radiofrequency spectroscopy. The interaction of radiation with a plasma is governed not only by the atomic properties of the individual particles in the gas, but also by collective properties, such as Holtzmark broadened spectral lines, plasma oscillations, interaction of a plasma with long-wavelength radiation, perturbation of energy levels and transition probabilities by long-range interactions, and so forth. These properties must be investigated in "idealized" plasmas, whose state is well known whether it is or is not near thermal equilibrium. Furthermore, it is desirable for many purposes that such experimental plasmas be optically "thin" and in collisional equilibrium, that is, that a small fraction of the energy be dissipated through radiation. These conditions are often very difficult to achieve, for optical lines are often self absorbed to some degree. The situation is even less promising in the microwave continuum of ultra-high temperature plasmas, which are often completely opaque in the normally accessible frequency range.

This part of the program can be divided into three parts: The technological development of methods to produce a hot, partially ionized gas in the laboratory; laboratory diagnostic studies of this plasma to provide thermodynamic parameters, such as electron temperature and electron density, and to lead to further understanding of atomic phenomena such as line-broadening; and theoretical developments necessary to synthesize and interpret experimental results. A fourth aspect of great importance, the application of the experimental and theoretical developments to observations of natural phenomena, such as the ionosphere and solar atmosphere, falls mainly in part C of this note, although no hard and fast division can be made. In the laboratory programs, the Heat Division in Washington and the Gaseous Physics Group in Boulder, Colorado, will have the most extensive effort, with more limited participation from the Mechanics and Applied Mathematics Divisions in Washington. The Heat Division will contribute mainly to the thermodynamic aspect by extending its high temperature program into the very-high-temperature range (10,000 to 10,000,000°K). The Boulder Laboratories' experimental work will utilize extensive experience in microwave probing and ionospheric physics. Parts B and C will be linked at the Boulder Laboratories through the optical spectroscopy programs, with its strong interrelation with the microwave diagnostics on one hand and the ionospheric and solar observations on the other. The theoretical work on non-LTE astrophysics will provide a bridge between the theoretical studies in this part of the program, and those in section C. It should be emphasized that a large body of theory on the non-LTE configuration has been already developed in this astrophysics program which is applicable both to the laboratory and the astrophysical environment.

Fully ionized gases have special macroscopic dynamic properties caused by their strong reactions to electric and magnetic fields. The properties form the subject of an extensive and complex theory in the currently developing field of magnetohydrodynamics. Here again, the fundamentals of this theory are properly part of this phase of the program, but its application to practical situations (in which velocity fields and instabilities occur) falls into part C. An outline of the studies of gases under near-equilibrium or idealized conditions (part B) is presented below.

1. Sources of Plasmas for Quantative Laboratory Studies

a. Conventional plasma arc "thermometry:" Study of the effects of transition probabilities on assessing the approach to LTE in the arc.

b. Production of plasmas and high-temperature gases in conventional shock tubes; in shocks generated electromagnetically, as in exploding wires, in magnetic shocks, and in resonating shock tubes; development of high-speed microwave, spectroscopic, and optical techniques; design of new methods of plasma generation suitable for quantitative studies.

2. Plasma Diagnostics and Collective Atomic Parameters

a. Theoretical investigations and measurements of cross sections and reaction rates for many-body interactions which are not amenable to direct microscopic measurement - such as three-body recombination, attachment, reassociation, and free-free absorption and emission in fields of atoms and ions.

b. Experimental and theoretical studies of averaged or statistical atomic properties which cannot be studied by direct microscopic measurement - such as electron and ion mobilities, collision frequency, velocity-averaged two-body recombination and attachment coefficients, and thermodynamic properties at ultra-high temperatures.[3]

c. Utilization of the above sources of plasmas in applying high-speed microwave methods to determine electron density, collision frequency, and shock velocity: Studies of thermal and nonthermal rf noise emission from plasmas related to rf noise standards.

d. Application of spectroscopic methods to determine line shapes under suitably controlled conditions and to study the broadening mechanisms; use of known transition probabilities to determine distribution of atomic states.

e. New diagnostic methods, such as particle velocity analysis by mass spectrometry; gamma-ray, X-ray, and neutron spectroscopy; Cerenkov radiation from probing particle beams; electron beam probes; and neutral beam attenuation.

f. Interactions of shock waves and plasmas with surfaces; influences of wall materials.

3. Statistical, Molecular, and Hydrodynamic Theory

a. Non-equilibrium statistical mechanics, including the study of many-body problems; the development of foundations for statistical mechanics, and the investigation of cooperative phenomena and transport properties, including radiation fields.

b. Determination of the thermodynamic transport properties of ionized gases through a study of long-range molecular forces and relevant molecular properties.

c. Investigation of the fundamental aspects of the flow of an ionized gas through electric and magnetic fields, including kinetic equations, electrical conductivity, and electrical hydrodynamics.

C. Phenomena Far from Equilibrium; Astrophysical and Geophysical Applications

In this phase of the program, data on atomic properties and on defined non-LTE gases are applied, with the appropriate diagnostic techniques, to astrophysical, geophysical, and specialized

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[3] In other words, plasma reaction rates rather than cross sections. This approach is taken only when direct approach fails, and then with careful attention to the actual distributions which are averaged in the measurement.

laboratory configurations. In this way it is possible to arrive at a physical understanding of these configurations and at the same time to test the efficacy of the diagnostic methods.

The configurations of interest occur in a very wide range of non-LTE states, ranging from ionized gas in interstellar space at kinetic temperatures of only 50°K to transient discharges in the laboratory and hot stellar atmospheres in the multimillion degree range. For purposes of discussion, it is convenient to distinguish four classes of configurations: the "very hot" (totally ionized) plasma with mean kinetic energies in the range $kT \sim 100$ ev ($T \sim$ 1,000,000°K), such as laboratory thermonuclear plasmas, stellar coronas, and possibly certain explosions; the "hot" plasma, substantially but not totally ionized, with kinetic temperatures of the order of $1 \text{ ev} < kT < 100$ ev, such as in strong arc and spark discharges, shock waves, stellar atmospheres, and certain interstellar regions; the "cool" plasma, weakly ionized with low-energy electrons ($1/20 \text{ ev} < kT <$ a few ev), often in room temperature gases, such as weak electric discharges, the earth's ionosphere and exosphere, and atmospheres of the cooler stars, certain flames, and low velocity waves; the unappreciably ionized, non-LTE gas, in which the energy transport of interest is through atomic collisions or chemical ractions. For each of these configurations, there are three characteristics of major interest: the properties of the configuration as a medium for the transmission of rf radiation; its properties in the astrophysical sense of inferring physical state from analysis of the optical and rf radiation emitted; and its peculiar dynamical properties due to its ionized state - the long-range interactions of the particles with each other and their interaction with external macroscopic magnetic fields.

The first two of these properties for "hot" and "cool" plasmas have been the subject of extensive study at the NBS Boulder Laboratories independently and in collaboration with the Sacremento Peak Observatory and the High Altitude Observatory. In addition, there has been an intensive theoretical effort on the astrophysical aspects, particularly on the theory of the solar atmosphere. Continued at their present level, and supplemented by the information provided in parts A and B of the program, these efforts are nearly adequate; additional theoretical work of a modest nature is required. Effort on the third property has been quite small.

Only a beginning has been made in the investigation of the "very hot" plasma. A very interesting project carried out by a group from the Boulder Laboratories at the British Atomic Energy Laboratories at Harwell consisted of a successful attempt to adapt a novel millimeter wave technique (Whistler mode propagation) to the measurement of the very high electron concentrations in a pinched discharge in the thermonuclear device Zeta.

A topical outline of the program which should be launched follows:

1. The Plasma as an rf Medium

a. Studies of extraordinary ray propagation in magnetized thermonuclear plasmas; em-wave boundary value problems and propagation in guided structures with plasmas as a medium; effect of inhomogeneities that are small compared to wavelengths in static media; propagation in turbulent and moving media.

b. Investigation of microwave propagation and microwave boundary value experiments as a diagnostic aid; diagnostic study of detonation and shock fronts by reflection and absorption.

c. Development of millimeter wavelength techniques as a further aid in diagnostics.

2. The Plasma as an Astrophysical and Geophysical Configuration, Natural and Simulated

a. Theoretical and analytical interpretation of present NBS-Sacremento Peak-High Altitude Observatory observational data on sun, airglow, ionosphere, general stellar atmospheres, and interplanetary and interstellar media.

b. Attempts to simulate astrophysical and geophysical effects in the laboratory by hydromagnetic coupling of atmospheric motions with microscopic accelerations; experimental studies of simple dynamical problems to develop analytical insight.

3. The Plasma as a Dynamical Phenomenon

a. Studies of confining fields as an aid to the production of hot plasmas; motions of weakly and more strongly ionized gases under magnetic fields; microscopic forces operating in plasma to distinguish the cases where hard collisions dominate from the cases where Coulomb interactions dominate.

b. Shock formation and propagation studies of exploding wires and explosive detonations.

c. Solving aerodynamic problems of flow for wholly gaseous mediums without a boundary, and for cases where the gas flows around and against a solid surface.

d. Development of magnetohydrodynamic theory accompanied by studies of trapped magnetic fields and instabilities.

IV. APPENDIX

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(Selected papers during the period 1955-1959)

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c. Line Shapes, Intensities, and Transition Probabilities

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d. Photoionization, Photodetachment

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e. Negative Ion Binding Energies

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f. Collision Cross Sections

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a. Theory of Non-Equilibrium Rate Processes and Mechanics

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b. Chemical Kinetics, Experimental

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c. Gas Phase Chemiluminescence

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e. Thermodynamic Properties of Ionized Gas

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a. Plasma Physics

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b. Astrophysics

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c. Solar Physics

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d. Upper Atmosphere Physics - Airglow and Aurorae

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e. Ionosphere

Chapman, S., The earth and its environment, Proc. Inst. Radio Engrs. 47, 137 (1959).

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Roach, F. E., The night airglow, Proc. Inst. Radio Engrs. 47, 267 (1959).

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B. PARTIAL LIST OF PARTICIPANTS

There follows a partial list of scientists engaged in activities described in this note, with indications of their research fields and organizational location within the National Bureau of Standards. The latter may be helpful in making contact with individuals for the purpose of obtaining reprints or further technical information.

ALLEN, Harry C., Jr.: Ph.D., University of Washington (Seattle), 1951; theory of molecular structure; Atomic Physics Division, Radiometry Section (at Cambridge University, Cambridge, England, through September, 1960).

BASS, Arnold M.: Ph.D., Duke University, 1949; spectroscopy with emphasis on the spectra of molecules in solids at low temperature, and on the use of spectroscopic methods in high temperature measurement; Heat Division, Chief, Free Radicals Section.

BEATY, Earl C.: Ph.D., Washington University, 1956; atomic mobilities and optical pumping, atomic clocks; Atomic Physics Division, Atomic Physics Section.

BECKETT, Charles W.: Ph.D., University of California, 1945; dynamic and transfer properties and related structural properties of matter throughout the temperature range from ordinary temperatures up to millions of degrees; Assistant Chief, Heat Division.

BRANSCOMB, Lewis M.: Ph.D., Harvard University, 1949; ionic physics and atomic collision phenomena, upper atmosphere physics; Chief, Atomic Physics Division.

BROIDA, Herbert P.: Ph.D., Harvard University, 1949; molecular spectroscopy, chemical physics, spectra of condensed radicals; Heat Division, Free Radicals Section (at University of Cambridge, Cambridge, England, through December, 1960).

BROWN, Lawrence M.: Ph.D. candidate, Catholic University; equation of state of gases, shock waves, exploding wire phenomena, compilation of properties of isotopic hydrogen compounds, review of isotope effects on chemical reaction rates; Heat Division, Equation of State Section.

CARRINGTON, Tucker: Ph.D., California Institute of Technology, 1952; spectroscopic study of molecular collisions; Heat Division, Molecular Kinetics Section.

COOPER, J. W.: Theoretical physics; photoionization cross sections; Office of the Director.

CORLISS, Charles H.: Spectrochemical analysis, description of atomic spectra, measurement of spectral intensity, development of spectroscopic light sources; Atomic Physics Division, Spectroscopy Section.

DIBELER, Vernon H.: Ph.D., Columbia University, 1950; application of mass spectrometry to molecular physics, electron impact phenomena in molecular gases; Atomic Physics Division, Mass Spectrometry Section.

FANO, U.: Dr. Sc., University Torino, Italy, 1929-34; theoretical physics, scattering theory, radiation transfer through materials; Office of the Director, Consultant.

GELTMAN, Sydney: Ph.D., Yale University, 1952; theory of ionic mobilities, atomic scattering, ionization, and photodetachment; Atomic Physics Division, Atomic Physics Section.

GREEN, Melville S.: Ph.D., Princeton, 1951; statistical mechanics of time-dependent phenomena, quantum statistical mechanics of many-body systems; equilibrium transport properties at high temperatures; Heat Division, Chief, Statistical Physics Section.

HERRON, John T.: Ph.D., McGill University, 1957; appearance potentials of positive and negative ions in halogen molecules; Atomic Physics Division, Mass Spectrometry Section.

HERZFELD, Charles M.: Ph.D., University of Chicago, 1951; solid state physics, trapped radicals, theory of spectra of atoms and solids, group theory; Chief, Heat Division.

HILSENRATH, Joseph: Thermodynamic properties of gases, liquids, and solids, high pressure thermodynamics, equation of state of highly ionized gases; Heat Division, Chief, Equation of State Section.

JACKSON, J. L.: Ph.D., New York University, 1950; application of statistical methods to various fields of physics, in particular - plasmas, trapped radicals, irreversible statistical mechanics, crystallization of polymers, and electrical noise; Heat Division, Statistical Physics Section.

KESSLER, Karl G.: Ph.D., University of Michigan, 1947; atomic spectra, wavelength standards of length; Atomic Physics Division, Chief, Spectroscopy Section.

KLEIN, M.: Ph.D. candidate, University of Maryland; transport and equilibrium properties of gases; Heat Division, Statistical Physics Section.

KOSTKOWSKI, Henry J.: Ph.D., Johns Hopkins University, 1954; infrared spectroscopy, temperatures of flames, optical pyrometry, plasma thermometry; Heat Division, Temperature Physics Section.

KRAUSS, Morris: Ph.D., University of Utah, 1955; molecular orbitals, mass spectra; Chemistry Division, Thermochemistry Section.

MARTIN, William C.: Ph.D., Princeton, 1956; atomic spectra; Atomic Physics Division, Spectroscopy Section.

MARTON, L.: Ph.D., University of Zurich, 1924; electron optics, interferometry, electron scattering in solids and gases; Atomic Physics Division, Chief, Electron Physics Section.

McKINLEY, John D., Jr.: Ph.D., New York University, 1953; kinetics of heterogeneous reactions; Heat Division, Molecular Kinetics Section.

MEIJER, Paul H. E.: Ph.D., Leyden University, 1950; theoretical physics, statistical mechanics, and quantum theory; Consultant, Heat Division (part-time at Catholic University).

MENDLOWITZ, Harold: Ph.D., University of Michigan, 1954; characteristic electron energy losses in solids, electron optics, electron-nuclear scattering, plasmas in solids, electron polarization, oscillator strengths, optical properties of solids, atomic scattering; Atomic Physics Division, Electron Physics Section.

MOHLER, Fred L.: Ph.D., Johns Hopkins University, 1917; atomic physics, ionization potentials, physics of the cesium positive column plasma, mass spectrometry; Atomic Physics Division, Chief, Mass Spectrometry Section.

NICHOLLS, Ralph W.: Ph.D., University of London, 1951; experimental and theoretical laboratory studies on molecular spectra of astrophysical, aeronomical, combustion, and radiation chemical interest; Heat Division (temporarily on leave of absence for the academic year 1959-60 from the University of Western Ontario).

OPPENHEIM, I.: Ph.D., Yale University, 1952; fundamentals of statistical mechanics and the statistical mechanics of fluids and plasmas, transport processes; Heat Division, Statistical Mechanics Section (at Convair, San Diego, through December, 1960).

PICCIRELLI, R. A.: Ph.D., Catholic University, 1956; statistical mechanics, evaluation of the quantum partition function, generalization of the Boltzmann equation to higher densities and to include inhomogeneities, derivation of a kinetic equation for plasmas which includes all collision effects; Heat Division, Statistical Physic Section.

PLYLER, Earle K.: Ph.D., Cornell University, 1924; infrared emission and absorption spectra; Atomic Physics Division, Chief, Radiometry Section.

REESE, Robert M.: Measuring excitation functions of multiply charged ions near the threshold; Atomic Physics Division, Mass Spectrometry Section.

RUBIN, Robert J.: Ph.D., Cornell University, 1951; plastic wave propagation in materials exhibiting strain-rate effects, vibrational relaxation and its influence on relative line intensities of diatomic molecules, chemical exchange reaction probabilities, models for Brownian motion; Heat Division, Temperature Physics Section.

SCHEER, Milton D.: Ph.D., New York University, 1951; kinetics of surface ionization and low temperature chemistry; Heat Division, Molecular Kinetics Section.

SCHUBAUER, Galen B.: Ph.D., Johns Hopkins University, 1934; aerodynamics, hydrodynamics, and hydraulics, specific field - turbulence and boundary layer research; Mechanics Division, Chief, Fluid Mechanics Section.

SHULER, Kurt E.: Ph.D., Catholic University, 1949; theoretical chemical physics, energy transfer in inelastic collisions, relaxation phenomena, non-equilibrium statistical mechanics; Consultant to the Chief, Heat Division.

SHUMAKER, John B., Jr.: Ph.D., Yale University, 1952; spectroscopic measurements in arc plasmas; Heat Division, Temperature Physics Section.

SIMPSON, J. Arol: Ph.D., Lehigh University, 1953; characteristic energy losses, electron spectroscopy; Atomic Physics Division, Electron Physics Section.

SITTERLY, Charlotte M.: Ph.D., University of California, 1931; compilation of atomic energy levels, preparation of multiplet tables, study of atomic spectra, identification of solar lines; Atomic Physics Division, Spectroscopy Section.

SMITH, Stephen J.: Ph.D., Harvard University, 1954; photodetachment of negative ions; electron-atom interaction; Atomic Physics Division, Chief, Atomic Physics Section.

TCHEN, Chan Mou: Dr. of Tech. Sci, Technical University, Delft, 1947; hydrodynamics, stochastic processes, theoretical plasma physics; Applied Mathematics Division, Mathematical Physics Section.

THOMPSON, R.: Experimental plasma physics; Heat Division, Equation of State Section.

TREES, Richard E.: Ph.D., University of Pennsylvania, 1951; atomic energy levels; Atomic Physics Division, Spectroscopy Section.

TSAI, D.: Sc.D., Massachusetts Institute of Technology, 1952; aircraft pneumatics, high temperature pvt measurement; Heat Division, Equation of State Section.

WIESE, Wolfgang L.: Ph.D., University of Kiel, Germany, 1957; plasma physics, atomic transition probabilities; Atomic Physics Division, Spectroscopy Section.

WOOLLEY, H. W.: Ph.D., University of Michigan, 1955; thermodynamic properties of hydrogen isotopes, ortho-para effects, ideal gas properties, gas imperfection effects, third virial coefficient, equations of state, thermodynamic functions for atoms and atomic ions at high temperature, equilibrium properties of gases at high temperatures; Heat Division, Statistical Physics Section.

ZWANZIG, R.: Ph.D., California Institute of Technology, 1952; statistical mechanics; Heat Division, Statistical Physics Section.

ZALUBAS, R.: Ph.D., Georgetown University, 1955; description and analysis of atomic spectra; Atomic Physics Division, Spectroscopy Section.

Participants in the Boulder Laboratories:

BAILEY, D. K.: Ionospheric physics, scatter propagation, physics of the lower ionosphere and cosmis rays; Radio Propagation Physics Division (Boulder).

GALLET, R. M.: Certificates in philosophy, physics, and mathematics, University of Sorbonne, 1942-43; theory of the exosphere, plasma physics, radio astronomy; Radio Propagation Physics Division, Chief, Upper Atmosphere Research Section (Boulder).

GATES, D.: Ph.D., University of Michigan, 1948; infrared spectroscopy of the upper atmosphere; Assistant Chief, Radio Propagation Physics Division (Boulder).

POWERS, R. S.: Candidate for Ph.D., University of Wisconsin; scattering theory and transport properties of gases; Gaseous Physics Group (Boulder).

RICHARDSON, J. M.: Ph.D., Harvard University, 1951; microwave standards, microwave spectroscopy of O_2 with application to atomic frequency standards, millimeter wave measurements and interferometry, plasma physics with regard to the interaction of microwave radiation with plasmas; Chief, Gaseous Physics Group (Boulder).

ROACH, F. E.: Ph.D., University of Chicago, 1934; upper atmosphere physics, physics of the airglow; Radio Propagation Physics Division, Chief, Airglow and Aurora Section.

ROHRLICH, F.: Ph.D., Harvard University, 1948; elementary particles, quantum electrodynamics, scattering theory, theory of atomic spectra; Consultant, Director's Office, (Boulder).

THOMAS, R. N.: Ph.D., Harvard University, 1948; theory of stellar atmospheres and radiation transfer in hot gases, gas dynamics; Consultant, Director's Office (Boulder).

VanZANDT, T.: Ph.D., Yale University, 1954; upper atmosphere theory, physics of the F2 layer; Radio Propagation Physics Division, Sun-Earth Relationships Section (Boulder).

WACKER, P. S.: Ph.D., Catholic University, 1954; microwave spectroscopy and molecular structure; Consultant, Radio Standards Laboratory. (Boulder).

WARWICK, C.: Ph.D., Radcliffe, 1952; solar physics and related ionospheric physics; Radio Propagation Physics Division, Sun-Earth Relationships Section (Boulder).

U.S. DEPARTMENT OF COMMERCE
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THE NATIONAL BUREAU OF STANDARDS

The scope of activities of the National Bureau of Standards at its major laboratories in Washington, D.C., and Boulder, Colorado, is suggested in the following listing of the divisions and sections engaged in technical work. In general, each section carries out specialized research, development, and engineering in the field indicated by its title. A brief description of the activities, and of the resultant publications, appears on the inside of the front cover.

WASHINGTON, D.C.

Electricity and Electronics. Resistance and Reactance. Electron Devices. Electrical Instruments. Magnetic Measurements. Dielectrics. Engineering Electronics. Electronic Instrumentation. Electrochemistry.

Optics and Metrology. Photometry and Colorimetry. Photographic Technology. Length. Engineering Metrology.

Heat. Temperature Physics. Thermodynamics. Cryogenic Physics. Rheology. Molecular Kinetics. Free Radicals Research.

Atomic and Radiation Physics. Spectroscopy. Radiometry. Mass Spectrometry. Solid State Physics. Electron Physics. Atomic Physics. Neutron Physics. Radiation Theory. Radioactivity. X-rays. High Energy Radiation. Nucleonic Instrumentation. Radiological Equipment.

Chemistry. Organic Coatings. Surface Chemistry. Organic Chemistry. Analytical Chemistry. Inorganic Chemistry. Electrodeposition. Molecular Structure and Properties of Gases. Physical Chemistry. Thermochemistry. Spectrochemistry. Pure Substances.

Mechanics. Sound. Mechanical Instruments. Fluid Mechanics. Engineering Mechanics. Mass and Scale. Capacity, Density, and Fluid Meters. Combustion Controls.

Organic and Fibrous Materials. Rubber. Textiles. Paper. Leather. Testing and Specifications. Polymer Structure. Plastics. Dental Research.

Metallurgy. Thermal Metallurgy. Chemical Metallurgy. Mechanical Metallurgy. Corrosion. Metal Physics.

Mineral Products. Engineering Ceramics. Glass. Refractories. Enameled Metals. Constitution and Microstructure.

Building Technology. Structural Engineering. Fire Protection. Air Conditioning, Heating, and Refrigeration. Floor, Roof, and Wall Coverings. Codes and Safety Standards. Heat Transfer. Concreting Materials.

Applied Mathematics. Numerical Analysis. Computation. Statistical Engineering. Mathematical Physics.

Data Processing Systems. SEAC Engineering Group. Components and Techniques. Digital Circuitry. Digital Systems. Analog Systems. Application Engineering.

- Office of Basic Instrumentation.
- Office of Weights and Measures.

BOULDER, COLORADO

Cryogenic Engineering. Cryogenic Equipment. Cryogenic Processes. Properties of Materials. Gas Liquefaction.

Radio Propagation Physics. Upper Atmosphere Research. Ionospheric Research. Regular Propagation Services. Sun-Earth Relationships. VHF Research. Radio Warning Services. Airglow and Aurora. Radio Astronomy and Arctic Propagation.

Radio Propagation Engineering. Data Reduction Instrumentation. Modulation Research. Radio Noise. Tropospheric Measurements. Tropospheric Analysis. Propagation Obstacles Engineering. Radio-Meteorology. Lower Atmosphere Physics.

Radio Standards. High Frequency Electrical Standards. Radio Broadcast Service. High Frequency Impedance Standards. Electronic Calibration Center. Microwave Physics. Microwave Circuit Standards.

Radio Communication and Systems. Low Frequency and Very Low Frequency Research. High Frequency and Very High Frequency Research. Ultra High Frequency and Super High Frequency Research. Modulation Research. Antenna Research. Navigation Systems. Systems Analysis. Field Operations.

NBS