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Infrared Spectra of Noble Gases (12000 to 19000 A)[1]

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The first spectra of helium, neon, argon, krypton, and xenon, excited by discharges in Geissler tubes, operated by direct connection to a transformer, have been explored in the infrared (12000 to 19000 A). A high-resolution, automatically recording, infrared spectrometer, employing a 15000-lines-per-inch grating and lead-sulfide photoconducting detector, was used as the dispersing instrument. A new set of wavelength values is reported for all these spectra. New data include 18 previously unreported lines of neon and 36 of krypton, all of which have been classified. The descriptions of the spectra of argon, krypton, and xenon represent essentially a repetition of the observations of Sittner and Peck. Several previously missing classifications are supplied, also a few amended interpretations. The analysis of these spectra may be regarded as complete. Use of selected lines as wavelength standards is suggested.

1. Introduction

The essentially complete character of both the description and interpretation of the photographed spectra of the noble atmospheric gases makes it apparent that any reopening of the subject can be justified only on the basis of the availability of new sources of information, such as a new technique of observation permitting an extension of the observations into a previously unexplored region, leading to significant additions to the experimental material. Such a technique is the utilization of lead-sulfide photoconducting detectors in combination with high-resolution gratings for radiometric observation. The lead-sulfide cell extends the range of such high-resolution observations beyond the photographic limit to the limit of its sensitivity near 30000 A, and because it is also sensitive to the visible and ultraviolet as far as 3500 A, at least, use of higher order standard lines for comparison is possible.

Three of these spectra, argon, krypton, and xenon, have been observed by this radiometric technique by Sittner and Peck, whose reported observations and analysis [1] [2] cover essentially the same region as those herein presented. These excellent observations appear to have been essentially complete, and the overwhelming majority of the classifications are correct. In the intervening period, however, sufficient new information has been accumulated to make it appear justifiable to prepare a new publication, which should complete these analyses as far as any reasonable effort will permit. Discussion of the specific points of difference between this analysis and that of Sittner and Peck, together with extensions to the analyses as reported in other earlier publications, will be included in the separate sections dealing with the respective spectra. In brief, these consist of inclusion of He I and Ne I, presentation of previously unreported data consisting mainly of 18 new lines in Ne I and 36 in Kr I, interpretation of nearly all reproducible previously unclassified lines, and amended classifications in a few instances.

Observations of Kr I and A I, obtained with a prism spectrometer, equipped with a glass prism and thermocouple detector were reported by Humphreys and Plyler [2]. These observations covered the same spectral region in which the data herein reported were obtained, but, because of well-known limitations affecting the precision of spectral data obtained by prism spectrometers with thermal detectors, may be considered as entirely superseded by the present work. The earlier paper may be referred to for a fairly extensive list of references on the first spectra of the noble gases, which will not be repeated in full here. It also reported two new levels, designated 4U and 4W, in Kr I, computed from photographic data by Meggers [3] but requiring confirmation by radiometric observation of infrared lines, arising from combinations of the same levels. The first, or neutral-atom, spectra of all the noble gases are very rich in infrared lines. Considerable portions of these infrared spectra lie in the photographically accessible region, and have been the subject of exhaustive investigations. Reference is made to a few of the more recent publications, which, in addition to those already mentioned, will serve as a background and introduction to the current work, and provide cross references to earlier work as required. A paper entitled "The Infrared Spectra of Neon, Argon, and Krypton", published by Meggers and Humphreys [4] in 1933 brought the analysis of these spectra essentially to completion. A separate paper by Humphreys and Meggers [5], and of similar scope, appearing a few months earlier, brought Xe I up to date. Shortly after this, plates incorporating new photosensitizing dyes, made available by the Eastman Kodak Co. [6], permitted photographic observation as far as 13000 A in favorable instances. With these new plates Meggers [3] reobserved all the noble gas spectra to the photographic limit and interpreted nearly all the new lines. In the intervening years no further extension of the range of photographic sensitivity has been accomplished, and no further observations of noble-gas spectra were made up to the time of the radiometric investigations at the National Bureau of Standards [2] and at Northwestern University [1].

2. Energy Levels of the Noble Gases

Although the analysis of the spectra of the noble gases may be regarded as essentially complete, in the sense that nearly all the levels predictable from the

[1] Presented, in part, at the meeting of the Optical Society of America, Buffalo, N. Y., Oct. 1949.
[2] Figures in brackets indicate the literature references at the end of this paper.

electron configurations have been found, and that, in most instances, long series have permitted highly precise calculation of absolute term values, these spectra are somewhat unusual in their structure in that they do not permit arrangement into regular multiplets with any reasonable conformity to rules regarding intervals or intensities. Paschen [7] adopted a special notation in reporting his analysis of Ne I. This notation has been retained in all subsequent publications on these spectra; evidently because it is not possible to describe the levels according to the currently accepted notation, which is actually meaningful only when vector coupling of *LS*-type is present. This inability to identify multiplets in rare-gas spectra points to the probable existence of a different type of coupling. This has generally been supposed to resemble the *jj*-case but evidence, principally from Zeeman effect, indicates that extreme *jj*-coupling is not realized, and that an intermediate type prevails. Considerable light was shed on the problem by a theoretical paper by Racah [8], who discussed an intermediate coupling scheme, designated *jl*, and discussed the conditions for its existence. It was pointed out that, whereas *ls*-coupling occurs when the spin-orbit interaction is weak compared to the electrostatic, and *jj*-coupling occurs when the electrostatic interaction is weaker, a third possibility, the *jl*-case, may be realized, according to which the electrostatic interaction is weak compared to the spin-orbit interaction of the parent ion, but is strong compared to the spin coupling of the external electron. The vectorial representation of this case is to combine the total angular moment j of the parent ion with the orbital moment l of the external electron to form a resultant K, known as the intermediate quantum number. Finally, K is combined with the spin of this electron to obtain the resultant J, which has the usual significance, namely, total angular moment of the resultant configuration.

Racah suggested a special notation for representing levels originating under the condition of *jl*-coupling. This notation has been selected for the appropriate sections, pertaining to noble-gas spectra, of "Atomic Energy Levels" [10]. This innovation has been followed in tabulating the descriptions of spectra listed in this paper, except for He I, which is described in conventional notation. The Racah notation has been abbreviated by omitting the description of the parent ion, $mp^5(^2P^\circ_{1½})$ or $(^2P^\circ_{0½})$, the omission or insertion of the prime with the letter indicating the running electron being sufficient to distinguish between the two respective possible cases. This usage is also borrowed from [10], which not only employes the prime in the manner indicated, but also supplies the complete parent ion description. Descriptions of the transitions, according to the Paschen notation, are also included along with the Racah notation in parallel columns in the tables pertaining to argon, krypton, and xenon. This is intended to permit ready comparison with earlier published analyses and to provide a basis for translating the old notation into the new. It is to be noted that every symbol in the new notation is physically significant. The number within the bracket is Racah's K or intermediate quantum number obtained by vectorial addition of the j-value of the parent ion to the l-value of the external electron. In the instance of the noble-gas configurations, where the parent ion has j-value$=1½$ (unprimed case), there can be a maximum of four K-values; and where the parent ion has j-value$=0½$ (primed case), no more than two values of K appear. For each K-value, by addition or subtraction of the spin moment S of the external electron, always$=0½$, two possible j-values appear for the resultant vector sum. We thus obtain a pair of levels for each K. A maximum total of twelve levels is possible for any rare-gas configuration where the external electron has l-value 2 or greater. As might be expected, this is the same total number and the same set of j-values that would be obtained with *LS*-coupling. Table 1 illustrates the development of the set of levels and appropriate quantum numbers associated with the binding of the f-electron in the configuration $mp^6\,nf$.

TABLE 1. *Development of notation for jl coupling, according to Racah, illustrated by f-type levels of noble gases*

Ion configuration	j_i	K			J
$p^5(^2P^\circ)$	1½	$+l=3$	[4½]	$+s=0½$	5 4
			[3½]	----------	4 3
			[2½]	----------	3 2
			[1½]	----------	2 1
$p^5(^2P^\circ)$	0½	$+l=3$	[3½]	$+s=0½$	4 3
			[2½]	----------	3 2

The pair structure resulting from the *jl*-coupling scheme was pointed out by Shortley and Fried [9]. This structure is quite apparent in the level schemes of the four noble-gas-atomic spectra, Ne I, A I, Kr I, and Xe I, up to and including the levels based on the configurations $p^6\,nd$. In the instance of the pair arrays from $p^6\,nf$ these features are much less obvious. They are developed in three out of four possible cases in Xe I, and show diminishing separations for the gases of smaller atomic number, until in Ne I these f-type pairs of levels merge into single levels even with the high resolving power now employed in presently available techniques. Lack of knowledge regarding these f-type levels has constituted the most conspicuous gap in the analysis of these spectra, and a considerable part of the information supplied by this investigation is concerned with these structures. Details for the respective spectra are given under the appropriate headings.

The numerical values of the levels used in obtaining the calculated wave numbers of emission lines that appear in the tables that follow, pertaining to A I, Kr I, and Xe I are those that are currently appearing in [10]. The levels reported in that publication for Ne I, A I, Kr I and Xe I, are taken from unpublished manuscript by Edlén. These values represent a revision, together with reassignments in a few instances, of the tables of levels listed in two publications already quoted [4, 5], and are based on the same data. A small number of missing levels, required to complete the arrays and predicted from series calculations, have been confirmed by observed transitions.

3. Experiments

The high-resolution grating spectrometer used for these observations has been described briefly in an earlier publication [11]. It is of conventional design incorporating a 15000-lines-per-inch Johns Hopkins grating, 1-meter focus off-axis paraboloidal collimating mirror, ground and figured in the Optical Instrument Shop of the National Bureau of Standards. The cone-bearing, grating-mounting, worm-gear assembly, and simultaneously movable bilateral slits were constructed in the Instrument Shops of the Department of Physics, University of Michigan. The slits conformed essentially to the design of Roemer and Oetjen [12]. Figure 1 shows the instrument with the cover and baffles removed. The amplifier shown on the table beneath the spectrometer was constructed by W. R. Wilson, and is of the same design as that used for similar purposes at Northwestern University [13]. The electronic components visible in the picture also serve to establish the scale of relative sizes of parts. It may be noted that the mirrors are 7 inches in diameter, and that the grating is ruled on a 9-inch blank, with segments cut off to adapt it to the ruling machine.

The data reported were obtained in most instances by using Geissler tubes as radiation sources. In instances where higher-order comparison standards from the same spectrum were employed, the source was simply imaged on the entrance slit by means of a quartz lens. Where lines of a different spectrum were used as standards an arrangement similar to that illustrated in the paper by the senior author on Ca I [14] was employed. In this system the quartz lens was left in position and a concave mirror was also set up on the optic axis in such a position that it formed an image of the source in the position of the conjugate focus of the lens with respect to the

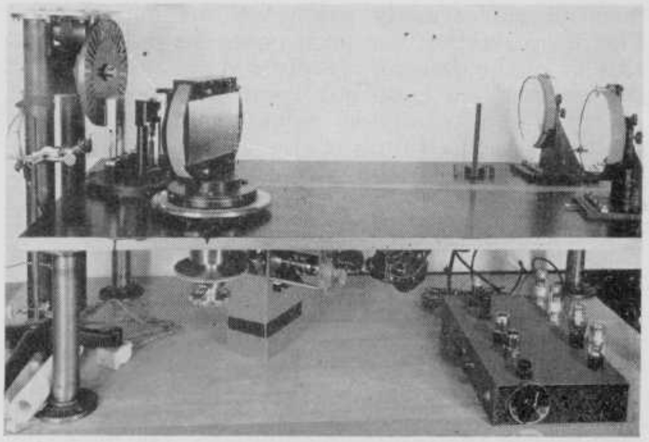

FIGURE 1. *National Bureau of Standards infrared grating spectrometer with the cover and baffles removed.*

slit. When the comparison source included a tube of fairly large bore, it was set up with its axis coincident with the image of the first source, so that both could be imaged on the slit simultaneously. In other cases, the comparison source was moved into or out of the described position, but the comparison lines were always introduced under the condition of continuous scanning.

4. Characteristic Features of Noble Gas Spectra

4.1. Helium

The observation of the helium spectrum was fo the purpose of improving the wavelength data, because there was no reasonable prospect of finding new level combinations of appreciable intensity in this thoroughly analyzed spectrum. The results are given in table 2 and comprise data on six lines. The first two lines listed, $3\,^3D-5\,^3F^{\circ}$, and $3\,^1D-5\,^1F^{\circ}$ were the lines of greatest wavelength reported by Meggers [3] and were evidently at the limit of photographic sensitivity. The wavelengths of the others are known only from the early radiometric measurements of Paschen [15]. Because of a radiometric application utilizing some of these lines, special care was taken to evaluate the relative intensities precisely. It is believed that the apparent relative in-

TABLE 2. *Description of* He I *in the infrared region*

Observed wavelength in air	Observed intensity	Term combination	Wave number		Difference (calc.−obs.)
			Observed	Calculated	
A			cm^{-1}	cm^{-1}	
12784. 79	10	$3d\,^3D-5f\,^3F^{\circ}$	7819. 66	7819. 89	0. 23
12790. 27	1	$3d\,^1D-5f\,^1F^{\circ}$	7816. 31	7815. 09	−1. 22
17003. 11	20	${}^{a}3p\,^3P^{\circ}-4d\,^3D$	5879. 67	5879. 73	0. 06
18685. 12	70	$3d\,^3D-4f\,^3F^{\circ}$	5350. 39	5350. 71	. 32
18697. 00	10	$3d\,^1D-4f\,^1F^{\circ}$	5346. 99	5348. 02	1. 03
20580. 9	5000	$2s\,^1S-2p\,^1P^{\circ}$	4857. 55	4857. 45	−0. 10

a Triple level unresolved in these experiments.

tensities are correctly evaluated, bearing in mind that no correction has been made for spectral sensitivity of the detector, or effect of the properties of the grating, on apparent spectral distribution of energy. The calculated values of wave numbers are based on the values of the levels quoted in [10]. The wavelengths of the various lines of the fundamental series have been evaluated by bracketing them between fairly close third-order neon lines. There is no possibility of an experimental error nearly as large as the difference between observed and calculated wave numbers indicated for the singlets, particularly since the relative precision of the determination of the singlet and triplet transitions for a given series member is high. It is suggested, therefore, that reevaluation of the first two members of the *f*-series is in order. The following values would bring the levels into agreement with the reported wavelength measurements:

$4f\ ^1F^\circ$, *191446.21*

$4f\ ^3F^\circ$, *191446.29*

$5f\ ^1F^\circ$, *193915.53*

$5f\ ^3F^\circ$, *193915.56*

The indicated extremely close proximity of the singlet and triplet F-terms of given order number is in accord with their relative positions for the higher series members. The difference between the observed and calculated wave numbers for $2s\ ^1S - 2p\ ^1P^\circ$, namely, 0.10 cm $^{-1}$, is close to the expected experimental error. The line at 17003 A arises from a transition between multiple levels, unresolved by available techniques. No revision of accepted level values based on the measured wavelengths of these two lines appears to be required.

4.2. Neon

The observations on Ne I have been confined to the limited wavelength region, 18035 to 18625 A, in which the electron transitions of the type $3d-4f$ occur. The only previous data pertaining to this region consist of a few lines reported by Hardy [16] that could not be resolved or measured by methods then available with sufficient precision to improve the existing set of level values. The new data are listed in table 3 and comprise 18 lines. A reproduction of a typical record is shown in figure 2. The wavelengths have been evaluated by interpolation between third-order neon lines included in the well-known group of red neon lines, which are accepted international standards. The calculated wave numbers are based on a set of adjusted values of *f*-levels determined from these observations rather than upon the values currently published [10]. These revised *f*-levels are compared with the current set in table 4. The bracketed values quoted are, of course, predictions, which are now confirmed by the present set of observations.

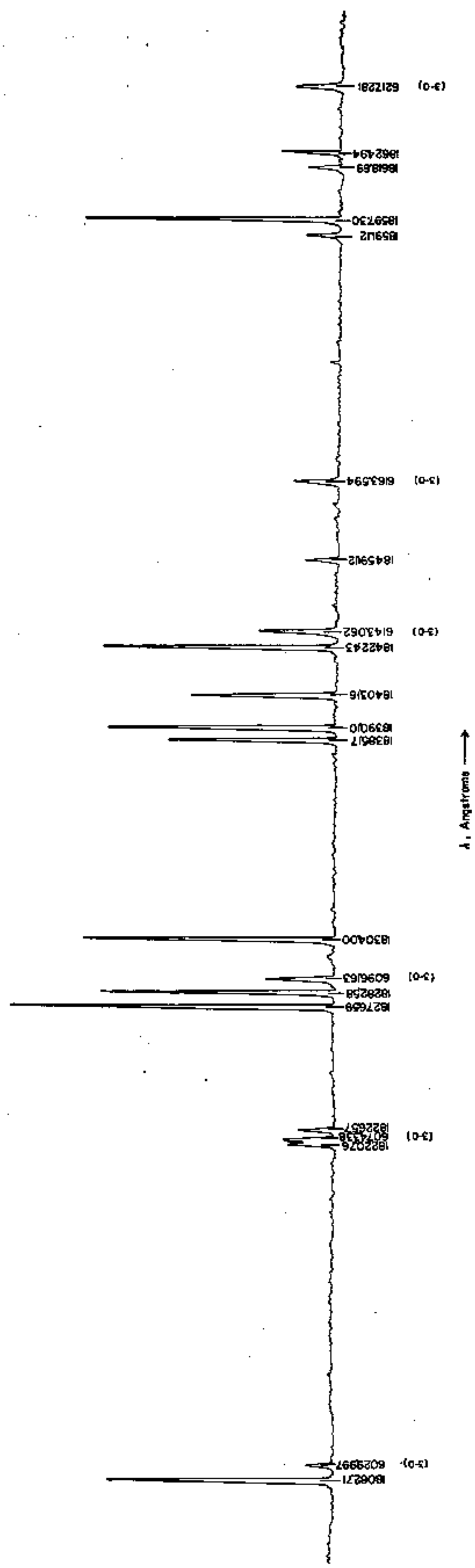

FIGURE 2. *Reproduction of tracing of chart record of infrared spectrum of neon, 18000 to 18700 A, including third-order standards.*

Table 3. *Newly observed and classified lines of* Ne I

Observed wavelength in air	Observed intensity	Term combination	Wave number		Difference (calc. − obs.)
			Observed	Calculated	
A			*cm*$^{-1}$	*cm*$^{-1}$	
18035.49	22	$3d\,[0\frac{1}{2}]^\circ_0 - 4f\,[1\frac{1}{2}]_{1,2}$	5543.11	5543.11	0.00
18082.71	130	$3d\,[0\frac{1}{2}]^\circ_1 - 4f\,[1\frac{1}{2}]_{1,2}$	5528.63	5528.57	−.06
18220.76	15	$3d\,[3\frac{1}{2}]^\circ_4 - 4f\,[3\frac{1}{2}]_{3,4}$	5486.74	5486.75	.01
18226.57	11	$3d\,[3\frac{1}{2}]^\circ_3 - 4f\,[3\frac{1}{2}]_{3,4}$	5485.00	5484.98	−.02
18276.59	260	$3d\,[3\frac{1}{2}]^\circ_4 - 4f\,[4\frac{1}{2}]_{4,5}$	5469.98	5469.97	−.01
18282.58	200	$3d\,[3\frac{1}{2}]^\circ_3 - 4f\,[4\frac{1}{2}]_{4,5}$	5468.19	5468.20	.01
18304.00	140	$3d\,[1\frac{1}{2}]^\circ_2 - 4f\,[2\frac{1}{2}]_{2,3}$	5461.79	5461.81	.02
18359.21	6	$3d\,[1\frac{1}{2}]^\circ_2 - 4f\,[1\frac{1}{2}]_{1,2}$	5445.37	5445.48	.11
18385.17	160	$3d'[2\frac{1}{2}]^\circ_2 - 4f'[3\frac{1}{2}]_{3,4}$	5437.68	5437.71	.03
18390.10	180	$3d'[2\frac{1}{2}]^\circ_3 - 4f'[3\frac{1}{2}]_{3,4}$	5436.22	5436.19	−.03
18403.16	65	$3d\,[1\frac{1}{2}]^\circ_1 - 4f\,[2\frac{1}{2}]_{2,3}$	5432.36	5432.45	.09
18422.43	110	$3d'[1\frac{1}{2}]^\circ_2 - 4f'[2\frac{1}{2}]_{2,3}$	5426.68	5426.68	.00
18458.58	10	$3d\,[1\frac{1}{2}]^\circ_1 - 4f\,[1\frac{1}{2}]_{1,2}$	5416.05	5416.12	.07
18475.79	3	$3d'[1\frac{1}{2}]^\circ_1 - 4f'[2\frac{1}{2}]_{2,3}$	5411.01	5410.98	−.03
18591.12	25	$3d\,[2\frac{1}{2}]^\circ_2 - 4f\,[3\frac{1}{2}]_{3,4}$	5377.44	5377.44	.00
18597.30	120	$3d\,[2\frac{1}{2}]^\circ_3 - 4f\,[3\frac{1}{2}]_{3,4}$	5375.65	5375.65	.00
18618.69	15	$3d\,[2\frac{1}{2}]^\circ_2 - 4f\,[2\frac{1}{2}]_{2,3}$	5369.48	5369.41	−.07
18624.94	22	$3d\,[2\frac{1}{2}]^\circ_3 - 4f\,[2\frac{1}{2}]_{2,3}$	5367.67	5367.62	−.05

Table 4. *Revision of f-type levels in* Ne I

Proposed values	Atomic Energy Levels [10]	Racah notation
167054.70	167054.59	$2p^5({}^2P^\circ_{1\frac{1}{2}})4f\,[1\frac{1}{2}]_{1,2}$
167062.28	[167062.5]	$4f\,[4\frac{1}{2}]_{4,5}$
167071.03	167071.08	$4f\,[2\frac{1}{2}]_{2,3}$
167079.06	[167079.1]	$4f\,[3\frac{1}{2}]_{3,4}$
167848.33	----------	$2p^5({}^2P^\circ_{0\frac{1}{2}})4f'[3\frac{1}{2}]_{3,4}$
167848.62	167848.67	$4f'[2\frac{1}{2}]_{2,3}$

It is to be noted that a total of only six of these *f*-levels have been found, two primed and four unprimed. This represents the complete development of the level system, but with the Racah pairs either coalesced or so close together that they cannot be distinguished in cases where there is a possible combination of both members of a pair with a given *d*-level, producing a close doublet. Such close levels might also be distinguished on the basis of a small difference in numerical value based on determinations from strictly single transitions according to selection rules, but here again the attainable precision appears inadequate for the *f*-levels of Ne I.

4.3. Argon

The observations on A I extend from approximately 12000 to 17000 A, covering essentially the region explored by Sittner and Peck [1], but slightly less extended in the directions of both shorter and longer wavelengths. There appeared to be no advantage in overlapping the region observed photographically by Meggers [3] below about 12000 A where the photographic emulsions were sufficiently sensitive to permit essentially complete recording of the spectrum. The principal reason for reobserving A I was that a considerable number of the lines beginning with 13273 A and lying in the region of greater wavelengths were either left unclassified by Sittner and Peck or had been assigned to transitions that appeared improbable. Part of Sittner and Peck's observations were made with flash tubes. The differences in excitation are responsible for considerable variation in the intensities of some level combinations, when Geissler tube and flash tube excitations are compared. In general, the effect of the flash tube excitation is to increase the intensities of combinations of levels where one or both the levels belong to the family converging to the higher level of the inverted doublet constituting the ion limit, namely, ${}^2P^\circ_{0\frac{1}{2}}$. A few of the weak lines observed by Sittner and Peck do not appear on our records and, vice versa. We have observed a small number not included in their list. These few weak lines remain unclassified, and there may be some doubt of their origin in A I. Table 5 contains the pertinent information regarding 66 lines included in the current set of observations. All but three of these lines are classified. The wave numbers observed by Sittner and Peck and by Meggers for the overlapping region are listed for comparison. A slight majority of the observed wave numbers show better agreement with the calculated values than those of Sittner and Peck, but the precision of observation is not regarded as being significantly improved. The observations on argon were not expected to give precise evaluations of intensities. The same remark also applies to the sections on krypton and xenon. Because of the

TABLE 5. *Description of* A I *in the infrared region*

Observed wavelength in air, Humphreys and Kostkowski	Observed intensity	Wave number observed			Term combination		Wave number calculated, Moore [10]
		Humphreys and Kostkowski	Sittner and Peck	Meggers	Paschen notation	Racah notation	
A		cm^{-1}	cm^{-1}	cm^{-1}			
12112. 20	300	8253. 87	8254. 06	8253. 81	$2p_9\ -3d_1'$	$4p\,[2\frac{1}{2}]_3-3d\,[2\frac{1}{2}]^{\circ}_3$	8253. 81
12139. 79	100	8235. 11	8235. 22	8235. 16	$2p_4\ -3s_1'$	$4p'[1\frac{1}{2}]_1-3d'[1\frac{1}{2}]^{\circ}_1$	8235. 14
12151. 57	15	8227. 13	8227. 33	8227. 32	$3d_1''\ -4W$	$3d\,[2\frac{1}{2}]^{\circ}_2-4f'[3\frac{1}{2}]_{3,4}$	8227. 35
12343. 72	150	8099. 06	8099. 40	8099. 30	$2p_8\ -3d_1'$	$4p\,[2\frac{1}{2}]_2-3d\,[2\frac{1}{2}]^{\circ}_3$	8099. 29
12356. 82	100	8090. 48	8090. 87	8090. 86	$3d_3\ -4Y$	$3d\,[1\frac{1}{2}]^{\circ}_2-4f\,[2\frac{1}{2}]_3$	8090. 83
12402. 88	400	8060. 43	8060. 44	8060. 47	$2p_7\ -3d_2$	$4p\,[1\frac{1}{2}]_1-3d\,[1\frac{1}{2}]^{\circ}_1$	8060. 45
12419. 39	20	8049. 71	8049. 95	8049. 74	$3d_3\ -4X$	$3d\,[1\frac{1}{2}]^{\circ}_2-4f\,[1\frac{1}{2}]_2$	8049. 68
12439. 19	500	8036. 90	8037. 02	8036. 81	$2p_{10}\ -3d_3$	$4p\,[0\frac{1}{2}]_1-3d\,[1\frac{1}{2}]^{\circ}_2$	8036. 84
12456. 05	400	8026. 02	8025. 83	8025. 98	$2p_8\ -2s_4$	$4p\,[2\frac{1}{2}]_2-5s\,[1\frac{1}{2}]^{\circ}_1$	8025. 95
12487. 63	700	8005. 72	8005. 68	8005. 71	$2p_9\ -2s_5$	$4p\,[2\frac{1}{2}]_3-5s\,[1\frac{1}{2}]^{\circ}_2$	8005. 75
12554. 44	5	7963. 12	7962. 87	7963. 43	$2p_9\ -3d_1''$	$4p\,[2\frac{1}{2}]_3-3d\,[2\frac{1}{2}]^{\circ}_2$	7963. 25
12596. 27	5	7936. 68	7936. 60	-------	$3d_1'\ -4W$	$3d\,[2\frac{1}{2}]^{\circ}_3-4f'[3\frac{1}{2}]_{3,4}$	7936. 79
12621. 82	6	7920. 61	7920. 09	7920. 78	$2p_5\ -2s_2$	$4p\,[0\frac{1}{2}]_0-5s'[0\frac{1}{2}]^{\circ}_1$	7920. 75
12639. 01	2	7909. 84	7909. 21	-------	$2p_6\ -3d_2$	$4p\,[1\frac{1}{2}]_2-3d\,[1\frac{1}{2}]^{\circ}_1$	7910. 15
12651. 14	2	7902. 26	-------	-------	------------	--------------------	-------
12702. 39	150	7870. 37	7870. 46	7870. 46	$2p_2\ -3s_1'$	$4p'[0\frac{1}{2}]_1-3d'[1\frac{1}{2}]^{\circ}_1$	7870. 44
12733. 59	75	7851. 09	7850. 91	7851. 22	$2p_8\ -2s_5$	$4p\,[2\frac{1}{2}]_2-5s\,[1\frac{1}{2}]^{\circ}_2$	7851. 23
12746. 31	40	7843. 25	7843. 09	7843. 38	$2p_4\ -2s_2$	$4p'[0\frac{1}{2}]_1-5s'[0\frac{1}{2}]^{\circ}_1$	7843. 31
*12802	300	-------	7808. 75	7808. 73	$2p_8\ -3d_1''$	$4p\,[2\frac{1}{2}]_2-3d\,[2\frac{1}{2}]^{\circ}_2$	7808. 73
12912. 26	4	7742. 45	-------	-------	------------	--------------------	-------
12933. 33	60	7729. 84.	7729. 26	7729. 99	$2p_4\ -2s_3$	$4p'[1\frac{1}{2}]_1-5s'[0\frac{1}{2}]^{\circ}_0$	7729. 91
12956. 59	250	7715. 96	7715. 92	7715. 94	$2p_{10}\ -3d_6$	$4p\,[0\frac{1}{2}]_1-3d\,[0\frac{1}{2}]^{\circ}_1$	7715. 95
13008. 47	200	7685. 19	7684. 99	7685. 39	$2p_3\ -2s_2$	$4p'[1\frac{1}{2}]_2-5s'[0\frac{1}{2}]^{\circ}_1$	7685. 32
13028. 27	5	7673. 51	7673. 28	------	$2p_4\ -3s_1''$	$4p'[1\frac{1}{2}]_1-3d'[1\frac{1}{2}]^{\circ}_2$	7673. 42
13214. 70	150	7565. 25	7565. 11	------	$2p_{10}\ -3d_6$	$4p\,[0\frac{1}{2}]_1-3d\,[0\frac{1}{2}]^{\circ}_0$	7565. 73
13228. 49	200	7557. 37	7557. 49	------	$2p_9\ -3d_4$	$4p\,[2\frac{1}{2}]_3-3d\,[3\frac{1}{2}]^{\circ}_3$	7557. 59
13231. 37	120	7555. 72	7555. 78	------	$2p_7\ -2s_4$	$4p\,[1\frac{1}{2}]_1-5s\,[1\frac{1}{2}]^{\circ}_1$	7555. 96
13273. 05	750	7532. 00	7532. 27	------	$2p_3\ -3s_1'''$	$4p'[1\frac{1}{2}]_2-3d'[2\frac{1}{2}]^{\circ}_3$	7532. 24
13302. 37	3	7515. 39	7515. 34	------	$2p_3\ -3s_1''$	$4p'[1\frac{1}{2}]_2-3d'[1\frac{1}{2}]^{\circ}_2$	7515. 43
13313. 39	600	7509. 17	7509. 41	------	$2p_4\ -3s_1''''$	$4p'[1\frac{1}{2}]_1-3d'[2\frac{1}{2}]^{\circ}_2$	7509. 28
13330. 32	7	7499. 64	7499. 67	------	$3d_4'\ -4U$	$3d\,[3\frac{1}{2}]^{\circ}_4-4f\,[3\frac{1}{2}]_{3,4}$	7499. 93
13367. 38	800	7478. 84	7479. 06	------	$2p_6\ -3d_1'$	$4p\,[1\frac{1}{2}]_2-3d\,[2\frac{1}{2}]^{\circ}_3$	7479. 01
13406. 57	250	7456. 98	7456. 92	------	$3d_4'\ -4V$	$3d\,[3\frac{1}{2}]^{\circ}_4-4f\,[4\frac{1}{2}]_5$	7457. 10
13499. 24	50	7405. 79	7405. 45	------	$2p_6\ -2s_4$	$4p\,[1\frac{1}{2}]_2-5s\,[1\frac{1}{2}]^{\circ}_1$	7405. 66
13503. 99	850	7403. 18	7403. 21	------	$2p_8\ -3d_4$	$4p\,[2\frac{1}{2}]_2-3d\,[3\frac{1}{2}]^{\circ}_3$	7403. 07
13543. 75	15	7481. 45	7380. 74	------	$2p_7\ -2s_5$	$4p\,[1\frac{1}{2}]_1-5s\,[1\frac{1}{2}]^{\circ}_2$	7381. 25
13573. 60	25	7365. 22	7364. 47	------	$2p_2\ -2s_3$	$4p'[0\frac{1}{2}]_1-5s'[0\frac{1}{2}]^{\circ}_0$	7365. 21
13599. 18	55	7351. 36	7351. 02	------	$2p_3\ -3s_1''''$	$4p'[1\frac{1}{2}]_2-3d'[2\frac{1}{2}]^{\circ}_2$	7351. 29
13622. 38	500	7338. 84	7338. 74	------	$2p_7\ -3d_1''$	$4p\,[1\frac{1}{2}]_1-3d\,[2\frac{1}{2}]^{\circ}_2$	7338. 75
13678. 53	300	7308. 72	7308. 83	------	$2p_2\ -3s_1''$	$4p'[0\frac{1}{2}]_1-3d'[1\frac{1}{2}]^{\circ}_2$	7308. 72
13718. 77	1000	7287. 28	7287. 54	------	$2p_9\ -3d_4'$	$4p\,[2\frac{1}{2}]_3-3d\,[3\frac{1}{2}]^{\circ}_4$	7287. 42
13825. 99	30	7230. 76	------	------	$2p_6\ -2s^5$	$4p\,[1\frac{1}{2}]_2-5s\,[1\frac{1}{2}]^{\circ}_2$	7230. 95
13828. 79	20	7229. 30	7229. 85	------	$3d_4\ -4U$	$3d\,[3\frac{1}{2}]^{\circ}_3-4f\,[3\frac{1}{2}]_{3,4}$	7229. 76
13907. 41	12	7188. 44	------	------	$2p_6\ -3d_1''$	$4p\,[1\frac{1}{2}]_2-3d\,[2\frac{1}{2}]^{\circ}_2$	7188. 45
13910. 83	150	7186. 67	7187. 34	------	$3d_4\ -4V$	$3d\,[3\frac{1}{2}]^{\circ}_3-4f\,[4\frac{1}{2}]_4$	7187. 38
14093. 61	120	7093. 46	7093. 33	------	$2p_5\ -3d_2$	$4p\,[0\frac{1}{2}]_0-3d\,[1\frac{1}{2}]^{\circ}_1$	7093. 43
14249. 93	7	7015. 65	7015. 82	------	$2p_4\ -3d_2$	$4p'[1\frac{1}{2}]_1-3d\,[1\frac{1}{2}]^{\circ}_1$	7016. 00
14257. 46	50	7011. 94	.7012. 16	------	$3s_1''''\ -4W$	$3d'[2\frac{1}{2}]^{\circ}_2-4f'[3\frac{1}{2}]_{3,4}$	7012. 36
14596. 27	40	6849. 18	6849. 14	------	$3s_1''\ -4Z$	$3d'[1\frac{1}{2}]^{\circ}_2-4f'[2\frac{1}{2}]_3$	6849. 14
14634. 11	80	6831. 47	6831. 49	------	$3s_1'''\ -4W$	$3d'[2\frac{1}{2}]^{\circ}_3-4f'[3\frac{1}{2}]_{3,4}$	6831. 41
14649. 97	60	6824. 07	6823. 98	------	$3d_1''\ -4U$	$3d\,[2\frac{1}{2}]^{\circ}_2-4f\,[3\frac{1}{2}]_{3,4}$	6824. 10
14692. 39	5	6804. 37	6803. 73	------	$3d_1''\ -4Y$	$3d\,[2\frac{1}{2}]^{\circ}_2-4f\,[2\frac{1}{2}]_{2,3}$	{6804. 02 {6803. 76
14739. 11	3	6782. 80	6782. 65	------	$2p_8\ -3d_4$	$4p\,[1\frac{1}{2}]_2-3d\,[3\frac{1}{2}]^{\circ}_3$	6782. 79
14786. 29	2	6761. 16	6760. 89	------	$2s_5\ -4Y$	$5s\,[1\frac{1}{2}]^{\circ}_2-4f\,[2\frac{1}{2}]_3$	6761. 26
15046. 42	70	6644. 27	6644. 31	------	$2p_1\ -3s_1'$	$4p'[0\frac{1}{2}]_0-3d'[1\frac{1}{2}]^{\circ}_1$	6644. 23

* Confused with S. O. Ne λ6402.

TABLE 5. *Description of* A I *in the infrared region*— Continued

Observed wavelength in air, Humphreys and Kostkowski	Observed intensity	Wave number observed			Term combination		Wave number calculated, Moore [10]
		Humphreys and Kostkowski	Sittner and Peck	Meggers	Paschen notation	Racah notation	
A		*cm*$^{-1}$	*cm*$^{-1}$	*cm*$^{-1}$			
15172. 33	22	6589. 13	6588. 82	------	$2p_5$ $-2s_4$	$4p\ [0\frac{1}{2}]_0-5s\ [1\frac{1}{2}]^{\circ}_1$	6588. 94
15229. 92	1	6564. 21	------	------	------------	------------	------
15302. 26	75	6533. 18	6533. 62	------	$3d'_1$ $-4\mathrm{U}$	$3d\ [2\frac{1}{2}]^{\circ}_3-4f\ [3\frac{1}{2}]_{3,4}$	6533. 54
15329. 56	5	6521. 54	6521. 73	------	$2p_8$ $-3d_3$	$4p\ [2\frac{1}{2}]_2-3d\ [1\frac{1}{2}]^{\circ}_2$	6521. 66
15349. 52	10	6513. 06	6513. 24	------	$3d'_1$ $-4\mathrm{Y}$	$3d\ [2\frac{1}{2}]^{\circ}_3-4f\ [2\frac{1}{2}]_3$	6513. 20
15353. 51	2	6511. 37	6511. 51	------	$2p_4$ $-2s_4$	$4p'[1\frac{1}{2}]_1-5s\ [1\frac{1}{2}]^{\circ}_1$	6511. 51
15402. 58	10	6490. 63	6490. 84	------	$3d'_1$ $-4\mathrm{V}$	$3d\ [2\frac{1}{2}]^{\circ}_3-4f\ [4\frac{1}{2}]_4$	6491. 16
15899. 93	20	6287. 60	6288. 42	------	$3s'_1$ $-4\mathrm{Z}$	$3d'[1\frac{1}{2}]^{\circ}_1-4f'\ [2\frac{1}{2}]_2$	6287. 68
15989. 34	20	6252. 44	6252. 32	------	$2p_1$ $-2s_2$	$4p'[0\frac{1}{2}]_0-5s'\ [0\frac{1}{2}]^{\circ}_1$	6252. 40
16436. 92	18	6082. 18	6082. 33	------	$3d_2$ $-4\mathrm{Y}$	$3d\ [1\frac{1}{2}]^{\circ}_1-4f\ [2\frac{1}{2}]_2$	6082. 32
16520, 14	9	6051. 55	6052. 55	------	$2p_7$ $-3d_3$	$4p\ [1\frac{1}{2}]_1-3d\ [1\frac{1}{2}]^{\circ}_2$	6051. 68
16549. 81	6	6040. 70	6041. 06	------	$3d_2$ $-4\mathrm{X}$	$3d\ [1\frac{1}{2}]^{\circ}_1-4f\ [1\frac{1}{2}]_{1,2}$	{6040. 59 {6040. 91
16739. 84	5	5972. 12	5971. 86	------	$2p_2$ $-2s_5$	$4p'[0\frac{1}{2}]_1-5s\ [1\frac{1}{2}]^{\circ}_2$	5972. 09
16940. 39	100	5901. 42	5901. 59	------	$2p_6$ $-3d_3$	$4p\ [1\frac{1}{2}]_2-3d\ [1\frac{1}{2}]^{\circ}_2$	5901. 38

essentially linear character of the dependence of detector response upon incident energy, these records do, nevertheless, provide an excellent means of intensity evaluation. Because of the limited scale range of the recorder, it is necessary to make a large number of records with different amounts of energy incident on the entrance slit or with different slit widths, or else to introduce controlled attenuation into the amplifier output in order to reveal the range of intensities between the strongest and weakest lines. Both devices have been used to a limited extent. The relative intensities may be considered reasonably good estimates over moderate ranges, but are subject to the limitations mentioned in the section on helium. The nonuniformity in spectral distribution associated with use of a grating with a pronounced "blaze" angle is probably the most important of these limitations. It seems fairly certain that the most intense line included among those originating in transitions of the classes studied is $2p_9-3d'_4$. The newly classified lines originate in most instances in combinations involving four newly discovered levels which are the first members of the old V, U, and W series previously known only in higher members. In the Racah or pair-coupling notation, these levels are $4f[4\frac{1}{2}]_5$, $4f[4\frac{1}{2}]_4$, $4f[3\frac{1}{2}]_{3,4}$, and $4f'[3\frac{1}{2}]_{3,4}$. It is to be noted that in the last two instances the separation of the pairs has not been directly observed, or inferred, from existing data. These newly interpreted levels were actually identified from the data in the Sittner and Peck publication, previous to the observations herein reported, and communicated to Dr. Moore for inclusion in the first volume of [10], as noted in the section on argon. The following are the wave numbers of lines for which no classification has been published previously: 7673.51, 7532.00, 7515.39, 7456.98, 7381.45, 7011.94, 6824.07, 6533.18, and 6490.63 cm^{-1}. New classifications are proposed for 7499.64, and 6831.47 cm^{-1}. Each of the lines of wave number 7229.85 and 7187.34 cm^{-1}, as listed by Sittner and Peck, has a close resolved companion. The companion line in each instance should have the classification listed by those authors, and new interpretations are proposed for the lines in the positions first reported.

4.4. Krypton

Considerably more effort has been devoted to the observation and interpretation of Kr I than to any other part of this study. The principal reason for this emphasis is that, of these noble-gas spectra, Kr I has the greatest population of fairly uniformly distributed lines in the region between 10000 and 20000 A, and, as such, shows considerable promise as a source of standard wavelengths. The wavelengths have been determined by use of second-order krypton, neon, and argon lines as comparison standards, and in some instances third-order lines of Fe I excited in an arc. A few first-order krypton lines originating in transitions of the type $1s-2p$, the wavelengths of which can be computed with great accuracy from known levels, were also used in regions where available. Actually, the relative scarcity of good standards was the principal impediment to the most satisfactory wavelength determinations. One of the sources used was a Geissler tube, imported several years ago from the firm of Robert Götze in Leipzig, and kindly loaned for this work by Wm. F. Meggers. This tube contained krypton of exceptional purity, and its operation under optimum conditions probably

TABLE 6. *Description of Kr I in the infrared region*

Observed wavelength in air, Humphreys and Kostkowski	Observed intensity	Wave number observed			Term combination		Wave number calculated, Edlén levels
		Humphreys and Kostkowski	Sittner and Peck	Meggers	Paschen notation	Racah notation	
A		cm^{-1}	cm^{-1}	cm^{-1}			cm^{-1}
11792.25	120	8477.82	--------	8477.67	$2p_{10}-3d_2$	$5p\,[0\frac{1}{2}]_1-4d\,[1\frac{1}{2}]^{\circ}_1$	8477.71
11819.43	2000	8458.33	--------	8458.33	$2p_{10}-2s_5$	$5p\,[0\frac{1}{2}]_1-6s\,[1\frac{1}{2}]^{\circ}_2$	8458.36
11996.00	25	8333.82	--------	--------	$3d_3-4Y$	$4d\,[1\frac{1}{2}]^{\circ}_2-4f\,[2\frac{1}{2}]_2$	8333.84
11997.08	480	8333.07	--------	8333.03	$3d_3-4T$	$4d\,[1\frac{1}{2}]^{\circ}_2-4f\,[2\frac{1}{2}]_3$	8333.08
12077.42	115	8277.64	8277.96	8277.79	$3d_3-4Z$	$4d\,[1\frac{1}{2}]^{\circ}_2-4f\,[1\frac{1}{2}]_2$	8277.80
12117.81	100	8250.05	8250.09	8250.06	$3d_4'-4W$	$4d\,[3\frac{1}{2}]^{\circ}_4-4f\,[3\frac{1}{2}]_{3,4}$	8250.04
*12123.47	40	--------	8245.82	8246.15	$1s_2-2p_5$	$5s'\,[0\frac{1}{2}]^{\circ}_1-5p\,[0\frac{1}{2}]_0$	8246.16
12156.97	2	8223.48	--------	--------	$3d_4'-4T$	$4d\,[3\frac{1}{2}]^{\circ}_4-4f\,[2\frac{1}{2}]_3$	8223.51
12204.39	700	8191.52	8191.13	8191.43	$3d_4'-4U$	$4d\,[3\frac{1}{2}]^{\circ}_4-4f\,[4\frac{1}{2}]_5$	8191.43
12229.23	4	8174.89	--------	--------	$2p_4-3s_4$	$5p'[1\frac{1}{2}]_1-7s\,[1\frac{1}{2}]^{\circ}_1$	8174.78
12240.81	2	8167.15	--------	--------	$3d_1'-4p_6$	$4d\,[2\frac{1}{2}]^{\circ}_3-7p\,[1\frac{1}{2}]_2$	8167.31
12321.48	9	8113.68	8113.83	--------	$3s_1''-1534.60$	$4d'[1\frac{1}{2}]^{\circ}_2-4f'[2\frac{1}{2}]_3$	8113.98
12598.19	15	7935.47	--------	--------	$3s_1''''-1536.49_3$	$4d'[2\frac{1}{2}]^{\circ}_2-4f'[3\frac{1}{2}]_3$	7935.75
12782.39	100	7821.11	8721.12	--------	$3d_4-4W$	$4d\,[3\frac{1}{2}]^{\circ}_3-4f\,[3\frac{1}{2}]_{3,4}$	7821.11
12825.08	5	7795.10	7794.70	--------	$3d_4-4T$	$4d\,[3\frac{1}{2}]^{\circ}_3-4f\,[2\frac{1}{2}]_3$	7794.58
					$3d_4-4Y$	$4d\,[3\frac{1}{2}]^{\circ}_3-4f\,[2\frac{1}{2}]_2$	7795.34
*12861.89	55	--------	7772.41	--------	$1s_3-2p_7$	$5s'\,[0\frac{1}{2}]^{\circ}_0-5p\,[1\frac{1}{2}]_1$	7772.78
12879.00	500	7762.46	7762.56	--------	$3d_4-4U$	$4d\,[3\frac{1}{2}]^{\circ}_3-4f\,[4\frac{1}{2}]_4$	7762.70
12934.48	1	7729.15	--------	--------	$2p_3-4d_2$	$5p'[0\frac{1}{2}]-5d\,[1\frac{1}{2}]^{\circ}_1$	7729.30
12977.98	2	7703.24	--------	--------	$2p_2-4d_2$	$5p'[1\frac{1}{2}]_2-5d\,[1\frac{1}{2}]^{\circ}_1$	7703.28
12985.08	12	7699.04	7698.32	--------	$2p_{10}-3d_1''$	$5p\,[0\frac{1}{2}]_1-4d\,[2\frac{1}{2}]^{\circ}_2$	7698.91
13022.05	15	7677.18	7676.47	--------	$3s_1'''-1536.49_3$	$4d'[2\frac{1}{2}]^{\circ}_3-4f'[3\frac{1}{2}]_{3,4}$	7676.97
13177.38	850	7586.70	7586.66	--------	$2p_8-2s_4$	$5p\,[2\frac{1}{2}]_2-6s\,[1\frac{1}{2}]^{\circ}_1$	7586.65
13210.56	10	7567.63	7566.35	--------	$2p_4-4d_1''$	$5p'[1\frac{1}{2}]_1-5d\,[2\frac{1}{2}]^{\circ}_2$	7567.58
13240.52	75	7550.51	7549.90	--------	$2p_4-2s_2$	$5p'[1\frac{1}{2}]_1-6s'[0\frac{1}{2}]^{\circ}_1$	7550.41
13304.30	5	7514.31	--------	--------	$2s_5-4p_9$	$6s\,[1\frac{1}{2}]^{\circ}_2-7p\,[2\frac{1}{2}]_3$	7514.31
13337.52	55	7495.59	7494.87	--------	$2p_4-2s_3$	$5p'[1\frac{1}{2}]_1-6s'[0\frac{1}{2}]^{\circ}_0$	7495.42
13622.28	800	7338.91	--------	--------	$2p_8-3d_2$	$5p\,[2\frac{1}{2}]_2-4d\,[1\frac{1}{2}]^{\circ}_1$	7338.84
13634.22	1700	7332.48	--------	--------	$2p_9-2s_5$	$2p\,[2\frac{1}{2}]_3-6s\,[1\frac{1}{2}]^{\circ}_2$	7332.47
13658.38	360	7319.51	--------	--------	$2p_8-2s_5$	$5p\,[2\frac{1}{2}]_2-6s\,[1\frac{1}{2}]^{\circ}_2$	7319.49
13711.23	100	7291.30	--------	--------	$2p_4-3s_1'$	$5p'[1\frac{1}{2}]_1-4d'[1\frac{1}{2}]^{\circ}_1$	7291.40
*13738.86	400	--------	--------	--------	$1s_2-2p_6$	$5s'[0\frac{1}{2}]^{\circ}_1-5p\,[1\frac{1}{2}]_2$	7276.64
13763.72	6	7263.49	--------	--------	$2p_2-4d_1'$	$5p'[1\frac{1}{2}]_2-5d\,[2\frac{1}{2}]^{\circ}_3$	7263.31
13800.03	3	7244.37	--------	--------	$2p_3-4d_1''$	$5p'[0\frac{1}{2}]_1-5d\,[2\frac{1}{2}]^{\circ}_2$	7244.35
13832.57	50	7227.33	--------	--------	$2p_3-2s_2$	$5p'[0\frac{1}{2}]_1-6s'[0\frac{1}{2}]^{\circ}_1$	7227.18
13882.64	240	7201.26	--------	--------	$2p_2-2s_2$	$5p'[1\frac{1}{2}]_2-6s'[0\frac{1}{2}]^{\circ}_1$	7201.16
13924.00	270	7179.87	--------	--------	$3d_1''-4W$	$4d\,[2\frac{1}{2}]^{\circ}_2-4f\,[3\frac{1}{2}]_3$	7179.97
13939.13	85	7172.08	--------	--------	$2p_3-2s_3$	$5p'[0\frac{1}{2}]_1-6s'[0\frac{1}{2}]^{\circ}_0$	7172.19
13974.15	70	7154.10	7154.11	--------	$3d_1''-4Y$	$4d\,[2\frac{1}{2}]^{\circ}_2-4f\,[2\frac{1}{2}]_2$	7154.20
14104.27	40	7088.10	--------	--------	$2p_3-4d_3$	$5p'[0\frac{1}{2}]_1-5d\,[1\frac{1}{2}]^{\circ}_2$	7088.10
14156.62	15	7061.89	--------	--------	$2p_2-4d_3$	$5p'[1\frac{1}{2}]_2-5d\,[1\frac{1}{2}]^{\circ}_2$	7062.08
14341.25	9	6970.97	--------	--------	$2p_2-4d_4$	$5p'[1\frac{1}{2}]_2-5d\,[2\frac{1}{2}]^{\circ}_3$	6971.31
14347.82	400	6967.78	6968.53	--------	$3d_1'-4W$	$4d\,[2\frac{1}{2}]^{\circ}_3-4f\,[3\frac{1}{2}]_{3,4}$	6968.00
----------	------	--------	--------	--------	$2p_3-3s_1'$	$5p'[0\frac{1}{2}]_1-4d'[1\frac{1}{2}]^{\circ}_1$	6968.16
----------	------	--------	6941.89	--------	$2p_2-3s_1'$	$5p'[1\frac{1}{2}]_2-4d'[1\frac{1}{2}]^{\circ}_1$	6942.14
					$3d_1'-4Y$	$4d\,[2\frac{1}{2}]^{\circ}_3-4f\,[2\frac{1}{2}]_2$	6942.23
14402.58	80	6941.29	--------	--------	$3d_1'-4T$	$4d\,[2\frac{1}{2}]^{\circ}_3-4f\,[2\frac{1}{2}]_3$	6941.47
14426.93	1100	6929.57	6929.97	--------	$2p_7-2s_4$	$5p\,[1\frac{1}{2}]_1-6s\,[1\frac{1}{2}]^{\circ}_1$	6929.64
14469.33	30	6909.27	6909.74	--------	$3d_1'-4U$	$4d\,[2\frac{1}{2}]^{\circ}_3-4f\,[4\frac{1}{2}]_4$	6909.59
14715.55	2	6973.66	--------	--------	$2p_1-4d_2$	$5p'[0\frac{1}{2}]_0-5d\,[1\frac{1}{2}]^{\circ}_1$	6973.38
14734.46	900	6784.95	--------	--------	$2p_9-3d_1'$	$5p\,[2\frac{1}{2}]_3-4d\,[2\frac{1}{2}]^{\circ}_3$	6784.99
14762.83	250	6771.90	6772.03	--------	$2p_8-3d_1'$	$5p\,[2\frac{1}{2}]_2-4d\,[2\frac{1}{2}]^{\circ}_3$	6772.01
14765.64	230	6770.62	6770.39	--------	$2p_6-2s_4$	$5p\,[1\frac{1}{2}]_2-6s\,[1\frac{1}{2}]^{\circ}_1$	6770.69
14961.76	110	6681.86	6681.56	--------	$2p_7-3d_2$	$5p\,[1\frac{1}{2}]_1-4d\,[1\frac{1}{2}]^{\circ}_1$	6681.83
14973.74	8	6676.52	--------	--------	$3d_5-3p_5$	$4d\,[0\frac{1}{2}]^{\circ}_1-6p\,[0\frac{1}{2}]_0$	6676.45
15005.57	25	6662.36	6661.74	--------	$2p_7-2s_5$	$5p\,[1\frac{1}{2}]_1-6s\,[1\frac{1}{2}]^{\circ}_2$	6662.48
15209.52	42	6573.02	6573.35	--------	$2p_9-3d_1''$	$5p\,[2\frac{1}{2}]_3-4d\,[2\frac{1}{2}]^{\circ}_2$	6573.02

See footnote at end of table.

TABLE 6. *Description of* Kr I *in the infrared region*—Continued

Observed wavelength in air, Humphreys and Kostkowski	Observed intensity	Wave number observed			Term combination		Wave number calculated, Edlén levels
		Humphreys and Kostkowski	Sittner and Peck	Meggers	Paschen notation	Racah notation	
A		cm^{-1}	cm^{-1}	cm^{-1}			cm^{-1}
15239. 85	900	6559. 94	6560. 05	--------	$2p_8-3d_1''$	$5p\,[2\frac{1}{2}]_2-4d\,[2\frac{1}{2}]^{\circ}_3$	6560. 04
15326. 87	35	6522. 69	6522. 53	--------	$2p_6-3d_2$	$5p\,[1\frac{1}{2}]_2-4d\,[1\frac{1}{2}]^{\circ}_1$	6522. 88
15335. 29	850	6519. 11	6519. 19	--------	$2p_{10}-3d_3$	$5p\,[0\frac{1}{2}]_1-4d\,[1\frac{1}{2}]^{\circ}_2$	6519. 27
15371. 89	350	6503. 58	6503. 09	--------	$2p_6-2s_5$	$5p\,[1\frac{1}{2}]_2-6s\,[1\frac{1}{2}]^{\circ}_2$	6503. 53
15433. 63	4	6477. 57	--------	--------	$2p_4-4d_6$	$5p'[1\frac{1}{2}]_1-5d\,[0\frac{1}{2}]^{\circ}_0$	6477. 56
*15474. 02	65	--------	6460. 84	--------	$1s_2-2p_8$	$5s\,[0\frac{1}{2}]^{\circ}_1-5p\,[2\frac{1}{2}]_2$	6460. 63
15634. 98	7	6394. 15	6394. 20	--------	$2s_5-4T$	$6s\,[1\frac{1}{2}]^{\circ}_2-4f\,[2\frac{1}{2}]_3$	6393. 99
15680. 94	75	6375. 41	6375. 59	--------	$3d_2-4Y$	$4d\,[1\frac{1}{2}]^{\circ}_1-4f\,[2\frac{1}{2}]_2$	6375. 40
15771. 44	1	6338. 83	--------	--------	$2s_5-4Z$	$6s\,[1\frac{1}{2}]^{\circ}_2-4f\,[1\frac{1}{2}]_2$	6338. 71
15820. 10	35	6319. 33	6319. 40	--------	$3d_2-4Z$	$4d\,[1\frac{1}{2}]^{\circ}_1-4f\,[1\frac{1}{2}]_2$	6319. 36
15823. 40	2	6318. 01	--------	--------	$3d_2-4X$	$4d\,[1\frac{1}{2}]^{\circ}_1-4f\,[1\frac{1}{2}]_1$	6318. 24
15890. 52	25	6291. 32	6290. 53	--------	$2p_1-2s_2$	$5p'[0\frac{1}{2}]_0-6s'[0\frac{1}{2}]^{\circ}_1$	6291. 26
15925. 64	6	6277. 45	--------	--------	$3d_5-3p_6$	$4d\,[0\frac{1}{2}]^{\circ}_1-6p\,[1\frac{1}{2}]_2$	6277. 42
16052. 31	2	6227. 91	6227. 31	--------	$3d_5-3p_7$	$4d\,[0\frac{1}{2}]^{\circ}_1-6p\,[1\frac{1}{2}]_1$	6228. 28
16109. 46	3	6205. 82	--------	--------	$2p_4-4d_5$	$5p'[1\frac{1}{2}]_1-5d\,[0\frac{1}{2}]^{\circ}_1$	6205. 88
16315. 58	12	6127. 42	6127. 23	--------	$2s_4-4Y$	$6s\,[1\frac{1}{2}]^{\circ}_1-4f\,[2\frac{1}{2}]_2$	6127. 59
16347. 31	5	6115. 53	--------	--------	$3d_6-3p_{10}$	$4d\,[0\frac{1}{2}]^{\circ}_0-6p\,[0\frac{1}{2}]_1$	6115. 69
16465. 29	15	6071. 70	--------	--------	$2s_4-4Z$	$6s\,[1\frac{1}{2}]^{\circ}_1-4f\,[1\frac{1}{2}]_2$	6071. 55
16573. 10	16	6032. 21	6032. 59	--------	$2p_1-3s_1'$	$5p'[0\frac{1}{2}]_0-4d'[1\frac{1}{2}]^{\circ}_1$	6032. 24
*16726. 48	70	--------	5976. 46	--------	$1s_3-2p_{10}$	$5s'[0\frac{1}{2}]^{\circ}_0-5p\,[0\frac{1}{2}]_1$	5976. 90
16784. 65	950	5956. 18	5956. 05	--------	$2p_6-3d_1'$	$5p\,[1\frac{1}{2}]_2-4d\,[2\frac{1}{2}]^{\circ}_3$	5956. 05
16853. 45	480	5931. 86	5931. 86	--------	$2p_9-3d_4$	$5p\,[2\frac{1}{2}]_3-4d\,[3\frac{1}{2}]^{\circ}_3$	5931. 88
16890. 40	1000	5918. 89	5918. 95	--------	$2p_8-3d_4$	$5p\,[2\frac{1}{2}]_2-4d\,[3\frac{1}{2}]^{\circ}_3$	5918. 90
16896. 58	700	5916. 72	5916. 75	--------	$2p_{10}-3d_5$	$5p\,[0\frac{1}{2}]_1-4d\,[0\frac{1}{2}]^{\circ}_1$	5916. 69
16935. 71	800	5903. 05	5903. 06	--------	$2p_7-3d_1''$	$5p\,[1\frac{1}{2}]_1-4d\,[2\frac{1}{2}]^{\circ}_2$	5903. 03
16994. 36	10	5882. 68	--------	--------	$2p_3-4d_5$	$5p'[0\frac{1}{2}]_1-5d\,[0\frac{1}{2}]^{\circ}_1$	5882. 65
17070. 04	10	5856. 60	--------	--------	$2p_2-4d_5$	$5p'[1\frac{1}{2}]_2-5d\,[0\frac{1}{2}]^{\circ}_1$	5856. 63
17098. 76	300	5846. 76	5846. 91	--------	$2p_4-3s_1''''$	$5p'[1\frac{1}{2}]_1-4d'[2\frac{1}{2}]^{\circ}_2$	5846. 74
17230. 21	10	5802. 15	--------	--------	$3d_5-3p_{10}$	$4d\,[0\frac{1}{2}]^{\circ}_1-6p\,[0\frac{1}{2}]_1$	5802. 00
17367. 98	360	5756. 13	5756. 36	--------	$2p_2-3s_1''''$	$5p'[1\frac{1}{2}]_2-4d'[2\frac{1}{2}]^{\circ}_3$	5756. 27
17404. 67	32	5743. 99	5744. 15	--------	$2p_6-3d_1'$	$5p\,[1\frac{1}{2}]_2-4d'[1\frac{1}{2}]^{\circ}_2$	5744. 08
17616. 57	37	5674. 90	5674. 22	--------	$3d_3-3p_6$	$4d\,[1\frac{1}{2}]^{\circ}_2-6p\,[1\frac{1}{2}]_2$	5674. 84
17630. 44	4	5670. 44	--------	--------	$2p_4-3s_1''$	$5p'[1\frac{1}{2}]_1-4d'[1\frac{1}{2}]^{\circ}_2$	5670. 40
17770. 21	4	5625. 84	--------	--------	$3d_3-3p_7$	$4d\,[1\frac{1}{2}]^{\circ}_2-6p\,[1\frac{1}{2}]_1$	5625. 70
17842. 70	270	5602. 98	5602. 97	--------	$2p_{10}-3d_6$	$5p\,[0\frac{1}{2}]_1-4d\,[0\frac{1}{2}]^{\circ}_0$	5603. 00
18001. 71	400	5553. 49	5553. 34	--------	$2p_5-3d_2$	$5p\,[0\frac{1}{2}]_0-4d\,[1\frac{1}{2}]^{\circ}_1$	5553. 36
18098. 46	10	5523. 80	5523. 50	--------	p_3-3s_1''''	$5p'[0\frac{1}{2}]_1-4d'[2\frac{1}{2}]^{\circ}_2$	5523. 51
18167. 12	1500	5502. 92	5502. 93	--------	$2p_9-3d_4'$	$5p\,[2\frac{1}{2}]_3-4d[3\frac{1}{2}]^{\circ}_4$	5502. 95
18184. 43	15	5497. 69	5497. 57	--------	$2p_2-3s_1''''$	$5p'[1\frac{1}{2}]_2-4d'[2\frac{1}{2}]^{\circ}_3$	5497. 49
18418. 82	4	5427. 72	--------	--------	$3d_3-3p_9$	$4d\,[1\frac{1}{2}]^{\circ}_2-6p\,[2\frac{1}{2}]_3$	5427. 87
18581. 19	30	5380. 29	5380. 45	--------	$2p_8-3d_3$	$5p\,[2\frac{1}{2}]_2-4d\,[1\frac{1}{2}]^{\circ}_2$	5380. 40
18695. 91	62	5347. 28	5346. 76	--------	$2p_3-3s_1''$	$5p'[0\frac{1}{2}]_1-4d'[1\frac{1}{2}]^{\circ}_2$	5347. 17
18785. 45	37	5321. 79	5321. 61	--------	$1s_2-2p_{10}$	$5s'[0\frac{1}{2}]^{\circ}_1-5p\,[0\frac{1}{2}]_1$	5321. 81
18787. 73	10	5321. 15	--------	--------	$2p_2-3s_1''$	$5p'[1\frac{1}{2}]_2-4d'[1\frac{1}{2}]^{\circ}_2$	5321. 15
18797. 59	40	5318. 36	5317. 88	--------	$3d_4'-3p_9$	$4d\,[3\frac{1}{2}]^{\circ}_4-6p[2\frac{1}{2}]_3$	5318. 30

*Calculated wavelength used as a comparison standard.

revealed all of the krypton spectrum that can be excited in this type of source. The description and interpretation of the observed krypton spectrum in the region investigated is displayed in table 6, which presents the data on 98 krypton lines, all of which are classified. Included in this number are 36 lines not reported by Sittner and Peck. About three-fourths of these are weak lines scattered throughout the region, but nine lines between 13600 and 14000 A are among the most intense in the infrared krypton spectrum and may have been omitted inadvertently from the description by Sittner and Peck. A portion of a record showing this group of lines is displayed in figure 3. This was a survey record run with relatively wide slits in order to reveal as many of the faint lines as possible. The peaks of many of the intense lines

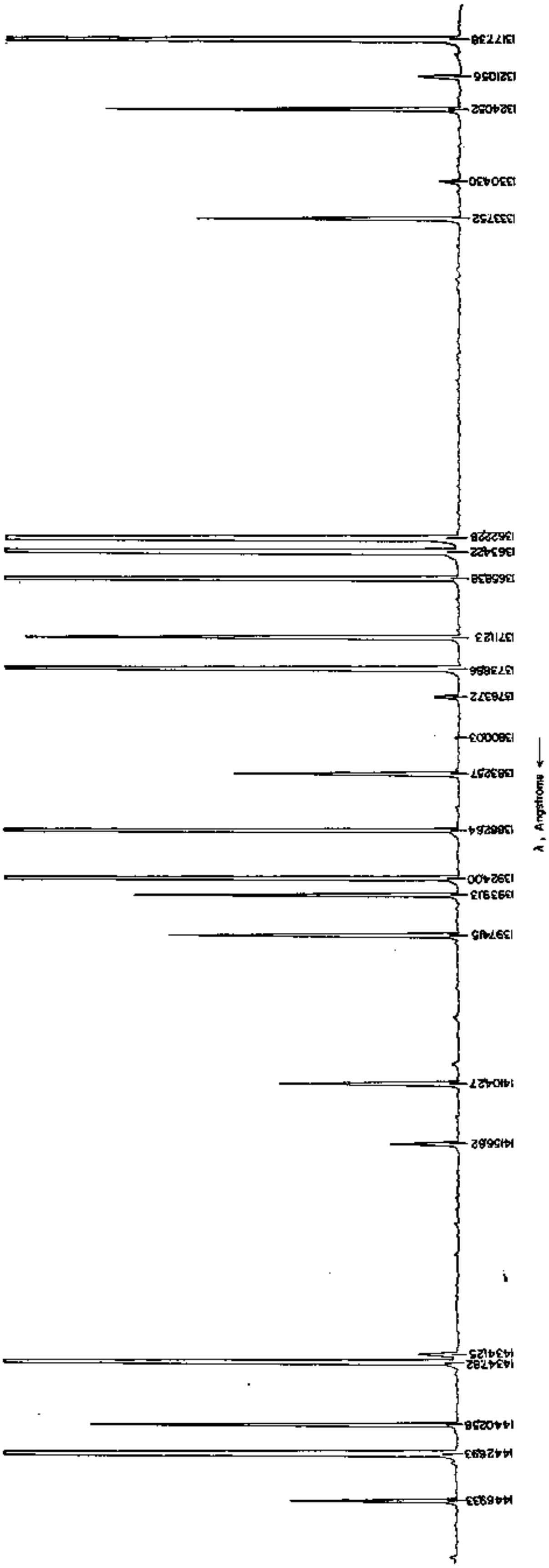

FIGURE 3. *Reproduction of tracing of chart record of infrared spectrum of krypton, 13100 to 14500 A.*

are cut off, because the deflections are off the scale of the recorder.

Edlén's revisions of the table of levels by Meggers and Humphreys [4] and listing of additional levels are the basis of the entries on Kr I in [10]. These changes are relatively few in number, emphasizing the fact that this analysis has long been regarded as essentially complete. The levels to which the designations $2s_2$ and $3s_1'$ were formerly assigned have been interchanged. A similar switch has been made with $3s_1''$ and $3s_1''''$. These changes should be taken into account in comparing Sittner and Peck's classifications with ours. The Edlén manuscript also supplied a complete set of values of the levels representing the first members of the various series originating in the $4f$ configuration, except that the doublet structure of the level designated 4W or $4f[3\frac{1}{2}]_{3,4}$ remained unresolved; a computed value only was proposed for one component of the 4U doublet, namely $4f[4\frac{1}{2}]_4$; and only three of the four possible $4f$-levels converging to the higher ion limit $p^5(^2\mathrm{P}^\circ_{0\frac{1}{2}})$ were proposed. The experimental confirmation of the 4U and 4W by Humphreys and Plyler [2], has been mentioned. The new compilation of levels of Kr I also includes the previously missing $2s_3$. Edlén listed two choices, but it was noted that one of Sittner and Peck's intense unclassified lines, $\nu=7494.87$ cm^{-1}, could be interpreted as $2p_4-2s_3$, if the level of absolute value 7823.56 were adopted as $2s_3$. Further confirmation is found in the classification of the moderately intense line, $\nu=7172.08$ cm^{-1}, as $2p_3-2s_3$. Two of the remaining intense lines reported without classification by Sittner and Peck are assigned to transitions involving $4f$-levels of the family converging to the higher limit. These are ν, 8113.83 cm^{-1}, classified in pair-coupling notation $4d'[1\frac{1}{2}]^\circ_2-4f'[2\frac{1}{2}]_3$, and ν, 7676.47 cm^{-1}, classified $4d'[2\frac{1}{2}]^\circ_3-4f'[3\frac{1}{2}]_{3,4}$. Sittner and Peck listed two other intense krypton lines without classification, ν, 7578.37 cm^{-1}, which we have been unable to reproduce with our sources, and ν, 5982.33 cm^{-1}, which seems almost certainly to be the third order of the intense visible line, λ, 5570.29 A. Of the two values of the pair 4U, or $4f[4\frac{1}{2}]_{4,5}$ proposed by Edlén, the one with J-value 4 was bracketed indicating a predicted value. The pair separation is given as 0.20 cm^{-1}. The only possibility of a combination of both levels of the pair with a common level is that involving the level $3d_4'$ or $4d[3\frac{1}{2}]^\circ_4$ yielding the line, ν, 8191.52 cm^{-1}. No structure has been observed, but a resolving power of over 40000 would be required to split this doublet, something beyond what we have obtained in any clearly demonstrable case. It is probable that most of the energy in this line is accounted for by the transition $4d[3\frac{1}{2}]^\circ_4-4f[4\frac{1}{2}]_5$. All other combinations of this 4U pair involve the level $J=4$, uniquely owing to the ΔJ selection rule.

Evidence, principally from the measured wavelength of the intense line representing the combination, $4d[3\frac{1}{2}]^\circ_3-4f[4\frac{1}{2}]_4$, for which we give λ12879.00, indicates that Edlén's estimated absolute value for $4f[4\frac{1}{2}]_4$, namely, 6925.92 cm^{-1}, is too small. The observed value, obtained by averaging our measured result with that of Sittner and Peck, is 6926.10, making the level indistinguishable from $4f[4\frac{1}{2}]_5$. As represented in [10], with the ground level=0, this level would become 105989.60 cm^{-1}. The Racah pair of closest separation that we have actually observed in combinations with a common level is $4d[1\frac{1}{2}]_2^\circ-4f[2\frac{1}{2}]_{2,3}$, represented by the wave numbers 8333.82, and 8333.07 cm^{-1}. The observed separation is 0.75 cm^{-1} as compared with the calculated, 0.768. The actual observation of this pair is extremely difficult on account of the great disparity in intensities of the components. The pair of widest separation in this $4f$ group, 4X and 4Z or $4f[1\frac{1}{2}]_{1,2}$ occurs in easily observable combinations with a common level. The best example is the pair of wave numbers 8879.23 and 8880.35 reported by Meggers and Humphreys [3,4] and also demonstrable by radiometric techniques. So far there is no clue to the magnitude of the splitting of 4W, and the missing level $4f'[3\frac{1}{2}]_4$ has not been found unless it is unresolved with respect to $4f'[3\frac{1}{2}]_3$. Otherwise, the level structure of Kr I may be considered complete.

4.5. Xenon

The observations on xenon were less extensive than on any of the other four noble gases because both preliminary recordings and study of the level scheme had revealed that there was little possibility of adding significantly to the existing observational material. A small number of records were made in order that some material on all the noble gas spectra might be included in the current survey. The results are presented in table 7, which is organized in the same fashion as the corresponding tables 5 and 6 for argon and krypton. These observations cover the same region as those of Sittner and Peck, and their classifications are repeated without revision for lines common to both lists.

The principal reason for the relative paucity of xenon lines in the 1.2— to 1.8—micron region is that the $2p$ and $3d$ levels fall in much the same range of numerical values, with the result that the $2p-3d$ combinations, that are responsible for many of the intense analogous lines in argon and krypton, represent wavelengths much deeper in the infrared and out of range of observation with lead-sulfide detectors. For instance, the position of the expected most intense combination in this group, $2p_8-3d_4'$, is predicted at 1793.6 cm^{-1}. Most of the possible $3d-4f$ combinations have been observed photographically. Of the f-type levels, only those of the family converging to the ${}^2P^\circ_{1\frac{1}{2}}$ ion limit have been found. Owing to the extremely wide separation of the series limits, the first members of the f-series converging to ${}^2P^\circ_{0\frac{1}{2}}$ are above the first ionization limit.

The only noteworthy changes in the Xe I level scheme made by Edlén since the last publication of this array [5] have been to change the designation of the level at 4215.65 from $2s_2$ to $3s_1'$, to supply level values for $2s_2$ and $2s_3$, and to separate the series formerly designated W, into two according to the Racah scheme. The first pair of this series $4f[3\frac{1}{2}]_{3,4}$ has a separation of 0.10 cm^{-1} on the basis of previously existing photographic data. Discrimination

TABLE 7. *Description of* Xe I *in the infrared region*

Observed wave length in air, Humphreys and Kostkowski	Observed intensity	Wave number observed			Term combination		Wave number calculated, Edlén levels
		Humphreys and Kostkowski	Sittner and Peck	Meggers	Paschen notation	Racah notation	
A		*cm*$^{-1}$	*cm*$^{-1}$	*cm*$^{-1}$			
11742. 01	90	8514. 09	8514. 77	8513. 92	$3d_1'-4W$	$5d[2\frac{1}{2}]_3^\circ-4f\,[3\frac{1}{2}]_4$	8513. 83
11793. 04	40	8477. 25	8476. 84	8476. 89	$3d_1'-4U$	$5d[2\frac{1}{2}]_3^\circ-4f\,[2\frac{1}{2}]_3$	8476. 89
11857. 00	30	8431. 52	8431. 47	8431. 31	$3d_1'-4Z$	$5d[2\frac{1}{2}]_3^\circ-4f\,[4\frac{1}{2}]_4$	8431. 31
11911. 44	3	8392. 99	8392. 50	8392. 53	$3d_5-2p_4$	$5d[0\frac{1}{2}]_1^\circ-6p'[1\frac{1}{2}]_1$	8392. 49
11952. 57	10	8364. 10	8363. 26	8363. 81	$3d_3-3p_6$	$5d[1\frac{1}{2}]_2^\circ-7p\,[1\frac{1}{2}]_2$	8363. 74
12084. 82	20	8272. 58	8272. 59	8272. 60	$3d_4'-3p_8$	$5d[3\frac{1}{2}]_4^\circ-7p\,[2\frac{1}{2}]_3$	8272. 57
12235. 14	80	8170. 93	8170. 88	8170. 88	$2p_{10}-2s_4$	$6p[0\frac{1}{2}]_1-7s\,[1\frac{1}{2}]_1^\circ$	8170. 88
12258. 10	6	8155. 63	8155. 85	8155. 83	$3d_6-3p_{10}$	$5d[0\frac{1}{2}]_0^\circ-7p\,[0\frac{1}{2}]_1$	8155. 85
12451. 21	2	8029. 14	8028. 32	--------	$3d_3-3p_9$	$5d[1\frac{1}{2}]_2^\circ-7p\,[2\frac{1}{2}]_2$	8028. 92
12590. 00	26	7940. 63	7940. 70	--------	$3d_5-3p_{10}$	$5d[0\frac{1}{2}]_1^\circ-7p\,[0\frac{1}{2}]_1$	7940. 49
12623. 32	300	7919. 67	7919. 30	7919. 63	$2p_{10}-2s_5$	$6p[0\frac{1}{2}]_1-7s\,[1\frac{1}{2}]_2^\circ$	7919. 66
13543. 16	5	7381. 77	--------	--------	$3d_4-3p_9$	$5d[3\frac{1}{2}]_3^\circ-7p\,[2\frac{1}{2}]_2$	7381. 27
13656. 48	150	7320. 52	7320. 19	--------	$2p_9-2s_4$	$6p[2\frac{1}{2}]_2-7s\,[1\frac{1}{2}]_1^\circ$	7320. 23
14142. 09	80	7069. 15	7068. 95	--------	$2p_9-2s_5$	$6p[2\frac{1}{2}]_2-7s\,[1\frac{1}{2}]_2^\circ$	7069. 01
14241. 39	40	7019. 85	7020. 18	--------	$3d_2-4V$	$5d[1\frac{1}{2}]_1^\circ-4f\,[2\frac{1}{2}]_2$	7020. 11
14364. 90	20	6959. 50	6959. 46	--------	$3d_2-4Y$	$5d[1\frac{1}{2}]_1^\circ-4f\,[1\frac{1}{2}]_2$	6959. 50
14659. 84	5	6819. 42	6819. 02	--------	$3d_1''-3p_7$	$5d[2\frac{1}{2}]_2^\circ-7p\,[1\frac{1}{2}]_1$	6819. 04
14732. 38	200	6785. 90	6785. 70	--------	$2p_8-2s_5$	$6p[2\frac{1}{2}]_3-7s\,[1\frac{1}{2}]_2^\circ$	6785. 75
15418. 01	110	6484. 13	6484. 16	--------	$2p_7-2s_4$	$6p[1\frac{1}{2}]_1-7s\,[1\frac{1}{2}]_1^\circ$	6483. 99
16052. 02	50	6228. 03	6227. 44	--------	$2p_6-2s_4$	$6p[1\frac{1}{2}]_2-7s\,[1\frac{1}{2}]_1^\circ$	6227. 56
16727. 52	50	5976. 52	5976. 05	--------	$2p_6-2s_5$	$6p[1\frac{1}{2}]_2-7s\,[1\frac{1}{2}]_2^\circ$	5976. 34

between levels this close is beyond the precision of the current observations.

The complete status of the level scheme of Xe I makes it unnecessary to consider further observations in order to improve the analysis. Future availability of photoconductors sensitive to energy of greater wavelengths, possibly as far as 7 microns would still make Xe I an attractive subject for study owing to the existence of several predicted lines of probable high intensity that might be useful as wavelength standards.

5. Conclusion

Observation and interpretation of the noble gas spectra over a period of over thirty years have led to the essentially complete analysis of the spectra of these gases. One of the most interesting features of this work is that it has been made possible largely by the development of techniques for observing in the infrared region by either photographic or radiometric methods. The noble gases have provided some of the best sources of standard wavelengths. The possibility of extending the range of highly precise observations farther into the infrared region by combining interferometric with radiometric methods still constitutes an attractive challenge.

Several members of the staff of the Bureau's Radiometry Laboratory, have given valuable assistance in bringing this work to completion. In particular, Arthur J. Cussen and Joseph J. Ball contributed to the operation and maintenance of the electronic instruments used with the photoconductive detector. Marshall E. Anderson assisted in obtaining and reducing the records. It is a pleasure to express to each of them appreciation for his contribution to the work.

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