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INTERFERENCE MEASUREMENTS IN THE FIRST SPECTRA OF NEON, ARGON, AND KRYPTON BETWEEN 4812 AND 3319 A[1]

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ABSTRACT

Wave-length measurements in the first spectra of neon, argon, and krypton have been made, using Fabry-Perot interferometers with aluminized quartz plates and etalons of 3, 7.5, 8, 8.4, 15, 20, and 25 mm length. The wave lengths have been determined relative to the adopted International Wave-Length Standards in Kr I. All but three of the 30 possible $1s-3p$ lines of Ne I are intense enough to permit interference measurements. This group lies between 3754 and 3370 A.

New measurements are reported of the intense $1s-3p$ group of A I, previously measured relative to Ne and Cd standards, but here, for the first time, relative to Kr I. The argon measurements also include 17 ultraviolet lines, the last at 3319 A.

Measurements in Kr I comprise 30 lines of wave lengths shorter than 4274 A, the limit of previous work. An additional f-type series has been revealed. It is now possible, by interference methods, to fix the various p-series of Kr I to four members. In addition, measurements were made of seven krypton lines between 4812 and 4302 A, not included among the International Wave-Length Standards of 1935.

The short wave-length limit of these measurements is set by the intensity decrement of lines approaching the series limits, the $1s$-levels (^1P, ^3P) of the noble-gas spectra. It is expected that the more-intense lines will prove useful as wave-length standards. The neon group is the most promising in this respect. The possibility of a pressure effect in higher series lines in neon and argon has been investigated to a limited extent by comparing wave lengths obtained with Geissler tubes filled with gas to "low" and "high" pressures. Without drawing general conclusions, it may be stated that no such effect was observed for the $1s-3p$ lines of neon, but that the use of argon tubes filled to 20-mm pressure led to very marked line broadening and some evidence of pressure displacement.

Construction of arrays of term combinations indicates a relative accuracy of the measurements of the same degree as that obtained in the case of the adopted secondary standards.

CONTENTS

I. INTRODUCTION

The spectra of the noble gases, particularly neon and krypton, have found considerable application as sources of wave-length stand-

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[1] A preliminary report of these measurements was given at the Washington meeting of the American Physical Society, April 1937, Phys. Rev. **51**, 1018A (1937).

ards for spectroscopic measurements and metrology. In 1935 the International Astronomical Union, which sponsors the specification and adoption of such standards, adopted wave-length values of 20 lines each of neon and krypton as international secondary standards [1][2]. The neon and krypton scales are regarded as agreeing with that of the primary standard, the red line of cadmium (6438.4696 A), to within 1 part in 50,000,000.

The noble-gas spectra have been the subject of numerous investigations at this Bureau, and an extensive series of interference measurements has been made. A paper by Meggers and the author [2], published in 1934, reported interference measurements in He I, Ne I, A I, Kr I, and Xe I, between 10 830 and 3948 A, and included results of previous work for comparison. It was stated there that "Geissler tubes containing noble gases are at present the most convenient and reproducible sources of secondary standards of wave length." In the same paper, the relative merits of the various noble gases, from the point of view of suitability as sources of wave-length standards, were discussed. This discussion, which included consideration of limiting orders of interference, reversibility, and isotopic hyperfine structure, need not be repeated, although some further discussion of the effect of the presence of isotopic hyperfine structures on the measurement of interference patterns will be given.

The purpose of the present investigation was twofold: First, to extend the interference measurements into the ultraviolet region, where standards are greatly needed, and also to remeasure certain visible lines, particularly in case of argon, for which additional independent observations are desirable.

Unfortunately, the number of ultraviolet noble-gas lines of sufficient intensity for interference measurements is small. Examination of the term values [3] shows why this must be true. The same discussion applies in essentials to Ne I, A I, Kr I, and Xe I. The combinations with the normal state, $s^2p^6\ {}^1S_0$ all lie in the extreme ultraviolet observable only with vacuum spectrographs.

The $1s-2p$ combinations (Paschen notation [4]) comprise the most intense visible and infrared lines of the noble-gas spectra. The $1s-3p$ lines are all ultraviolet in neon, mostly visible in argon and krypton, and all visible in xenon. (Series converging to the $2p$ levels are all visible or infrared.) The available ultraviolet lines are limited therefore to higher series members of the $1s-np$ type and a few combinations with f-type levels. The short wave-length limit to the observations is set by the intensity decrement of lines approaching the series limits, the $1s$-levels (${}^1P$, ${}^3P$). The first spectra of the noble gases contain no lines between the $1s_5$ limits and the extreme ultraviolet combinations. These $1s_5$ limits have been evaluated as follows: Ne, 39887.6 cm^{-1} or 2506.3 A; A, 33767.7 cm^{-1} or 2943.1 A; Kr, 32943.2 cm^{-1} or 3034.6 A; and Xe 30766.4 cm^{-1} or 3249.4 A.

II. DISCUSSION OF PRESSURE EFFECT AND ISOTOPIC HYPERFINE STRUCTURE

A possible objection to the use of ultraviolet noble-gas lines as standards is that inasmuch as they involve combinations of high

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[2] Numbers in brackets refer to publications listed at the end of this paper.

levels they may be more susceptible to pressure effect than lines in the less refrangible part of the spectrum.

In 1936, Jackson [5] reported determinations relative to the cadmium primary standard of 47 visible and ultraviolet krypton lines between 6456 and 3424 A, including 14 of the ultraviolet lines measured in this investigation. He compared results from tubes filled to pressures of 0.1, 4, 10, and 20 mm of mercury. His results indicated pressure displacement proportional to the square of the pressure for any given term. The pressure shift was also found to be dependent only on the principal quantum number of the terms, within experimental error. It was concluded that the maximum operating pressures for the various krypton series, without introducing pressure shifts sufficient to affect interferometer comparisons by 0.0001 A, were as follows: for $1s-2p$, 10 mm; for $1s-3p$, 4 mm; and for $1s-4p$, less than 1 mm. The $1s-3p$ lines of neon which were observed in this investigation are analogous in origin to the blue krypton group, 4502 to 4273 A, comprising most of the adopted krypton secondary standards. One would expect the pressure effect to be of about the same magnitude for the corresponding transitions. It seems certain that no difficulty with pressure effect will be experienced if an operating pressure of the order of 1 mm is specified. The matter will be referred to again in connection with the account of our experimental work.

The effect of isotopic hyperfine structure on the wave-length measurements in neon has been the subject of considerable discussion, and it is felt that it can be treated in some detail here. The two abundant isotopes of neon are of atomic weight 20 and 22, in proportions of about 9 to 1. In the observed spectrum each neon line should have a close satellite due to isotope 22. Unless, however, the source is cooled by use of liquid air, this pattern is usually not resolved and the measured wave length will be that of the blend. The most probable comparator setting would be on the centroid of the pattern. Ritschl and Schober [6] have recently measured the isotope separation for all the strong neon lines, permitting a calculation of the displacements of a large number of terms.

Most of the $1s-2p$ lines have a separation of about 55×10^{-3} cm^{-1}, whereas in the case of the $1s-3p$ lines, it is generally about 85×10^{-3} cm^{-1}; the difference being due to the smaller displacement of higher p terms. It is apparent, therefore, that measurements of $1s-3p$ lines will be affected by isotope displacements to a slightly greater degree than those of $1s-2p$ lines. When interference patterns are measured, the effect of an unresolved satellite upon the apparent wave length depends upon the order of interference. The experience of various observers was discussed at the 1935 meeting of the IAU [7], and, in adopting the recommended standards in neon, it was agreed to specify "that they apply only to the conditions under which they were determined, viz., with interferometers of high resolving power but etalons not exceeding about 4 cm."

The following discussion based on the geometry of an interference pattern from a Fabry-Perot interferometer is intended to account for the observed results, in particular why a separation of 4 cm is somewhat critical for the neon case. The order of interference is given by

$$P=\frac{2e}{\lambda}\cos\theta, \quad [8]$$

where e is the separation (length of etalon) and θ is the angular separation of the fringe corresponding to P from the optical axis. The dispersion is given by the partial derivative

$$\frac{\delta\theta}{\delta\lambda}=-\frac{1}{\sin\theta}\frac{P}{2e}$$

Inasmuch as the ratio $P/2e$ is constant, it follows that for a given θ the separation of a satellite from a principal component will be constant. The angular separation of orders will, however, differ with retardation, and while a satellite will maintain its separation from the principal component of the same order, it will change its position with respect to the principal component of next higher or lower order. Figure 1 illustrates the interference pattern of a neon line for three different retardations. The faint line due to Ne 22 is always of shorter wave length than the heavy line due to Ne 20. It is first assumed that the pattern is resolved completely.

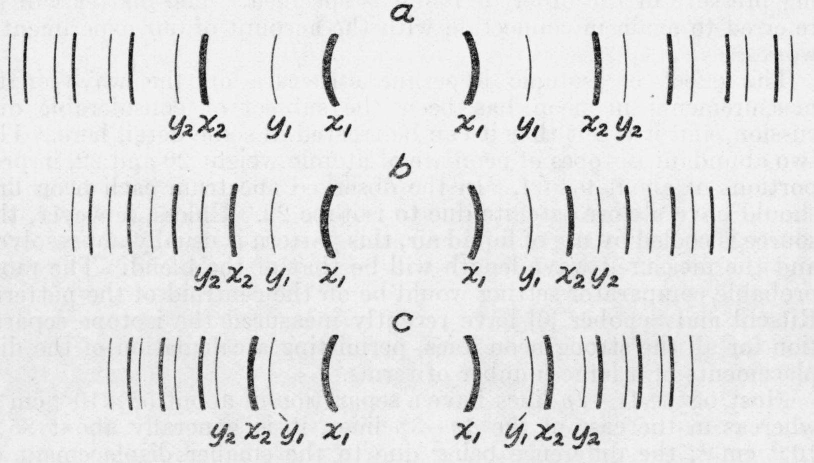

FIGURE 1.—*Effect of increasing interference path on hyperfine structure pattern consisting of two components, the fainter being of shorter wave length.*

Case a represents the pattern for a small separation. Case b shows the situation when the satellite is just midway between the principal components of successive orders. In case c, with increasing separation, the satellite y_1, although of the same order as x_1, is actually nearer to x_2. Suppose that the patterns are not resolved. For case a, the settings will fall outside the principal component, giving a result slightly smaller than if the setting were on the heavy fringe. For case b, the settings will be on the heavy components, so that the wave lengths will be those of Ne 20.

For case c, the settings will be inside and the apparent wave lengths will be greater. Another possibility is the superposition of the light and heavy fringes which will occur for twice the separation corresponding to case *b*. This will give the same result as for *b*.

We see then, that there will be a cycle of increasing and diminishing apparent wave lengths. We are hardly interested in more than one phase of it, however, for that will represent the maximum path over which neon interferences can occur. Case *b* will occur for the majority of the $1s-2p$ lines with an etalon of a little less than 5 cm. If we choose one of the $1s-3p$ lines, the critical value will be slightly less than 3 cm. This discussion agrees with the experience of observers that the neon red lines have apparent wave lengths somewhat smaller, if determined with etalons of less than 4 cm length, than if greater retardations are employed. Inasmuch as we have employed etalons of 2.5 cm or less in the present investigation, the results should be on the same scale as the adopted secondary standards in neon.

III. EXPERIMENTS

The interferometer consisted of the same pair of crystal quartz plates, coated with evaporated aluminum, which were used in the recent determination of wave lengths of iron in the ultraviolet region. The coated surfaces of these plates were separated by etalons each made of three invar rods of 3, 7.5, 8, 8.4, 15, 20, or 25 mm length. All of these etalons were used only in the observations of neon.

A Littrow-type quartz spectrograph (Hilger *E1*) was employed for most of the exposures, although a few exposures were made in a Cornu prism spectrograph (Hilger *E2*). Two Zeiss quartz-fluorite objectives were available for projecting the interference pattern upon the slit of the spectrograph, one of 25 cm, the other of 50-cm focal length, the choice being determined by the length of etalon. The 25-cm projector was used in a few instances with the 7.5-mm etalon and in all cases with the 3-mm etalon. The interferometer was illuminated with parallel light by means of a quartz lens. Care was taken to line up the interferometer and all optical accessories coincident with the axis of the spectrograph. The interferometer was also placed at such a distance from the ring projector as to be focused upon the prism of the spectrograph.

All wave-length determinations here reported are relative to the krypton secondary standards in the wave-length interval between 4502 and 4274 A [1]. Krypton was chosen because of the superior sharpness of the standard lines and because the location of these lines at the lower wave-length end of the visible region simplifies comparisons with lines in the same region and in the nearby ultraviolet, and minimizes errors due to the necessity of focusing a spectrograph for widely separated regions. In making measurements in the krypton spectrum relative to krypton standards only one source is needed, affording the obvious advantage of identical conditions of illumination for all lines. The same advantage might be claimed for comparing neon ultraviolet lines with neon standards, but the intensity disparity is so great that it is practically impossible to record the first without overexposing the latter. Krypton standards seemed the obvious choice for the argon comparisons, because the blue and violet argon lines lie in the same region as the krypton standards, so that atmospheric and phase corrections are negligible over a considerable wave-length interval. It was also felt that inasmuch as previous determinations had been made relative to cadmium or neon, it was advantageous to make independent comparisons with krypton.

The krypton sources were Geissler tubes purchased from Robert Götze, in Leipzig. These tubes are listed in the maker's catalog as type *D*. They have a small capillary bore, about 1.5 mm, cylindrical aluminum electrodes, and are designed for either end-on or side-on illumination. The pressures are not specified for the krypton-filled tubes, but in these experiments the discharge characteristics indicated 1 mm or less. The krypton tubes were always used in the side-on position.

Several different neon tubes were used, and part of these were of the same manufacture and type as the krypton tubes. Others were of similar design but of larger capillary bore, made by the Linde Air Products Co. Still another, filled with gas at a pressure of several millimeters, was used in a series of observations to see whether pressure displacements could be measured. No systematic variations were found in the results to indicate that wave lengths obtained from different tubes were not identical within the limits of accidental error.

Both Linde and Götze argon tubes were used. The exhaustion of our supply of "low" pressure Götze tubes early in the investigation proved something of a handicap, because the illumination from the Linde tubes was of low intensity. Götze tubes filled to a pressure of 20 mm of Hg did not prove satisfactory, because there was very noticeable line broadening and some evidence of pressure displacement. It is not felt that the present investigation warrants any conclusions regarding pressure effect, except that it is a negligible factor if the pressures within the sources are of the order of 1 mm of Hg.

The pressure in a tube filled with a noble gas diminishes during operation due to the occlusion of gas by material sputtered from the electrodes. This is the usual cause of eventual tube failure. This lowering of pressure during use makes an accurate quantitative estimate of pressure in a sealed tube practically impossible. We have already referred to the work of Jackson [5] on the pressure effect of krypton. Further quantitative measurements are desirable in view of theoretical studies which are being made [9]. In any such investigation the sources should be connected to pressure gages, permitting simultaneous accurate determinations of both wave lengths and pressures.

Because of the difference in intensities of the various lines, a very large range in exposure times was necessary to record satisfactory patterns. These ranged from a few minutes for the strongest neon lines to 16 hours for the weakest krypton lines. Patterns of krypton and neon photographed with a 3-mm etalon are reproduced in figure 2. With this interference path, the fringes of close neon pairs at 3593, 3418, and 3370 A are fully separated.

In the work with neon or argon where two sources are required, simultaneous exposures were made in most instances. This procedure necessitates such a disposition of both sources that each illuminates the apparatus in a manner optically equivalent. The usual scheme

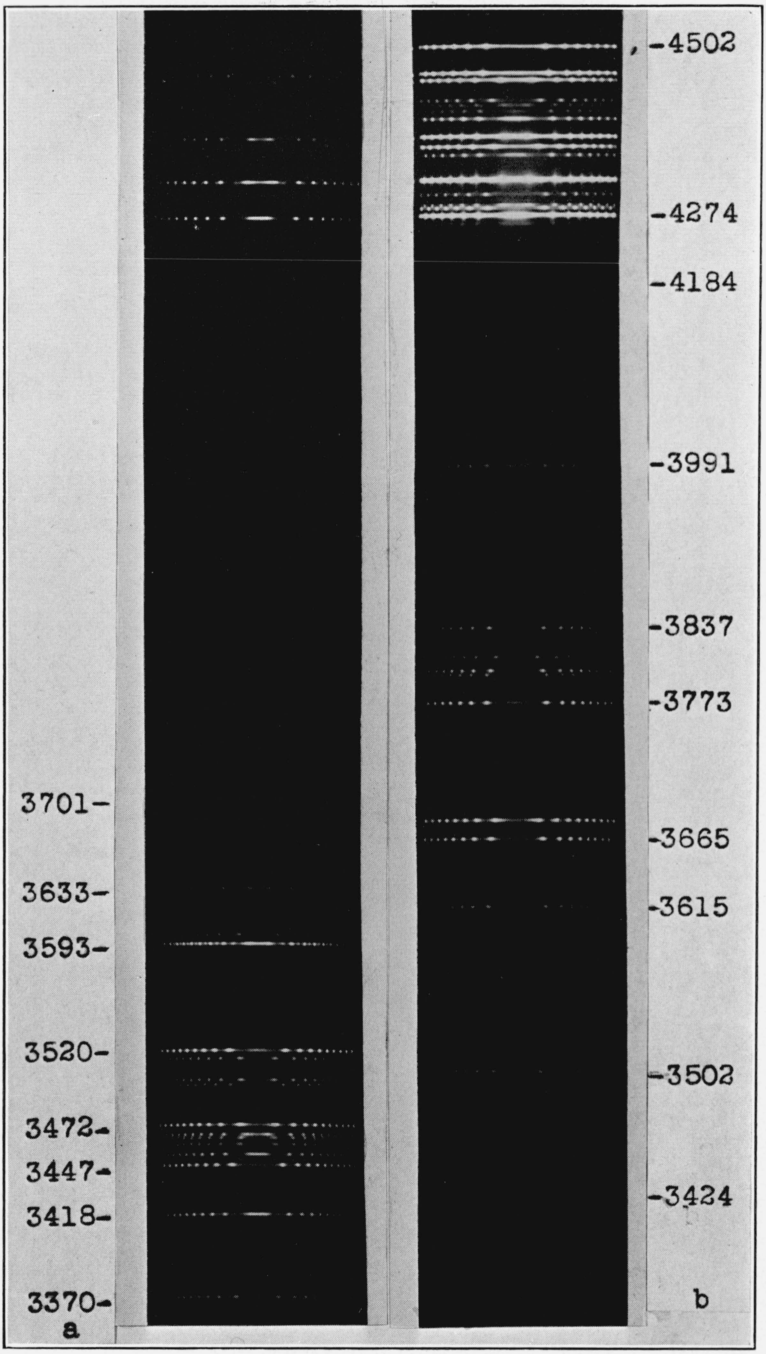

FIGURE 2.—*Fabry-Perot interference patterns of (a) neon photographed simultaneously with krypton and (b) krypton (3-mm etalon).*

is to place an inclined transparent plane mirror (a quartz plate in these experiments) between the first source and condensing lens, and reflect light from the second source into the path of the direct beam by aid of this mirror. The choice of sources for the two positions will depend on the relative intensities of the lines to be compared. A second scheme, feasible only if one of the tubes is of large capillary bore, is to place this tube in the correct position for best illumination of the interferometer. Behind the source and in line with the other units in the setup is placed a concave mirror at a distance about equal to its radius of curvature and slightly inclined to the axis. The second source is placed at the conjugate focus of this mirror and its image is brought into coincidence with the first source. In the smaller number of instances where exposures were alternated, the alternations were made frequently and the total exposure time was short, so that on the average the atmospheric conditions during the exposure of each tube could be regarded as equivalent.

The procedure of measuring, reducing, correcting, and adjusting the observations to arrive at the final reported wave-length values was carried out in accordance with methods which have been described fully in other publications. The theory of the Fabry-Perot interferometer given originally by Fabry and Buisson [10] was discussed in some detail in an earlier paper by the author [8]. The interference patterns were measured with the micrometer designed for this purpose, which is illustrated in the recent publication on interference measurements in the iron spectrum [11]. This paper also gives the details of the method of reducing observations which is followed at present. As far as possible, the same over-all size of interference pattern was measured for both primary and secondary standards. This could be accomplished conveniently by measuring the diameters of five rings in the ultraviolet and four in the region of the krypton standards. The correct order numbers for the standard lines and the length of the interference path were obtained by the method illustrated for neon by Meggers [12].

The corrections for deviations of atmospheric density from standard conditions (dry air at 15° C and 760 mm of Hg) derived from observations of the mean air temperature and barometric pressure for each exposure, were taken from tables prepared for this purpose by Meggers and Peters [13].

The corrections for dispersion of phase change at reflection were obtained by comparison of the data from 25- and 3-mm etalons, 20- and 3-mm etalons, and 7.5- and 3-mm etalons [12]. These corrections were positive below 3950 A and increased in magnitude to a maximum near 3400, amounting to about 0.001 A for the 7.5 etalon in this region. This behavior of the plates, a little surprising in view of the negative correction in the region between 3500 and 2000 A found when iron wave lengths were determined relative to neon, indicates that the correction curve has a minimum near 4000 A and a maximum near 3400 A.

IV. RESULTS

The final results of the determinations of wave length in the first spectra of neon, argon, and krypton are presented in tables 1, 3, and 5. The values were arrived at by taking a weighted mean of the averages of the corrected values obtained with the various etalons. The weights were based on the number of observations and the length of interference path, except in cases of pairs of lines most clearly resolved by certain etalons, in which cases the weights were chosen arbitrarily. The total number of observations is reported with each wave length.

Construction of arrays of term combinations, as displayed in tables 2, 4, and 6, shows that term differences are repeated to within one- or two-thousandths of a wave number in the great majority of cases. The retention of eight figures in the reported wave-length values is amply justified in all but a few cases. Calculation of the probable error of the weighted mean gave an average probable error of about 1 in the eighth place and gave a little under 3 for the neon wave length regarded as being least reliably determined. These probable errors are not reported because it is questioned if the variation in observed values, after all corrections are applied, conforms closely enough to the theory of accidental errors. For instance, it frequently happens that individual values obtained with the same etalon agree more closely than the averages from different etalons for the same line, indicating a dependence of apparent wave length upon order. Hyperfine structure or the presence of a nearby line, which may or may not be observed, can account for this, but the theory of errors is hardly applicable to such cases.

1. NEON

The adopted secondary standards of neon include most of the $1s-2p$ quantum transitions. This investigation is concerned with the next set of series members $1s-3p$. The visible blue and violet krypton, and the blue and violet argon lines originate in analogous transitions from corresponding levels in the respective atoms. The theory predicts 30 such transitions. One of these, $1s_3-3p_7$, has never been observed. Of the 29 remaining, 27 have been observed by interference methods in the present investigation. All of these are shown in table 1. A maximum of 40 exposures were recorded for some of the neon lines. This number, somewhat greater than required to arrive at satisfactory final values, was accumulated because the correction curve for dispersion of phase change at reflection showed a somewhat unexpected form in the region under investigation and an unusually large number of observations were needed to fix it precisely. Additional observations with critical lengths of interference path were also occasioned by the attempt to separate close pairs of lines. The 8.4-mm etalon was made available through the kindness of the staff of the Allegheny Observatory. Its length is very nearly one of the calculated separations required to give the optimum resolution of the close pairs of lines involving the $3p_2$ and $3p_4$ levels, which are only 0.88 cm^{-1} apart.

TABLE 1.—*Neon I interference measurements*

λ_{air}A	Number of observations	ν_{vac}cm^{-1}	Combination
3754.2160	22	26629.180	$1s_2-3p_{10}$
3701.2250	36	27010.424	$1s_2-3p_8$
3685.7359	36	27123.931	$1s_2-3p_7$
3682.2428	32	27149.660	$1s_2-3p_6$
3633.6646	38	27512.613	$1s_2-3p_3$
3609.1793	19	27699.259	$1s_3-3p_{10}$
3600.1693	38	27768.579	$1s_2-3p_5$
3593.6398	32	27819.031	$1s_2-3p_2$
3593.5259	32	27819.913	$1s_2-3p_4$
3520.4717	40	28397.194	$1s_2-3p_1$
3515.1908	38	28439.854	$1s_4-3p_8$
3510.7214	33	28476.059	$1s_5-3p^{10}$
3501.2165	39	28553.362	$1s_4-3p_7$
3498.0644	39	28579.091	$1s_4-3p_6$
3472.5711	40	28788.893	$1s_5-3p_9$
3466.5786	40	28838.658	$1s_3-3p_5$
3464.3389	38	28857.302	$1s_5-3p_8$
3460.5245	38	28889.108	$1s_3-3p_2$
3454.1952	40	28942.041	$1s_4-3p_3$
3450.7653	37	28970.808	$1s_5-3p_7$
3447.7029	40	28996.541	$1s_5-3p_6$
3423.9127	24	29198.009	$1s_4-3p_5$
3418.0066	25	29248.461	$1s_4-3p_2$
3417.9036	40	29249.342	$1s_4-3p_4$
3375.6498	6	29615.450	$1s_5-3p_5$
3369.9081	38	29665 909	$1s_5-3p_2$
3369.8086	24	29666.784	$1s_5-3p_4$

The complete array of term combinations, $1s-2p$ and $1s-3p$, have been assembled in table 2. Except for 29615.450 cm^{-1}, which is the faintest of the group, and 29666.784 cm^{-1} which is difficult to measure on account of proximity to 29665.909 cm^{-1}, the relative accuracy of the $1s-3p$ group is fully equal to that shown in the $1s-2p$ array, which includes all the adopted neon secondary standards. The remaining eight-figure wave numbers of visible and infrared lines appearing in table 2 are averages of the determinations relative to cadmium and neon reported by Meggers and Humphreys in 1934 [2]. A few seven-figure values required to complete the table are quoted from Paschen [4]. Only interferometer determinations are considered in estimating term values or relative accuracy. The term values shown in table 2 are revised to give the best agreement with all the experimental material. The difference, calculated minus observed wave number, is recorded beneath the last figure of each wave number value, considered in adopting term values. The average deviation of calculated term combinations from the observed wave numbers is 1 part in 20,000,000. Calculated values of wave numbers of lines too faint to be observed by interferometers are shown in parenthesis beneath values resulting from measurements of grating spectrograms.

TABLE 2.—*Neon* I *array of 1s—2p and 1s—30 combinations*

Term symbol ↓	*j* ↓	Term value ↓	$1s_2$ $j=1$ 38040.730	Diff. 1070.079	$1s_3$ 0 39110.809	Diff. 359.353	$1s_4$ 1 39470.163	Diff. 417.448	$1s_5$ 2 39887.610
$3p_1$	0	9643.536	28397.194		*		29826.65 (6.626)		*
$3p_2$	1	10221.701	27819.031 −2	1070.077	28889.108 ±0	359.353	29248.461 ±0	417.448	29665.909 ±0
$3p_3$	0	10528.119	27512.613 −2		*		28942.041 +2		*
$3p_4$	2	10220.819	27819.913 −2		*	----	29249.342 +1	417.442	29666.784 +7
$3p_5$	1	10272.152	27768.579 −1	1070.079	28838.658 −1	359.351	29198.009 +1	417.441	29615.450 +8
$3p_6$	2	10891.070	27149.660 ±0		*		28579.091 +1	417.450	28996.541 −1
$3p_7$	1	10916.800	27123.931 −1				28553.362 ±0	417.446	28970.808 +2
$3p_8$	2	11030.307	27010.424 −1		*		28439.854 +1	417.448	28857.302 +1
$3p_9$	3	11098.717	*		*	*	*		28788.893
$3p_{10}$	1	11411.550	26629.180 ±0	1070.079	27699.259 ±0		28058.69 (8.612)		28476.059 +1
$2p_1$	0	20958.703	17082.027 ±0		*		18511.459 ±0		*
$2p_2$	1	22890.987	15149.743 ±0	1070.078	16219.821 +1	359.354	16579.175 ±0	417.448	16996.623 ±0
$2p_3$	0	23012.009	15028.71		*		16458.153		*
$2p_4$	2	23070.932	14969.798 ±0		*		16399.231 −1	417.447	16816.678 ±0
$2p_5$	1	23157.328	14883.402 ±0	1070.079	15953.481 ±0	359.350	16312.831 +3	417.451	16730.282 ±0
$2p_6$	2	23613.579	14427.150 +1		*		15856.582 +1	417.450	16274.032 −1
$2p_7$	1	23807.849	14232.880 +1	1070.079	15302.959 +1	359.355	15662.314 −1	417.447	16079.761 ±0
$2p_8$	2	24105.219	13935.509 +2		*		15364.943 ±0	417.448	15782.391 ±0
$2p_9$	3	24272.400	*		*		*		15615.210
$2p_{10}$	1	25671.654	12369.076 ±0	1070.079	13439.155 ±0	359.353	13798.508 ±0	417.450	14215.958 −2

2. ARGON

The suitability of argon lines as standards, on account of extreme homogeneity and freedom from structure, was recognized at the 1935 meeting of the IAU. The repetition and extension of measurements were recommended. The results given in table 3 include determinations relative to krypton of 40 lines over the range from 4702 to 3319 A. Etalons of 15, 20, and 25 mm length were used in the comparisons. The sources used did not give very intense spectra, so that a number of ultraviolet lines remain, which could be observed by interference methods if sufficiently bright sources were employed. The earlier measurements of Meggers and Humphreys [2] and of Meggers [16] are included in table 3 for comparison insofar as they are within the wave-length range covered by this investigation. The agreement with Meggers' seven-figure values, published in 1921, is somewhat closer than with the 1934 results of Meggers and Humphreys. The latter are systematically lower, the difference being a little over 0.001 A for most lines. While we are certain that the relative accuracy of the 1934 values is at least as good as that of the results here reported, it still seems most probable that the systematic error is in the measurements of 1934.

TABLE 3.—*Argon* I *interference measurements*

λ_{air}, Kr standard	Number of observations	Meggers and Humphreys [2] Cd standard	Meggers and Humphreys [2] Ne standard	Meggers [16] Cd standard	ν_{vac} cm^{-1} Kr standard	Combination
A		A	A	A		
4702. 3164	11		3151	317	21260. 184	$1s_2-3p_{10}$
4628. 4410	10		4398	445	21599. 518	$1s_2-3p_8$
4596. 0970	11		0964	096	21751. 516	$1s_2-3p_7$
4522. 3238	11		3216	325	22106. 347	$1s_3-3p_{10}$
4510. 7333	13	7324	7322	733	22163. 149	$1s_2-3p_5$
4345. 1682	13		1666	168	23007. 623	$1s_2-3p_4$
4335. 3380	13	3363	3370		23059. 791	$1s_2-3p_2$
4333. 5612	13	5601	5595	561	23069. 245	$1s_2-3p_3$
4300. 1011	13	1000	0995	101	23248. 750	$1s_4-3p_8$
4272. 1690	13	1678	1680	169	23400. 751	$1s_4-3p_7$
4266. 2867	13	2855	2853	286	23433. 014	$1s_4-3p_6$
4259. 3618	13	3607	3603	362	23471. 111	$1s_2-3p_1$
4251. 1852	13		1842	184	23516. 254	$1s_5-3p_{10}$
4200. 6751	13	6738	674	676	23799. 015	$1s_5-3p_9$
4198. 3170	13	3160	316	316	23812. 383	$1s_4-3p_5$
4191. 0296	7	0270		027	23853. 787	$1s_3-3p_4$
4190. 7127	7	7098		714	23855. 591	$1s_5-3p_8$
4181. 8838	13	8825	8826	884	23905. 955	$1s_3-3p_2$
4164. 1800	13	1789	1788	180	24007. 587	$1s_5-3p_7$
4158. 5906	13	5895	5896	591	24039. 854	$1s_5-3p_6$
4054. 5254	7		5250		24656. 860	$1s_4-3p_4$
4045. 9658	7				24709. 022	$1s_4-3p_2$
4044. 4182	13		4173	419	24718. 477	$1s_4-3p_3$
3948. 9788	13		977	980	25315. 863	$1s_5-3p_2$
3947. 5043	9				25325. 319	$1s_5-3p_3$
3894. 6602	6				25668. 934	$1s_2-4p_{10}$
3834. 6785	12				26070. 436	$1s_2-4p_5$
3781. 3609	2				26438. 023	$1s_4-4X$
3770. 3688	2				26515. 098	$1s_3-4p_{10}$
3690. 8957	7				27086. 013	$1s_5-4Y$
3649. 8324	9				27390. 742	$1s_2-4p_1$
3634. 4605	8				27506. 588	$1s_4-4p_7$
3632. 6837	8				27520. 042	$1s_4-4p_6$
3606. 5224	12				27719. 664	$1s_4-4p_5$
3567. 6565	13				28021. 631	$1s_5-4p_9$
3554. 3061	13				28126. 882	$1s_5-4p_6$
3461. 0780	5				28884. 489	$1s_4-4p_3$
3393. 7517	5				29457. 490	$1s_5-5p_4$
3373. 481	2				29634. 49	$1s_4-5p_5$
3319. 3446	3				30117. 793	$1s_5-5p_6$

The argon lines lie in the same wave-length region as the blue and violet krypton standards, eliminating the possibility of an error in the new measurements due to the spectrograph not being focused exactly alike for both sources, or an error due to incorrect estimate of the correction for dispersion of phase change at reflection. An error of the kind first mentioned is possible when a prism spectrograph is being used and comparisons are being made, relative to standards in the red region, of lines in the blue or ultraviolet. The reason is that the patterns due to the standard lines appear at one end of the plate where the focusing is less satisfactory than at the center. The plate curvature in such a spectrograph gives only a fair approximation to the true focal surface. The difficulty is somewhat increased by the fact that the spectrograph is slightly astigmatic, and it is necessary to choose the most satisfactory compromise between the best adjustments for vertical and horizontal images, this compromise to be the same, if possible, for all spectral regions.

TABLE 4.—*Argon I array of $1s-np$ combinations*

Term symbol ↓	j ↓	Term value ↓	$1s_2$ $j=1$ 31711.630	Diff. 846.163	$1s_3$ 0 32557.793	Diff. 803.068	$1s_4$ 1 33360.861	Diff. 606.839	$1s_5$ 2 33967.700
$4p_1$	0	4320.888	27390.742		*		29039.69 (9.973)		*
$4p_3$	2	4476.372	27235.47 (5.258)		*		28884.489		29491.39 (1.328)
$4p_5$	0	5641.196	26070.436 −2		*		27719.664 +1		*
$4p_6$	2	5840.818	25870.87 (0.812)		*		27520.042 +1	606.840	28126.882 ±0
$4p_7$	1	5854.273	25857.35 (7.357)		26703.55 (3.520)		27506.588		28113.72 (3.427)
$4p_9$	3	5946.069	*		*		*		28021.631
$4p_{10}$	1	6042.696	25668.934 ±0	846.164	26515.098 −1		27318.38 (8.165)		
$3p_1$	0	8240.519	23471.111		*		25120.41 (0.342)		*
$3p_2$	1	8651.838	23059.791 +1	846.164	23905.955 ±0	803.067	24709.022 +1	606.841	25315.863 −1
$3p_3$	2	8642.383	23069.245 +2		*		24718.477 +1	606.842	25325.319 −2
$3p_4$	1	8704.006	23007.623 +1	846.164	23853.787 ±0	803.073	24656.860 −5		
$3p_5$	0	9548.480	22163.149 +1		*		23812.383 −2		*
$3p_6$	2	9927.846	21783.78 (3.784)		*		23433.014 +1	606.840	24039.854 ±0
$3p_7$	1	9960.113	21751.516 +1		22597.75 (7.680)		23400.751 −3	606.836	24007.587 ±0
$3p_8$	2	10112.111	21599.518 +1		*		23248.750 ±0	606.841	23855.591 −2
$3p_9$	3	10168.685	*		*		*		23799.015
$3p_{10}$	1	10451.446	21260.184 ±0	846.163	22106.347 ±0		22909.44 (9.415)		23516.254 ±0
$2p_1$	0	18388.832	13322.799 −1		*		14972.027 +2		*
$2p_2$	1	19615.037	12096.593 ±0	846.163	12942.756 ±0	803.068	13745.824 ±0	606.839	14352.663 ±0
$2p_3$	2	19821.753	11889.877 ±0		*		13539.108 ±0	606.839	14145.947 ±0
$2p_4$	1	19979.745	11731.885 ±0	846.163	12578.048		13381.08 (1.116)		13987.955 ±0
$2p_5$	0	20057.181			*		13303.680		*
$2p_6$	2	20873.903	10837.727 ±0		*		12486.959 −1	606.838	13093.797 ±0
$2p_7$	1	21024.195	10687.435 ±0	846.163	11533.598 ±0	803.068	12336.666 ±0	606.839	12943.505 ±0
$2p_8$	2	21494.185	10217.445 ±0		*		11866.676 ±0	606.838	12473.514 +1
$2p_9$	3	21648.696	*		*		*		12319.004
$2p_{10}$	1	23009.356	8702.31 (2.274)		9548.437 ±0	803.068	10351.505 ±0	606.838	10958.343 +1

The array of argon term combinations shown in table 4 follows the same plan as the corresponding array for neon with the addition of a few $1s-4p$ transitions for which wave numbers determined by interference measurements are available. All eight figures wave numbers in the $1s-3p$ and $1s-4p$ arrays are from the results of this investigation. The $1s-2p$ array is assembled from the interference measurements by Meggers and Humphreys [2]. The values used are the averages of the determinations relative to cadmium and those relative to neon. The few seven-place wave numbers required to complete the array are Meissner's [14]. The term values are adjusted from the interference determinations. The relative accuracy of the measurements, which can be judged from the agreement of the observed with calculated wave numbers, and the constancy of repeated term differences is of the same order as that shown by the neon array.

3. KRYPTON

The possibility of making interference measurements of ultraviolet krypton lines became apparent when a number of them appeared among the $1s-3p$ neon lines which were being determined relative to krypton. By rather long exposures, it was possible to obtain measurable patterns for 30 ultraviolet lines. Measurements were made on several fourth members of $1s-np$-type series, permitting the evaluation of all but one of the $5p$ terms by interference measurements. Several combinations of f type terms were observed. Two lines, 3837.8162 and 3503.8981 A, were shown by more precise measurements to be first and second members of a new series, $1s_5-n\mathrm{T}$, and not $1s_5-n\mathrm{Y}$, as at present classified [15]. The T series of terms have j-value, 3, and combine only with s_5. A new line, 3837.7028 A, was revealed as a close companion to 3837.8162 A and is properly classified as $1s_5-4\mathrm{Y}$. Interference measurements were made of seven lines not included in the list of secondary standards but lying in the same region. Etalons of 3, 7.5, 20, and 25 mm length were used in the wave-length comparisons, the results of which are assembled in table 5, together with the results of previous measurements in the same wave-length interval.

TABLE 5.—*Krypton I interference measurements*

λ_{air} Kr standard	Number of observations	Jackson [5] Cd standard	Humphreys [8] Ne standard	Meggers and Humphreys [2] Ne standard	ν_{vac} cm^{-1} Kr standard	Combination
A		A	A	A		
4812.6367	4		607		20772.843	$1s_3-4\mathrm{X}$
4550.2985	5	2985	298		21970.441	$1s_4-3p_{10}$
4425.1908	8	1906	1909	190	22591.573	$1s_2-3p_4$
4418.7626	8	764	769		22624.437	$1s_2-5\mathrm{Z}$
4416.8838	5				22634.061	$1s_2-5\mathrm{X}$
4410.3685	8	3687	369		22627.498	$1s_2-3p_3$
4302.4455	3				23236.081	$1s_2-5p_{10}$
4263.2881	4				23449.496	$1s_2-5p_5$
4184.4726	7				23891.164	$1s_3-5p_{10}$
3991.2581	10				25047.699	$1s_4-4\mathrm{X}$
3991.0797	11				25048.818	$1s_4-4\mathrm{Z}$
3982.1699	5				25104.862	$1s_4-4\mathrm{Y}$
3845.9778	9				25993.845	$1s_5-4\mathrm{Z}$
3837.8162	10	8162			26049.122	$1s_5-4\mathrm{T}$
3837.7028	2				26049.892	$1s_5-4\mathrm{Y}$
3812.2155	11	2159			26224.049	$1s_4-4p_8$
3800.5437	11	5440			26304.584	$1s_4-4p_7$
3796.8839	11	8844			26329.938	$1s_4-4p_6$
3773.4241	15	4247			26493.630	$1s_4-4p_5$
3698.0452	17	047			27033.649	$1s_5-4p_{10}$
3679.6111	9				27169.078	$1s_5-4p_8$
3679.5609	22				27169.448	$1s_5-4p_9$
3668.7363	10	7374			27249.609	$1s_5-4p_7$
3665.3259	22	3263			27274.963	$1s_5-4p_6$
3632.4896	5				27521.512	$1s_4-3p_4$
3628.1570	9	1571			27554.376	$1s_4-5\mathrm{Z}$
3615.4755	11	4749			27651.022	$1s_4-3p_2$
3540.9538	6				28232.940	$1s_4-5p_7$
3539.5416	6				28244.204	$1s_4-5p_6$
3522.6747	10	675			28379.436	$1s_4-5p_5$
3511.8963	6				28466.533	$1s_5-3p_4$
3503.8981	7				28531.510	$1s_5-5\mathrm{T}$
3502.5537	11				28542.461	$1s_5-3p_3$
3495.9900	7	9897			28596.049	$1s_5-3p_2$
3434.1423	5				29111.037	$1s_5-5p_{10}$
3431.7217	10	7511			29131.571	$1s_5-5p_9$
3424.9433	10	9720			29189.224	$1s_5-5p_6$

Jackson's [5] observations in the ultraviolet were made using a krypton tube filled to 4-mm pressure, whereas ours were with pressures of 1 mm or less. The small but systematic difference between the two sets of values for the $1s-4p$ transitions is in essential agreement with Jackson's estimated pressure shifts. No attempt is made to explain the disagreement of Jackson's wave lengths of the lines 3431.7217 and 3424.9433 A with ours. Only the second value can be checked from the term array, but our value of the wave number 29189.224 cm^{-1} gives a fair fit, whereas Jackson's is outside the range of accidental error. Previous National Bureau of Standards' measurements of the visible lines included in the data were all from relatively faint patterns. The standards, and consequently the fainter lines, were not so heavily exposed as is necessary when making comparisons with ultraviolet lines. The agreement is, therefore, considered satisfactory. The disagreement of the 1930 [8] value for 4812 A was owing to an incorrect choice of order in the single available determination. A recheck of the original determination shows that it should have given 4812.636 A.

Construction of the array of $1s-np$ term combinations in krypton, leads to a somewhat more extensive table than is the case with neon or argon, if all wave numbers determined by interference measurements are included. This is attributable to the appearance of higher series members in the more accessible part of the ultraviolet region. Such an array is shown in table 6. The wave numbers there assembled include all results of this investigation, all krypton secondary standards [1] which are represented by transitions of $1s-np$ type, and the 1934 interference measurements by Meggers and Humphreys [2] of lines not included in the first two groups. The third group, consisting mostly of infrared, had been determined relative both to cadmium and neon. An average was adopted for use in this array. A considerable number of $1s-np$ transitions give lines too faint for interference measurements. For the sake of completeness, these are included in the table, the values being given by the latest National Bureau of Standards grating observations [15]. As in the previous cases, the term values have been adjusted to give the best conformity to the entire set of interference observations. The relative accuracy of the ultraviolet determinations compares favorably either with that of the secondary standards or the group of infrared lines.

Calculated values of wave numbers in the inaccessible infrared region are shown in parentheses.

Attention is called to a similar array published in 1930 [8] using the measurements then available, but not including ultraviolet data. It will be seen that the changes due to repeated measurements of increased precision are practically negligible.

TABLE 6.—*Krypton* I *array of 1s—np combinations*

Term symbol ↓	j ↓	Term value ↓	$1s_2$ $j=1$ 27068.199	Diff. 655.087	$1s_3$ 0 27723.286	Diff. 4274.853	$1s_4$ 1 31998.139	Diff. 945.026	$1s_5$ 2 32943.165
5T	3	4411. 655	*		*		*		28531. 510
5X	1	4434. 138	22634. 061		23289. 16 (9. 148)		27563. 85 (4. 001)		28509. 04 (9. 027)
5Z	2	4443. 763	22624. 437 −1		*		27554. 376 ±0		28449. 45
$5p_5$	0	3618. 703	23449. 496 ±0		*		28379. 436 ±0		*
$5p_6$	2	3753. 938	23314. 25 (4. 261)		*		28244. 204 −3	945. 020	29189. 224 +3
$5p_7$	1	3765. 199			23957. 82 (8. 087)		28232. 940		29177. 92 (7. 966)
$5p_9$	3	3811. 594	*		*		*		29131. 571
$5p_{10}$	1	3832. 120	23236. 081 −2	655. 083	23891. 164 +2		28165. 44 (6. 019)		29111. 037 +8
4T	3	6894. 043	*		*		*		26049. 122
4X	1	6950. 442	20117. 72 (7. 757)		20772. 843 +1	4274. 856	25047. 699 −2		25992. 88 (2. 723)
4Y	2	6893. 275	20174. 92 (4. 924)		*		25104. 862 +2	945. 030	26049. 892 −2
4Z	2	6949. 321	20118. 85 (8. 878)		*		25048. 818 ±0	945. 027	25993. 845 −1
$4p_5$	0	5504. 509	21563. 65 (3. 690)		*		26493. 630		*
$4p_6$	2	5668. 201	21399. 92 (9. 998)		*		26329. 938 ±0	945. 025	27274. 963 +1
$4p_7$	1	5693. 555	21374. 53 (4. 644)		22029. 69 (9. 731)		26304. 584 ±0	945. 025	27249. 609 +1
$4p_8$	2	5774. 089	21294. 04 (4. 010)		*		26224. 049 +1	945. 029	27169. 078 −2
$4p_9$	3	5773. 717	*		*		*		27169. 448
$4p_{10}$	1	5909. 516	21158. 61 (8. 683)						27033. 649
$3p_1$	0	4093. 318	22974. 881		*				*
$3p_2$	2	4347. 117	22721. 082 ±0		*		27651. 022 ±0	945. 027	28596. 049 −1
$3p_3$	1	4400. 701	22667. 498 ±0	655. 087	23322. 585 ±0		27597. 18 (7. 438)		28542. 461 +3
$3p_4$	1	4476. 626	22591. 573 ±0	655. 087	23246. 660 ±0	4274. 852	27521. 512 +1	945. 021	28466. 533 +6
$3p_5$	0	9153. 254	17914. 93 (4. 945)		*		22844. 885		*
$3p_6$	2	9552. 275	17515. 93 (5. 924)		*		22445. 864 ±0	945. 026	23390. 890 ±0
$3p_7$	1	9601. 416	17466. 81 (6. 783)		18121. 89 (1. 870)		22396. 723 ±0	945. 025	23341. 748 +1
$3p_8$	2	9793. 947	17274. 47 (4. 252)		*		22204. 392 ±0	945. 027	23149. 419 −1
$3p_9$	3	9799. 251	*		*		*		23143. 914
$3p_{10}$	1	10027. 698	17040. 53 (0. 501)		17695. 585 +3	4274. 856	21970. 441 ±0	945. 029	22915. 470 −3
$2p_1$	0	14059. 829	13008. 370		*		17938. 27 (8. 310)		*
$2p_2$	2	14969. 730	12098. 469 ±0		*		17028. 409 ±0	945. 027	17973. 436 −1
$2p_3$	1	14995. 749	12072. 450 ±0	655. 087	12727. 537 ±0		17002. 42 (2. 390)		17947. 417 −1
$2p_4$	1	15318. 982	11749. 218 −1	655. 087	12404. 305 −1	4274. 852	16679. 157 ±0	945. 025	17624. 182 +1
$2p_5$	0	18822. 038	(8246. 161)		*		13176. 101		*
$2p_6$	2	19791. 560	(7276. 639)		*		12206. 579 ±0	945. 027	13151. 606 −1
$2p_7$	1	19950. 506	(7117. 693)		(7772. 780)		12047. 633 ±0	945. 026	12992. 659 ±0
$2p_8$	2	20607. 523	(6460. 673)		*		11390. 616 ±0	945. 027	12335. 643 −1
$2p_9$	3	20620. 501	*		*		*		12322. 664
$2p_{10}$	1	21746. 387	(5321. 812)		(5976. 899)		10251. 751 +1	945. 027	11196. 778 ±0

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