

## SOME ATOMIC PARAMETERS FOR ULTRAVIOLET LINES

CARLOS M. VARSAVSKY

Physics Department, University of Colorado\*

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## ABSTRACT

With the advent of rocket-borne and satellite-borne spectrographs, it is becoming possible to study celestial objects in the hitherto inaccessible ultraviolet. The spectroscopic analysis will require the knowledge of the basic atomic parameters of the lines observed. In the present paper the screening method of Layzer and Varsavsky is applied to the computation of electric dipole matrix elements for many lines of interest. The method is especially suitable for the treatment of a particular transition along an iso-electronic sequence. Numerical results are given for allowed transitions in the sequences from helium through chlorine (except neon). The L-S coupling scheme is used to go from matrix elements to transition probabilities; the Bethe approximation is used to compute excitation cross-sections.

## I. INTRODUCTION

When studying stellar atmospheres with instruments placed on the earth's surface, we must work within a spectral range limited, on the short-wave-length side, to about 3000 Å. Since 1946, however, rockets have been able to carry spectrographs and other detectors above most of the atmosphere, so that we now possess a considerable amount of information about the far ultraviolet spectrum of the sun. It is to be expected that in the near future satellites, placed in an orbit well above the atmospheric absorbing layers and capable of staying aloft for several months—as compared with a few minutes in the case of rockets—will enormously enlarge our knowledge of the far ultraviolet spectra of celestial objects.

Up to the present time the only known ultraviolet spectrum is that of the sun. Identification of the observed emission lines is far from complete, but it is quite obvious that many of these lines must originate in the upper chromosphere and in the corona. Violett and Rense (1959), for example, give ample evidence to prove this assertion.

Let us consider the lines of elements other than H and He (for a treatment of the ultraviolet spectra of these two elements see Athay 1960). They are suitable for the solution of three problems:

1. The lines of C, N, and O will permit, in principle, the direct determination of the chemical abundances of these three elements, which, so far, have had to be inferred from molecules. Lines of C I through IV, N I through V, and O I through VI have been identified. A line of Ne VIII has been tentatively identified, and so we may be in a position to determine the abundance of this element also.

2. The lines of moderately and highly ionized atoms can be used to study the physical conditions in the upper chromosphere and corona. In regions of the atmosphere where the effective temperature is greater than about  $2 \times 10^5$  degrees, H and He are completely ionized; hence we can obtain information about the physical conditions in these layers only from a study of the lines of other elements.

3. A systematic study of the radiation of all ions that are present in the solar chromosphere and corona will enable us to settle the important question of the amount of far ultraviolet radiation emitted by the sun and also the related problem of the energy balance in these two regions.

Furthermore, ultraviolet lines also open up the possibility of detecting coronas in other stars; a study of the presence and characteristics of stellar coronas along the spectral sequence would be extremely interesting.

\* Present address: Facultad de Ciencias Exactas, Perú 222, Buenos Aires, Argentina.

To make effective use of the ultraviolet data, we need the values of certain atomic parameters. Atoms are ionized or excited by photointeractions or collisions; therefore, we require a knowledge of transition probabilities and of cross-sections for different processes, such as photoionization and collisional ionization, collisional excitation, photo-recombination, and three-body recombination.

The aim of the present paper is to describe a method which allows the computation of certain matrix elements that, in some specific cases, can be related to transition probabilities and cross-sections for excitation by electronic impact, thus providing us with some of the atomic parameters needed for the analysis of ultraviolet spectra. The method is amply illustrated with tables and examples.

## II. THE SCREENING METHOD

### a) Transition Probabilities

A method has been recently proposed that allows the calculation of the quantity

$$\sigma^2 = \frac{1}{4l_{>} - 1} \left| \int_0^\infty R_i R_f r dr \right|^2,$$

where  $R_i/r$  and  $R_f/r$  are the initial and final radial wave functions, and  $l_{>}$  is the larger of the two orbital quantum numbers, in a large number of cases with considerable accuracy. The theoretical basis of the method and its application to the eigenvalue problem have been described by Layzer (1959); Varsavsky (1958) discusses its application to the calculation of  $\sigma^2$  (a more refined method will be presented in a future paper by Layzer and Varsavsky). Here we apply the technique developed by Varsavsky to the computation of line strengths for transitions of interest in the ions that belong to the isoelectronic sequences of He I through Cl I, with the exception of Ne I (this element is omitted because it departs considerably from L-S coupling). To illustrate the mechanics of the method, we work out in detail a few examples of increasing complexity, covering all the possibilities that may arise in practice.

According to Varsavsky (1958), transitions that do not involve a change in the principal quantum number can be treated successfully by means of an incomplete first-order approximation that neglects the interactions between different configurations belonging to the same complex, and also the effects of external screening, in the computation of  $\Delta E_1$ . Let us recall that the screening constant,  $\mathfrak{S}$ , is given by (Varsavsky 1958, eqs. [3]–[5])

$$\mathfrak{S} = n^2 \Delta E_1,$$

where  $n$  is the principal quantum number of the active electron, and  $\Delta E_1$  is defined as the electrostatic energy of the atom or ion in question in a given state of a given configuration minus the electrostatic energy of the parent state that results when the active electron is removed. After computing  $\mathfrak{S}$  and  $\mathfrak{S}'$  for the initial and final states of the transition, the quantity  $\sigma^2$  can be obtained by substituting these parameters in the transition integrals (several of these integrals are listed by Varsavsky 1958, Table 5; notice that  $z = Z - \mathfrak{S}$ ,  $z' = Z - \mathfrak{S}'$ ).

Let us now consider four actual cases that will help the reader in applying the method to any case of interest.

The easiest situation is that of one electron outside closed shells. For example, let us compute the screening constant of the ground state of lithium. The electronic configuration is  $(1s)^2 2s$ , and the only possible state is  $^2S$ . Its total electrostatic energy is equal to the energy of the  $(1s)^2$  shell plus the energy of the interaction between the  $2s$  electron and the  $(1s)^2$  shell. Symbolically,

$$E[(1s)^2 2s \ ^2S] = \{1s - 1s\} + \{(1s)^2 - 2s\}. \quad (1)$$

The parent ion is  $(1s)^2 {}^1S$ . Its electrostatic energy is

$$E[(1s)^2 {}^1S] = \{1s - 1s\}. \quad (2)$$

Subtracting equation (9) from equation (8), we obtain

$$\Delta E_1[2s {}^2S]_{Li} = \{(1s)^2 - 2s\}. \quad (3)$$

The electrostatic interaction between an electron and a closed shell is given by Condon and Shortley (1951, eq. [9<sup>6</sup> 11]). In the case under consideration,

$$\Delta E_1[2s {}^2S]_{Li} = 2F^0(1s, 2s) - G^0(1s, 2s) = 0.397805$$

(for the numerical values of Slater integrals see Varsavsky 1958, Table 6).

Now consider the calculation of  $\mathfrak{S}$  for the ground state of carbon  $(1s)^2 (2s)^2 (2p)^2 {}^3P$ , when one of the 2p electrons makes a jump. In this case the parent ion is  $(1s)^2 (2s)^2 2p {}^2P$ . Then

$$\begin{aligned} \Delta E_1[(2p)^2 {}^3P] &= \{1s - 1s\} + \{2s - 2s\} + 4\{1s - 2s\} + 4\{1s - 2p\} \\ &\quad + 4\{2s - 2p\} + \{2p - 2p {}^3P\} \\ &\quad - \{1s - 1s\} - \{2s - 2s\} - 4\{1s - 2s\} - 2\{1s - 2p\} - 2\{2s - 2p\} \\ &= 2\{1s - 2p\} + 2\{2s - 2p\} + \{2p - 2p {}^3P\}. \end{aligned} \quad (4)$$

From Varsavsky (1958, Table 7), and Condon and Shortley (1951, p. 198) we have

$$\Delta E_1[(2p)^2 {}^3P] = 0.927511 \quad \text{or} \quad \mathfrak{S} = 3.710045.$$

Next let us consider the  ${}^2P$  state of the ground configuration of nitrogen. If we remove one 2p electron, we have left a carbon-like ion with possible states  ${}^3P$ ,  ${}^1S$ , and  ${}^1D$ . All three can give rise to the  ${}^2P$  state in nitrogen; hence, in calculating  $\Delta E_1[(2p)^3 {}^2P]$ , we must subtract from the nitrogen atom a linear combination of the possible parents:

$$\begin{aligned} \Delta E_1[(2p)^3 {}^2P] &= E[(2p)^3 {}^2P] - aE[(2p)^2 {}^3P] - bE[(2p)^2 {}^1S] \\ &\quad - cE[(2p)^2 {}^1D], \end{aligned} \quad (5)$$

where  $a$ ,  $b$ , and  $c$  are the coefficients of fractional parentage defined by Racah (1943). In this particular case

$$a = \frac{1}{2}, \quad b = \frac{2}{9}, \quad c = \frac{5}{18}. \quad (6)$$

So far, we have treated cases where one of the outermost electrons makes the transition. Consider, however, the transition

$$(1s)^2 (2s)^2 2p {}^2P \rightarrow (1s)^2 2s (2p)^2 {}^2S.$$

In this case the active electron is 2s, and the parent ion is  $(1s)^2 2s 2p {}^1{}^3P$ ; hence

$$\Delta E_1[(2s)^2 2p {}^2P] = E[(2s)^2 2p {}^2P] - aE[2s2p {}^1P] - bE[2s2p {}^3P]. \quad (7)$$

In most of the transitions considered in our tables, the active electron is indeed an inner one. Our method can handle these transitions without ambiguity, whereas most other methods are inapplicable.

There are few experimental or theoretical data concerning the transitions presented in the tables that could be used to check the accuracy of our results. In the few cases where such data exist—for some neutral or singly ionized atoms—the agreement is very

satisfactory. Such agreement is encouraging because, as the ions become more hydrogenic along the isoelectronic sequence, the accuracy of the method is progressively higher. When using the tables, it should be kept in mind that in no case can the expected accuracy be better than 10 per cent.

### b) Collisional Cross-Sections

The total excitation cross-sections are given by (Mott and Massey 1949)

$$Q_{nl, n'l'}(v) = \int_{K_{\min}}^{K_{\max}} I_{nl, n'l'}(K) dK, \quad (8)$$

where  $I_{nl, n'l'}$  is the differential cross-section,  $K$  the change in momentum of the colliding electron, and  $v$  its velocity. If the energy of the incident electron is large compared with the excitation energy of the line, we may calculate  $I_{nl, n'l'}(K)$  by means of the first Born approximation. Furthermore, if we can assume that  $I_{nl, n'l'}(K)$  decreases quickly with  $K$ , we can obtain for  $Q_{nl, n'l'}$ , an expression which is known as the Bethe approximation (see, for example, Seaton 1955):

$$Q_{nl, n'l'} = \frac{8E_0}{3\varpi_n} \frac{I^2}{W} \ln \frac{K_{\max}}{K_{\min}}. \quad (9)$$

Here  $E_0$  is the ionization potential of hydrogen in electron volts,  $\varpi_n = 2L + 1$  for the lower level,  $W$  is the kinetic energy of the incident electron in electron volts,  $I^2 = (4l_{\geq}^2 - 1)\sigma^2$ , where  $\sigma^2$  was defined in the previous section,

$$K_{\min} = \frac{E_{n'l'} - E_{nl}}{(2W)^{1/2}}, \quad (10)$$

expressed in atomic units, and, according to Bates, Fundaminsky, and Massey (1950), we can take

$$K'_{\max} = (E_{n'l'} - E_{nl})^{1/2}. \quad (11)$$

Substituting equations (10) and (11) in equation (9), we have

$$Q_{nl, n'l'} = \frac{4E_0}{3\varpi_n} \frac{I^2}{W} \ln \frac{2W}{E_{n'l'} - E_{nl}}, \quad (12)$$

with  $Q$  given in units of  $\pi a_0^2$  ( $a_0$  = first Bohr radius). The numbers given in Table 16 should be used with caution. The relative values are probably correct, the absolute values may be somewhat overestimated.

### c) Description of the Tables

Tables 1 through 15 give some numerical examples of the application of the screening method. At the head of each table we give the first ion in the isoelectronic sequence and the lower and upper states of the transition. The first column gives the name of the ion; the headings of the remaining columns have the following meaning:

I.P.: ionization potential in electron volts;

$S_M$ : matrix element for the multiplet, in atomic units;

$(\varpi f)_M$ : oscillator strength of the multiplet times the statistical weight of the multiplet,  $\varpi_M = (2S + 1)(2L + 1)$ ;

$J_{u, l}$ : total angular momentum of the upper ( $u$ ) or lower ( $l$ ) states;

(E.P.) $_{u, l}$ : excitation potential in electron volts (subscripts have the same meaning as above);

$\lambda$ : wave length corresponding to the transition, in angstroms;

$S_L$ : matrix element for the line, in atomic units;  
 $(\omega f)_L$ : oscillator strength of the line times the statistical weight of the line,  $\omega_L = 2J + 1$ ;  
 $A$ : transition probability in  $\text{sec}^{-1}$ .

Most of the data on ionization and excitation potentials and wave lengths were obtained from Charlotte Moore (1949, 1952). Ionization potentials not available in Moore's work were taken from Finkelnburg and Humbach (1955). Excitation potentials and wave lengths not given by Moore were taken from Rohrlich (1959) and from extrapolation of the experimental data.

Table 16 gives the total excitation cross-section by electronic impact for energies such that  $W \geq 6\Delta E$  (in a few cases  $5\Delta E \leq W \leq 6\Delta E$ ; these cases are shown in script). We include only those ions that are likely to be present in the solar corona. The cross-sections are computed for two values of  $W_1$  within the range of energies to be expected in the corona.

I wish to express my thanks to Dr. W. A. Rense for having invited me to spend the necessary time at the University of Colorado to carry out the work here reported, and to the National Science Foundation, who made this invitation possible. The computations are based on a method developed while I was a student at Harvard University. My deep thanks go to Dr. D. Layzer, who supervised the work, and to Dr. D. H. Menzel, who gave it his fullest support.

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Table 1

## Helium I Sequence

$$1s^2 \left( {}^1S_0 \right) - 1s\,2p \left( {}^1P_1^o \right)$$

Ion	I. P.	(E. P.) <sub>u</sub>	$\lambda$	S <sub>L</sub>	$\frac{\lambda}{(\omega f)_L}$	A x 10 <sup>-11</sup>
He I	24.580	21.212	584.4	0.846	0.44	0.03
Li II	75.619	62.202	199.3	0.412	0.63	0.37
Be III	217.657	123.64	100.2	0.230	0.70	1.5
B IV	259.30	205.5	60.31	0.146	0.74	4.7
C V	391.99	307.8	40.27	0.100	0.75	10
N VI	551.9	430.6	28.79	0.073	0.77	21
O VII	739.1	573.8	21.60	0.055	0.70	37

Table 2  
Lithium I Sequence  
 $1s^2 2s \left( {}^2S_{1/2} \right) - 1s^2 2p \left( {}^2P_{1/2}^o \cdot 3/2 \right)$

Ion	I. P.	$S_M$	$\nu$ ( $\omega f$ ) <sub>M</sub>	$J_u$	(E. P.) <sub>u</sub>	$\lambda$	$S_L$	$\nu$ ( $\omega f$ ) <sub>L</sub>	$A \times 10^{-8}$
Li I	5.390	35.94	1.63	1/2	1.847	6709.8	11.98	0.54	0.40
Be II	18.206	11.12	1.08	3/2	1.847	6709.6	23.96	1.09	0.40
				1/2	3.958	3132.0	3.706	0.36	1.22
B III	37.920	5.292	0.78	3/2	3.958	3131.3	7.414	0.72	1.22
				1/2	5.994	2067.8	1.764	0.26	2.03
C IV	64.476	3.078	0.60	3/2	5.998	2066.4	3.528	0.52	2.03
				1/2	7.993	1550.7	1.026	0.20	2.77
N V	97.863	2.004	0.49	3/2	8.006	1548.2	2.052	0.40	2.78
				1/2	9.974	1242.8	0.668	0.16	3.45
O VI	138.080	1.410	0.41	3/2	10.006	1238.8	1.336	0.33	3.47
				1/2	11.95	1037.6	0.470	0.14	4.34
F VII	185.139	1.044	0.36	3/2	12.01	1031.9	0.940	0.27	4.38
				1/2	13.91	890.8	0.348	0.12	4.99
Ne VIII	239.1	0.804	0.31	3/2	14.04	883.1	0.696	0.24	5.11
				1/2	15.88	792.5	0.268	0.10	5.84
Na IX	299.78	0.642	0.28	3/2	16.11	782.4	0.536	0.21	5.99
				1/2	17.85	694.3	0.214	0.09	6.56
Mg X	367.36	0.522	0.26	3/2	18.18	681.7	0.429	0.19	6.82
				1/2	19.82	625.3	0.174	0.09	7.22
Al XI	441.9	0.432	0.23	3/2	20.33	609.8	0.348	0.17	7.60
				1/2	21.80	568.5	0.144	0.08	7.74
Si XII	523.2	0.366	0.22	3/2	22.54	550.0	0.288	0.15	8.25
				1/2	23.79	521.1	0.122	0.07	8.60
P XIII	611.45	0.312	0.20	3/2	24.83	499.3	0.244	0.15	9.35
				1/2	25.75	481.4	0.104	0.07	9.35
				3/2	27.18	456.1	0.208	0.13	10.4



Table 3

Beryllium I Sequence

$$1s^2 2s^2 \left( {}^1S_o \right) - 1s^2 2s2p \left( {}^1P_1^o \right)$$

Ion	L P.	(E. P.) <sub>u</sub>	λ	S <sub>L</sub>	$\frac{\nu}{(\omega f)_L}$	A x 10 <sup>-9</sup>
Be I	9.320	5.276	2349.3	22.81	3.92	1.6
B II	25.149	9.098	1362.4	8.64	1.93	2.3
C III	47.864	12.687	977.0	4.45	1.38	3.2
N IV	77.450	16.200	765.1	2.70	1.07	4.1
O V	113.873	19.684	629.7	1.81	0.87	5.0
F VI	157.117	23.160	535.2	1.29	0.73	5.7
Ne VII	207.3	26.654	473.1	0.98	0.63	6.5
Na VIII	264.155	30.148	411.1	0.76	0.56	7.3
Mg IX	327.90	33.677	368.1	0.61	0.50	8.0
Al X	398.5	37.236	332.9	0.49	0.45	9.0
Si XI	476.0	40.830	303.6	0.41	0.41	10
P XII	560.3	44.480	278.7	0.35	0.38	11



TABLE 4

## Boron I Sequence

$$1s^2 2s^2 2p(^2P^o_{1/2, 3/2}) \sim 1s^2 2s 2p^2(^2D_{3/2, 5/2})$$

Ion	I.P.	$S_M$	$(\tilde{\omega}f)_M$	$J_u$	$(E.P.)_u$	$J_l$	$(E.P.)_l$	$\lambda$	$S_L$	$(\tilde{\omega}f)_L$	$\tilde{\omega}A \times 10^{-9}$
B I	8.296	22.57	3.28	5/2, 3/2	5.932	3/2	0.002	2090.2	15.05	2.19	3.34
				3/2		1/2	0	2089.6	7.52	1.09	1.66
C II	24.376	10.17	2.32	5/2, 3/2	9.288	3/2	0.008	1335.7	6.78	1.55	5.79
				3/2		1/2	0	1334.5	3.39	0.77	2.88
N III	47.426	5.40	1.66	5/2, 3/2	12.523	3/2	0.022	991.5	3.60	1.11	7.53
				3/2		1/2	0	989.8	1.80	0.55	3.74
O IV	77.394	3.67	1.41	5/2, 3/2	15.736	3/2	0.048	790.1	2.45	0.94	10.0
				3/2		1/2	0	787.7	1.22	0.47	5.05
F V	114.214	2.54	1.18	5/2, 3/2	18.952	3/2	0.092	657.2	1.69	0.79	12.2
				3/2		1/2	0	654.0	0.85	0.39	6.08
Ne VI	157.91	1.86	1.01	5/2, 3/2	22.190	3/2	0.163	562.8	1.24	0.67	14.1
				3/2		1/2	0	558.6	0.62	0.34	7.26
Na VII	208.444	1.43	0.89	5/2, 3/2	25.466	3/2	0.265	491.9	0.95	0.59	16.3
				3/2		1/2	0	486.7	0.48	0.30	8.44
Mg VIII	265.957	1.12	0.78	5/2, 3/2	28.795	3/2	0.410	436.7	0.75	0.52	18.2
				3/2		1/2	0	430.5	0.37	0.26	9.35
Al IX	330.1	0.91	0.71	5/2, 3/2	32.19	3/2	0.606	392.4	0.61	0.47	20.3
				3/2		1/2	0	385.0	0.30	0.24	10.8
Si X	401.3	0.75	0.65	5/2, 3/2	35.68	3/2	0.866	356.1	0.50	0.43	22.6
				3/2		1/2	0	347.4	0.25	0.22	12.2
P XI	479.4	0.63	0.60	5/2, 3/2	39.32	3/2	1.202	325.2	0.42	0.40	25.2
				3/2		1/2	0	315.3	0.21	0.20	13.4
S XII	567	0.54	0.55	5/2, 3/2	42.7	3/2	1.644	302	0.36	0.37	27.0
				3/2		1/2	0	290	0.18	0.18	14.3
Cl XIII	667	0.46	0.51	5/2, 3/2	46.3	3/2	2.16	281	0.31	0.34	28.7
				3/2		1/2	0	268	0.15	0.17	16.4
A XIV	754	0.40	0.47	5/2, 3/2	49.8	3/2	2.843	264	0.27	0.31	29.8
				3/2		1/2	0	249	0.13	0.16	17.3

TABLE 5  
Carbon I Sequence

$1s^2 2s^2 2p^2 ({}^3P_{0,1,2}) - 1s^2 2s 2p^3 ({}^3D^o_{1,2,3})$									
Ion	$S_M$	$(\omega f)_M$	$J_u$	$(E.P.)_u$	$J$	$\lambda$	$S_L$	$(\omega f)_L$	$\omega A \times 10^{-10}$
C I	24.40	4.69	3	7.944	2	1561.4	11.39	2.16	0.59
			2,1	7.945	2	1561.3	2.17	0.42	0.11
			2,1		1	1560.7	8.13	1.58	0.43
N II	12.21	3.43	1		0	1560.3	2.71	0.53	0.15
			3	11.43	2	1085.7	5.70	1.60	0.90
			2,1	11.44	2	1085.5	1.09	0.31	0.18
			2,1		1	1084.6	4.07	1.14	0.65
			1		0	1084.0	1.36	0.38	0.22
O III	7.23	2.63	3	14.88	2	835.3	3.37	1.23	1.18
			2,1	14.88	2	835.1	0.64	0.23	0.22
			2,1		1	833.7	2.41	0.88	0.84
			1		0	832.9	0.80	0.29	0.28
F IV	4.82	2.16	3	18.33	2	679.2	2.25	1.01	1.46
			2,1	18.33	2	679.0	0.43	0.19	0.27
			2,1		1	677.2	1.61	0.72	1.05
			1		0	676.1	0.54	0.24	0.35
Ne V	3.40	1.79	3	21.80	2	572.3	1.59	0.84	1.71
			2,1	21.81	2	572.1	0.30	0.15	0.31
			2,1		1	569.8	1.13	0.60	1.23
			1		0	568.4	0.38	0.20	0.41
Na VI	2.55	1.57	3	25.30	2	494.4	1.19	0.73	1.99
			2,1	25.32	2	494.1	0.23	0.14	0.38
			2,1		1	491.3	0.85	0.53	1.46
			1		0	489.5	0.28	0.17	0.47
Mg VII	1.98	1.40	3	28.86	2	435.3	0.92	0.64	2.25
			2,1	28.88	2	434.7	0.18	0.13	0.46
			2,1		1	431.3	0.66	0.47	1.68
			1		0	429.1	0.22	0.16	0.58

TABLE 5 (Cont.)

Ion	S <sub>M</sub>	( $\omega f$ ) <sub>M</sub>	J <sub>u</sub>	(E.P.) <sub>u</sub>	J	$\lambda$	S <sub>L</sub>	( $\omega f$ ) <sub>L</sub>	$\omega A \times 10^{-10}$
Al VIII	1.58	1.25	3	32.50	2	388.0	0.74	0.58	2.57
			2,1	32.52	2	387.7	0.14	0.11	0.49
			2,1		1	383.7	0.53	0.42	1.90
Si IX	1.28	1.12	1		0	381.1	0.18	0.14	0.64
			3	36.22	2	350.0	0.60	0.52	2.83
			2,1	36.24	2	349.7	0.11	0.10	0.54
			2,1		1	345.0	0.43	0.38	2.13
P X	1.06	1.02	1		0	342.0	0.14	0.12	0.68
			3	40.01	2	318.2	0.49	0.47	3.09
			2,1	40.05	2	318.0	0.09	0.09	0.59
			2,1		1	312.8	0.35	0.34	2.32
S XI	0.90	0.95	1		0	309.4	0.12	0.12	0.83
			3	43.85	2	293	0.42	0.44	3.42
			2,1	43.9	2	292	0.08	0.08	0.63
			2,1		1	287	0.30	0.32	2.59
Cl XII	0.76	0.86	1		0	282	0.10	0.11	0.92
			3	47.5	2	272	0.35	0.40	3.60
			2,1	47.6	2	272	0.07	0.07	0.67
			2,1		1	265	0.25	0.29	2.75
A XIII	0.66	0.80	1		0	260	0.08	0.10	0.99
			3	51.3	2	255	0.31	0.37	3.79
			2,1	51.4	2	254	0.06	0.07	0.72
			2,1		1	247	0.22	0.27	2.95
K XIV	0.58	0.75	1		0	241	0.07	0.09	1.03
			3	55.1	2	240	0.27	0.35	4.05
			2,1	55.2	2	240	0.05	0.07	0.78
			2,1		1	231	0.19	0.25	3.12
Ca XV	0.51	0.70	1		0	224	0.06	0.08	1.09
			3	58.8	2	228	0.24	0.32	4.13
			2,1	59.0	2	227	0.05	0.07	0.84
			2,1		1	218	0.17	0.23	3.23
			1		0	210	0.06	0.08	1.16

TABLE 6

Nitrogen I Sequence

Ion	I. P.	S <sub>M</sub>	( $\bar{\omega}f$ ) <sub>M</sub>	J <sub>u</sub>	(E. P.) <sub>u</sub>	$\lambda$	S <sub>L</sub>	( $\bar{\omega}f$ ) <sub>L</sub>	A x 10 <sup>-9</sup>
$1s^2 2s^2 2p^3 \left( {}^4S_{3/2} \right) - 1s^2 2s 2p^4 \left( {}^4P_{1/2, 3/2, 5/2} \right)$									
N I	14.54	15.66	4.20	1/2	10.93	1134.1	2.61	0.70	1.81
				3/2	10.93	1134.3	5.22	1.40	1.81
				5/2	10.92	1135.0	7.83	2.10	1.81
O II	35.146	8.45	3.08	1/2	14.88	832.8	1.41	0.51	2.46
				3/2	14.87	833.3	2.82	1.03	2.46
				5/2	14.85	834.5	4.22	1.54	2.46
F III	62.646	5.22	2.40	1/2	18.89	656.1	0.87	0.40	3.10
				3/2	18.87	656.9	1.74	0.80	3.09
				5/2	18.83	658.3	2.61	1.20	3.07
Ne IV	96.77	3.53	1.97	1/2	22.81	541.1	0.59	0.33	3.76
				3/2	22.77	542.1	1.18	0.66	3.74
				5/2	22.70	543.9	1.76	0.98	3.68
Na V	138.60	2.54	1.67	1/2	26.95	459.9	0.42	0.28	4.41
				3/2	26.89	461.0	0.85	0.56	4.39
				5/2	26.76	463.3	1.27	0.83	4.30
Mg VI	186.86	1.91	1.45	1/2	31.04	399.3	0.32	0.24	5.06
				3/2	30.94	400.7	0.64	0.49	5.02
				5/2	30.73	403.3	0.95	0.72	4.92
Al VII	241.93	1.49	1.28	1/2	35.20	352.2	0.25	0.22	5.91
				3/2	35.04	353.8	0.50	0.43	5.72
				5/2	34.73	356.9	0.74	0.63	5.49

TABLE 6 (Cont.)

Ion	I. P.	S <sub>M</sub>	( $\bar{\omega}f$ ) <sub>M</sub>	J <sub>u</sub>	(E. P.) <sub>u</sub>	$\lambda$	S <sub>L</sub>	( $\bar{\omega}f$ ) <sub>L</sub>	A x 10 <sup>-9</sup>
Si VII	303.87	1.20	1.13	1/2	39.44	314.3	0.20	0.19	6.47
				3/2	39.20	316.2	0.40	0.38	6.35
				5/2	38.76	319.8	0.60	0.57	6.14
P IX	372.62	0.98	1.03	1/2	43.76	283.2	0.16	0.17	7.28
				3/2	43.44	285.4	0.33	0.35	7.12
				5/2	42.81	289.5	0.49	0.51	6.82
S X	448.2	0.82	0.95	1/2	48.0	258	0.14	0.16	8.01
				3/2	47.6	260	0.27	0.32	7.89
				5/2	46.9	264	0.41	0.47	7.49
Cl XI	530.9	0.70	0.88	1/2	52.1	238	0.12	0.15	8.82
				3/2	51.7	240	0.23	0.29	8.39
				5/2	50.9	244	0.35	0.44	8.21
A XII	620.4	0.60	0.82	1/2	56.3	220	0.10	0.14	9.64
				3/2	55.8	222	0.20	0.27	9.13
				5/2	54.8	226	0.30	0.41	8.92
K XIII	716.7	0.52	0.76	1/2	60.5	205	0.09	0.13	10.3
				3/2	60.0	207	0.17	0.25	9.72
				5/2	58.8	211	0.26	0.38	9.48
Ca XIV	819.8	0.46	0.72	1/2	64.8	191	0.08	0.12	11.0
				3/2	64.2	193	0.15	0.24	10.7
				5/2	62.8	197	0.23	0.36	10.3

TABLE 7

Oxygen I Sequence

$$1s^2 2s^2 2p^4 \left( {}^3P_{2,1,0} \right) \sim 1s^2 2s 2p^5 \left( {}^3P_{2,1,0}^o \right)$$

Ion	I. P.	S <sub>M</sub>	( $\bar{\omega}f$ ) <sub>M</sub>	J <sub>u</sub>	(E. P.) <sub>u</sub>	J	(E. P.)	$\lambda$	S <sub>L</sub>	( $\bar{\omega}f$ ) <sub>L</sub>	A x 10 <sup>-9</sup>
O I	13.614	18.83	7.22	2	15.65	2	0	792.0	7.85	3.01	6.40
				1	15.66	2		791.5	2.62	1.01	3.58
				2		1	0.02	793.0	2.62	1.00	2.12
				1		1		792.5	1.57	0.60	2.12
				0	15.67	1		792.2	2.09	0.80	8.50
F II	34.84	10.30	5.15	1		0	0.03	792.9	2.09	0.80	2.83
				2	20.34	2	0	606.8	4.29	2.15	7.78
				1	20.38	2		605.7	1.43	0.72	4.36
				2		1	0.04	608.1	1.43	0.71	2.56
				1		1		606.9	0.86	0.43	2.59
Ne III	63.5	6.70	4.16	0	20.40	1		606.3	1.14	0.57	10.3
				1		0	0.06	607.5	1.14	0.57	2.92
				2	25.22	2	0	489.5	2.79	1.73	9.62
				1	25.29	2		488.1	0.93	0.58	5.41
				2		1	0.08	491.0	0.93	0.58	3.22
Na IV	98.88	4.66	3.46	1		1		489.6	0.56	0.35	3.24
				0	25.33	1		488.9	0.74	0.46	12.8
				1		0	0.11	490.3	0.74	0.46	4.25
				2	30.21	2	0	410.4	1.94	1.44	11.4
				1	30.33	2		408.7	0.65	0.48	6.38
				2		1	0.14	412.2	0.65	0.48	3.77
				1		1		410.5	0.39	0.29	3.82
				0	30.40	1		409.6	0.52	0.39	15.5
				1		0	0.20	411.3	0.52	0.38	4.99

TABLE 7 (Cont.)

Ion	I. P.	$S_M$	$(\omega f)_M$	$J_u$	$(E. P.)_u$	$J$	$(E. P.)$	$\lambda$	$S_L$	$(\omega f)_L$	$A \times 10^{-9}$
Mg V	141.23	3.44	2.97	2	35.11	2	0	353.1	1.43	1.23	13.1
				1	35.31	2		351.1	0.48	0.42	7.57
				2		1	0.22	355.3	0.48	0.41	4.33
				1		1		353.3	0.29	0.25	4.43
				0	35.41	1		352.2	0.38	0.33	17.7
Al VI	190.42	2.63	2.60	1		0	0.31	354.2	0.38	0.33	5.84
				2	40.04	2	0	309.6	1.10	1.08	15.0
				1	40.34	2		307.2	0.37	0.37	8.71
				2		1	0.34	312.2	0.37	0.36	4.92
				1		1		309.8	0.22	0.22	5.08
				0	40.51	1		308.6	0.29	0.29	16.1
				1		0	0.47	310.9	0.29	0.28	6.44
				2	45.02	2	0	275.4	0.86	0.95	16.7
				1	45.46	2		272.6	0.29	0.32	9.57
				2		1	0.50	278.4	0.29	0.32	5.50
P VIII	309.26	1.68	2.07	1		1		275.7	0.17	0.19	5.53
				0	45.71	1		274.2	0.23	0.25	22.2
				1		0	0.69	276.8	0.23	0.25	7.24
				2	50.05	2	0	247.6	0.70	0.86	18.7
				1	50.69	2		244.6	0.23	0.29	10.8
				2		1	0.71	251.2	0.23	0.29	6.12
				1		1		248.0	0.14	0.17	6.13
				0	51.04	1		246.3	0.19	0.23	25.3
				1		0	0.97	249.3	0.19	0.23	8.22
				2	55.3	2	0	224	0.58	0.78	20.7
S IX	378.95	1.38	1.86	1	55.8	2		222	0.19	0.25	11.3
				2		1	0.99	228	0.19	0.25	6.61
				1		1		226	0.11	0.16	6.76
				0	56.4	1		224	0.15	0.21	27.9
				1		0	1.32	227	0.15	0.21	9.05



TABLE 7 (Cont.)

Ion	I.P.	S <sub>M</sub>	( $\bar{\omega}$ f) <sub>M</sub>	J <sub>u</sub>	(E.P.) <sub>u</sub>	J	(E.P.)	$\lambda$	S <sub>L</sub>	( $\bar{\omega}$ f) <sub>L</sub>	A x 10 <sup>-9</sup>
Cl X	455.3	1.16	1.70	2	60.3	2	0	206	0.48	0.71	22.3
				1	60.9	2		204	0.16	0.23	12.3
				2		1	1.35	210	0.16	0.23	7.35
				1		1		208	0.10	0.15	7.60
				0	61.7	1		206	0.13	0.19	29.8
A XI	538.6	0.99	1.57	1		0	1.72	209	0.13	0.19	9.66
				2	65.4	2	0	190	0.41	0.66	24.4
				1	66.1	2		188	0.14	0.22	13.8
				2		1	1.78	195	0.14	0.22	7.71
				1		1		193	0.08	0.13	7.75
K XII	628.7	0.85	1.45	0	67.0	1		190	0.11	0.17	31.4
				1		0	2.22	194	0.11	0.17	10.0
				2	70.5	2	0	176	0.35	0.61	26.2
				1	71.2	2		174	0.12	0.20	14.6
				2		1	2.34	182	0.12	0.20	8.02
Ca XIII	725.7	0.74	1.35	1		1		180	0.07	0.12	8.23
				0	72.2	1		177	0.09	0.16	34.0
				1		0	2.82	181	0.09	0.16	10.8
				2	75.6	2	0	164	0.31	0.56	27.8
				1	76.4	2		162	0.10	0.19	16.1
				2		1	3.03	171	0.10	0.19	8.56
				1		1		169	0.06	0.11	8.66
				0	77.5	1		166	0.08	0.15	36.3
				1		0	3.56	170	0.08	0.15	11.5

TABLE 8

Fluorine I Sequence

$1s^2 2s^2 2p^5 \left( 2P^{\circ}_{1/2, 3/2} \right) - 1s^2 2s 2p^6 \left( 2S_{1/2} \right)$									
Ion	I.P.	$S_M$	$(\tilde{\omega}f)_M$	(E.P.) <sub>u</sub>	J	(E.P.)	$\lambda$	$S_L$	$(\tilde{\omega}f)_L$ A x 10 <sup>-10</sup>
F I	17.42	5.011	2.59	20.89	3/2	0	593	3.341	1.74
Ne II	41.07	2.991	1.98	26.90	1/2	0.050	595	1.670	0.85
					3/2	0	460.7	1.994	1.32
Na III	71.65	1.977	1.59	32.78	1/2	0.097	462.4	0.997	0.66
					3/2	0	378.1	1.318	1.06
Mg IV	109.29	1.400	1.32	38.62	1/2	0.169	380.1	0.659	0.53
					3/2	0	321.0	0.933	0.88
Al V	153.77	1.042	1.13	44.48	1/2	0.276	323.3	0.467	0.44
					3/2	0	278.7	0.695	0.76
Si VI	205.11	0.805	0.99	50.39	1/2	0.426	281.4	0.347	0.37
					3/2	0	246.0	0.537	0.66
P VII	263.31	0.640	0.88	56.37	1/2	0.632	249.1	0.268	0.33
					3/2	0	219.9	0.427	0.59
S VIII	328.80	0.521	0.79	62.42	1/2	0.901	223.5	0.213	0.29
					3/2	0	198.6	0.347	0.53
Cl IX	400.7	0.432	0.72	68.6	1/2	1.256	202.6	0.174	0.26
					3/2	0	181	0.288	0.48
A X	479.0	0.364	0.66	74.6	1/2	1.686	185	0.144	0.24
					3/2	0	166	0.243	0.44
K XI	562.7	0.311	0.60	80.7	1/2	2.239	171	0.121	0.22
					3/2	0	154	0.207	0.40
Ca XII	656.9	0.269	0.56	86.7	1/2	2.910	159	0.104	0.20
					3/2	0	143	0.179	0.37
					1/2	3.722	149	0.090	0.19
									2.85

Table 9  
Sodium I Sequence  
 $1s^2 2s^2 2p^6 3s \left( 2S_{1/2} \right) - 3p \left( 2P_{1/2, 3/2}^o \right)$

Ion	I.P.	S <sub>M</sub>	( $\tilde{\omega}f$ ) <sub>M</sub>	J <sub>u</sub>	(E.P.) <sub>u</sub>	$\lambda$	S <sub>L</sub>	( $\tilde{\omega}f$ ) <sub>L</sub>	A x 10 <sup>-9</sup>
Na I	5.12	37.30	1.92	3/2	2.102	5897.6	24.87	1.28	0.061
				1/2	2.104	5891.6	12.43	0.64	0.061
Mg II	14.97	21.64	2.34	3/2	4.40	2802.7	14.43	1.56	0.33
				1/2	4.41	2795.5	7.21	0.78	0.33
Al III	28.33	13.90	2.27	3/2	6.63	1862.8	9.27	1.51	0.73
				1/2	6.66	1854.7	4.63	0.76	0.74
Si IV	44.95	9.636	2.12	3/2	8.80	1402.7	6.42	1.42	1.20
				1/2	8.86	1393.7	3.21	0.70	1.20
P V	65.01	7.044	1.90	3/2	10.99	1128.0	4.69	1.26	1.65
				1/2	11.09	1118.0	2.35	0.64	1.71
S VI	87.67	5.36	1.73	3/2	13.07	944.5	3.57	1.15	2.15
				1/2	13.23	933.4	1.79	0.58	2.22
Cl VII	114.27	4.23	1.59	3/2	15.25	813.0	2.82	1.05	2.65
				1/2	15.48	800.7	1.41	0.54	2.81
A VIII	143.46	3.41	1.46	3/2	17.36	714.0	2.27	0.97	3.17
				1/2	17.70	700.4	1.14	0.49	3.33
K IX	175.94	2.81	1.35	3/2	19.48	636.3	1.87	0.89	3.66
				1/2	19.95	621.4	0.94	0.46	3.97
Ca X	211.29	2.35	1.26	3/2	21.59	574.0	1.57	0.83	4.20
				1/2	22.22	557.7	0.78	0.43	4.61
Sc XI	249.76	2.00	1.17	3/2	23.68	523.5	1.33	0.77	4.68
				1/2	24.51	505.8	0.67	0.40	5.21

Table 9  
(cont.)

Ion	I. P.	S <sub>M</sub>	( $\omega f$ ) <sub>M</sub>	J <sub>u</sub>	(E. P.) <sub>u</sub>	$\lambda$	S <sub>L</sub>	( $\omega f$ ) <sub>L</sub>	A x 10 <sup>-9</sup>
Ti XII	291.47	1.72	1.10	3/2	25.82	480.1	1.15	0.72	5.21
				1/2	26.89	460.9	0.57	0.38	5.96
V XIII	336.29	1.49	1.04	3/2	27.93	443.8	0.99	0.68	5.75
				1/2	29.31	423.0	0.50	0.36	6.71
Cr XIV	384.20	1.31	0.98	3/2	30.05	412.5	0.87	0.64	6.26
				1/2	31.77	390.1	0.44	0.34	7.44
Mn XV	435	1.16	0.94	3/2	32.16	385.4	0.77	0.61	6.84
				1/2	34.29	361.5	0.39	0.33	8.42
Fe XVI	489	1.03	0.89	3/2	34.27	361.7	0.69	0.58	7.38
				1/2	36.87	336.2	0.34	0.31	8.90
Co XVII	547	0.930	0.85	3/2	36.39	340.6	0.62	0.55	7.89
				1/2	39.53	313.5	0.31	0.30	10.10
Ni XVIII	607	0.834	0.81	3/2	38.5	322	0.55	0.52	8.35
				1/2	42.3	293	0.28	0.29	11.25
Cu XIX	671	0.756	0.79	3/2	40.6	305	0.51	0.51	9.14
				1/2	45.1	275	0.25	0.28	12.34

TABLE 10

## Magnesium I Sequence

$$1s^2 2s^2 2p^6 3s^2 \left( {}^1S_o \right) - 3s 3p \left( {}^1P_1^o \right)$$

Ion	I. P.	(E. P.) <sub>u</sub>	$\lambda$	S <sub>L</sub>	( $\omega f$ ) <sub>L</sub>	A x 10 <sup>-9</sup>
Mg I	7.61	4.33	2852.1	29.27	3.12	0.85
Al II	18.75	7.39	1670.1	18.09	3.29	2.62
Si III	33.32	10.23	1206.5	12.11	3.05	4.66
P IV	51.15	12.99	950.7	8.60	2.75	6.76
S V	72.2	15.70	786.5	6.41	2.48	8.91
Cl VI	96.7	18.46	671.4	4.95	2.24	11.0
A VII	124.0	21.16	585.8	3.94	2.04	13.2
K VIII	155	23.87	519.4	3.20	1.87	15.4
Ca IX	188	26.59	466.2	2.65	1.73	17.7
Sc X	225.5	29.31	422.8	2.24	1.61	20.0
Ti XI	266	32.1	386	1.91	1.50	22.4
V XII	309	34.8	356	1.65	1.41	24.7
Cr XIII	355	37.6	330	1.43	1.32	26.9
Mn XIV	404	40.3	308	1.27	1.25	29.3
Fe XV	457	43.0	288	1.12	1.18	31.6
Co XVI	512	45.8	271	1.00	1.12	33.9
Ni XVII	529	48.6	255	0.89	1.06	36.2

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TABLE 12  
Silicon Sequence

$1s^2 2s^2 2p^6 3s^2 3p^2 \left( {}^3P_{0,1,2} \right) - 3s 3p^3 \left( {}^3D^o_{3,2,1} \right)$									
Ion	$S_M$	$(\tilde{\omega}f)_M$	$J_u$	$(E.P.)_u$	J	$\lambda$	$S_L$	$(\tilde{\omega}f)_L$	$\tilde{\omega}A \times 10^{-10}$
Si I	47.08	6.95	1	6.01	0	2065.5	5.23	0.77	0.12
			2,1		1	2061.2	15.69	2.31	0.36
			2,1		2	2067.4	4.19	0.62	0.10
			3		2	2054.8	21.97	3.25	0.51
P II	30.45	6.01	1	6.06	0	1532.6	3.38	0.67	0.19
			2,1		1	1536.2	10.15	2.01	0.57
			2,1		2	1543.4	2.71	0.53	0.15
			3		2	1542.3	14.21	2.80	0.78
S III	21.56	5.47	1	8.10	0	1190.2	2.40	0.61	0.29
			2,1		1	1194.2	7.19	1.83	0.87
			2,1		2	1201.9	1.92	0.49	0.23
			3		2	1201.0	10.06	2.54	1.17
Cl IV	16.05	4.97	1	10.42	0	973.2	1.78	0.56	0.39
			2,1		1	977.7	5.35	1.66	1.16
			2,1		2	985.9	1.43	0.44	0.30
			3		2	984.9	7.49	2.31	1.59
A V	12.39	4.53	1	12.75	0	822.2	1.38	0.51	0.50
			2,1		1	827.2	4.13	1.52	1.48
			2,1		2	836.0	1.10	0.40	0.38
			3		2	834.9	5.78	2.10	2.01
K VI	9.84	4.15	1	15.10	0	710.5	1.09	0.47	0.62
			2,1		1	716.1	3.28	1.39	1.81
			2,1		2	725.4	0.87	0.36	0.46
			3		2	724.4	4.59	1.93	2.45



TABLE 12 (Cont.)

Ion	$S_M$	$(\tilde{\omega}f)_M$	$J_u$	(E.P.) <sub>u</sub>	J	$\lambda$	$S_L$	$(\tilde{\omega}f)_L$	$\tilde{\omega}A \times 10^{-10}$
Ca VII	8.00	3.83	1		0	624.4	0.89	0.43	0.74
			2,1	19.86	1	630.6	2.67	1.29	2.16
			2,1		2	640.5	0.71	0.34	0.55
Sc VIII	6.63	3.54	3	19.90	2	639.2	3.73	1.77	2.89
			1		0	556	0.74	0.40	0.86
			2,1		1	563	2.21	1.19	2.50
Ti IX	5.58	3.30	3,2,1	22.3	2	574	3.68	1.95	3.94
			1		0	502	0.62	0.38	1.00
			2,1		1	510	1.86	1.11	2.84
V X	4.77	3.08	3,2,1	24.7	2	521	3.10	1.81	4.44
			1		0	456	0.53	0.35	1.12
			2,1		1	464	1.59	1.04	3.22
Cr XI	4.11	2.87	3,2,1	27.2	2	477	2.65	1.69	4.95
			1		0	419	0.46	0.33	1.25
			2,1		1	429	1.37	0.97	3.51
Mn XII	3.60	2.71	3,2,1	29.6	2	441	2.28	1.57	5.38
			1		0	387	0.40	0.31	1.38
			2,1		1	398	1.20	0.92	3.87
Fe XIII	3.15	2.53	3,2,1	32.0	2	412	2.00	1.48	5.81
			1		0	360	0.35	0.29	1.49
			2,1		1	373	1.05	0.86	4.12
Co XIV	2.79	2.37	3,2,1	34.4	2	386	1.75	1.38	6.17
			1		0	337	0.31	0.28	1.64
			2,1		1	351	0.93	0.80	4.33
Ni XV	2.49	2.24	3,2,1	36.8	2	364	1.55	1.29	6.49
			1		0	316	0.28	0.27	1.80
			2,1		1	333	0.83	0.76	4.57
			3,2,1	39.2	2	346	1.38	1.21	6.74

TABLE 13  
Phosphorus Sequence

$1s^2 2s^2 2p^6 3s^2 3p^3 \left( {}^4S_{3/2}^o \right) - 3s 3p^4 \left( {}^4P_{1/2, 3/2, 5/2} \right)$									
Ion	I. P.	S <sub>M</sub>	( $\tilde{\omega}f$ ) <sub>M</sub>	J <sub>u</sub>	(E. P.) <sub>u</sub>	$\lambda$	S <sub>L</sub>	( $\tilde{\omega}f$ ) <sub>L</sub>	A x 10 <sup>-9</sup>
P I	10.9	30.70	5.57	1/2	7.38	1671.7	5.12	0.93	1.11
				3/2	7.37	1674.7	10.23	1.86	1.10
				5/2	7.35	1679.7	15.35	2.78	1.09
S II	23.3	21.30	5.15	1/2	9.87	1250.5	3.55	0.86	1.83
				3/2	9.85	1253.8	7.10	1.72	1.82
				5/2	9.80	1259.5	10.65	2.57	1.80
Cl III	39.7	15.52	4.66	1/2	12.28	1005.3	2.59	0.78	2.57
				3/2	12.24	1008.8	5.17	1.56	2.56
				5/2	12.16	1015.0	7.76	2.32	2.54
A IV	59.6	11.76	4.22	1/2	14.70	840.0	1.96	0.71	3.35
				3/2	14.63	843.8	3.92	1.41	3.30
				5/2	14.51	850.6	5.88	2.10	3.22
K V	82.6	9.20	3.85	1/2	17.21	720.4	1.53	0.65	4.17
				3/2	17.11	724.4	3.07	1.29	4.10
				5/2	16.94	731.8	4.60	1.91	3.96
Ca VI	109	7.38	3.52	1/2	19.69	629.6	1.23	0.59	4.96
				3/2	19.56	633.8	2.46	1.18	4.89
				5/2	19.31	641.9	3.69	1.75	4.72
Sc VII	139	6.05	3.25	1/2	22.21	558.0	1.01	0.55	5.89
				3/2	22.03	562.6	2.02	1.09	5.74
				5/2	21.70	571.3	3.02	1.61	5.48
Ti VIII	172	5.04	3.01	1/2	24.8	500	0.84	0.51	6.80
				3/2	24.6	504	1.68	1.01	6.63
				5/2	24.1	514	2.52	1.49	6.26

TABLE 13 (Cont.)

Ion	I. P.	S <sub>M</sub>	( $\tilde{\omega}f$ ) <sub>M</sub>	J <sub>u</sub>	(E. P.) <sub>u</sub>	$\lambda$	S <sub>L</sub>	( $\tilde{\omega}f$ ) <sub>L</sub>	A x 10 <sup>-9</sup>
V IX	206	4.27	2.80	1/2	27.3	454	0.71	0.48	7.76
				3/2	27.0	459	1.42	0.94	7.44
				5/2	26.5	468	2.13	1.38	7.00
Cr X	246	3.66	2.62	1/2	29.8	416	0.61	0.44	8.47
				3/2	29.4	422	1.22	0.88	8.23
				5/2	28.9	429	1.83	1.30	7.85
Mn XI	288	3.17	2.46	1/2	32.3	384	0.53	0.42	9.49
				3/2	31.9	388	1.06	0.83	9.19
				5/2	31.3	396	1.58	1.21	8.57
Fe XII	333	2.77	2.31	1/2	34.8	356	0.46	0.39	10.3
				3/2	34.4	360	0.92	0.78	10.0
				5/2	33.6	369	1.38	1.14	9.30
Co XIII	381	2.45	2.19	1/2	37.2	333	0.41	0.37	11.1
				3/2	36.8	337	0.82	0.74	10.9
				5/2	36.0	344	1.22	1.08	10.1
Ni XIV	432	2.17	2.06	1/2	39.8	311	0.36	0.35	12.0
				3/2	39.3	315	0.72	0.69	11.6
				5/2	38.4	323	1.08	1.02	10.9

TABLE 14  
Sulphur Sequence

$1s^2 2s^2 2p^6 3s^2 3p^4(^3P_{2,1,0}) - 3s 3p^5(^3P_{2,1,0})$											
Ion	I. P.	$S_M$	$(\delta f)_M$	$J_u$	$(E. P.)_u$	$J$	$(E. P.)$	$\lambda$	$S_L$	$(\delta f)_L$	$A \times 10^{-9}$
S I	10.31	36.88	8.06	2	8.89	2	0	1388.4	15.37	3.36	2.32
				1	8.94	2		1381.6	5.12	1.13	1.32
				2		1	0.05	1396.1	5.12	1.11	0.76
				1		1		1389.2	3.07	0.67	0.77
				0	8.96	1		1385.5	4.10	0.90	3.13
Cl II	23.70	26.71	7.58	1		0	0.07	1392.6	4.10	0.89	1.02
				2	11.57	2	0	1071.0	11.13	3.16	3.67
				1	11.65	2		1063.8	3.71	1.06	2.08
				2		1	0.09	1079.1	3.71	1.04	1.19
				1		1		1071.8	2.23	0.63	1.22
A III	40.90	20.05	6.93	0	11.69	1		1068.0	2.97	0.85	4.97
				1		0	0.12	1075.2	2.97	0.84	1.61
				2	14.05	2	0	878.7	8.35	2.89	4.99
				1	14.17	2		871.1	2.78	0.97	2.84
				2		1	0.14	887.4	2.78	0.95	1.61
K IV	60.90	15.53	6.34	1		1		879.6	1.67	0.58	1.66
				0	14.24	1		875.5	2.23	0.77	6.70
				1		0	0.19	883.2	2.23	0.77	2.19
				2	16.63	2	0	745.3	6.47	2.64	6.34
				1	16.82	2		737.1	2.16	0.89	3.64
				2		1	0.21	754.7	2.16	0.87	2.04
				1		1		746.3	1.29	0.53	2.11
				0	16.91	1		741.9	1.73	0.71	8.60
				1		0	0.29	750.0	1.73	0.70	2.76

TABLE 14 (Cont.)

Ion	I.P.	S <sub>M</sub>	( $\bar{\omega}f$ ) <sub>M</sub>	J <sub>u</sub>	(E.P.) <sub>u</sub>	J	(E.P.)	$\lambda$	S <sub>L</sub>	( $\bar{\omega}f$ ) <sub>L</sub>	A x 10 <sup>-9</sup>
Ca V	84.39	12.35	5.81	2	19.17	2	0	646.6	5.15	2.42	7.72
				1	19.43	2		637.9	1.72	0.82	4.48
				2		1	0.30	656.8	1.72	0.80	2.47
				1		1		647.9	1.03	0.48	2.54
				0	19.57	1		643.1	1.37	0.65	10.5
Sc VI	111.1	10.04	5.35	1		0	0.41	651.6	1.37	0.64	3.35
				2	21.73	2	0	570.3	4.18	2.23	9.14
				1	22.09	2		561.2	1.39	0.75	5.29
				2		1	0.42	581.4	1.39	0.73	2.88
				1		1		571.9	0.84	0.45	3.06
Ti VII	140.8	8.32	4.96	0	22.28	1		566.8	1.12	0.60	12.5
				1		0	0.55	575.6	1.12	0.59	3.96
				2	24.33	2	0	509.5	3.47	2.07	10.6
				1	24.80	2		499.8	1.16	0.71	6.31
				2		1	0.56	521.6	1.16	0.68	3.33
V VIII	173.7	7.00	4.60	1		1		511.4	0.69	0.41	3.48
				0	25.06	1		505.9	0.92	0.55	14.3
				1		0	0.73	515.0	0.92	0.54	4.52
				2	26.8	2	0	462	2.92	1.92	12.0
				1	27.4	2		452	0.97	0.65	7.07
Cr IX	209.6	5.96	4.28	2		1	0.74	475	0.97	0.62	3.66
				1		1		464	0.58	0.38	3.92
				0	27.8	1		457	0.78	0.52	16.6
				1		0	0.94	468	0.78	0.51	5.17
				2	29.4	2	0	422	2.48	1.78	13.3
				1	30.1	2		412	0.83	0.61	7.98
				2		1	0.97	436	0.83	0.58	4.07
				1		1		426	0.50	0.36	4.41
				0	30.6	1		419	0.66	0.48	5.67
				1		0	1.19	429	0.66	0.47	17.0

TABLE 14 (Cont.)

Ion	I. P.	S <sub>M</sub>	( $\bar{\omega}f$ ) <sub>M</sub>	J <sub>u</sub>	(E. P.) <sub>u</sub>	J	(E. P.)	$\lambda$	S <sub>L</sub>	( $\bar{\omega}f$ ) <sub>L</sub>	A x 10 <sup>-9</sup>
Mn X	248	5.13	4.02	2	32.0	2	0	387	2.14	1.68	15.0
				1	32.8	2		378	0.72	0.58	9.02
				2		1	1.24	403	0.72	0.54	4.43
				1		1		392	0.43	0.33	4.77
				0	33.3	1		387	0.57	0.45	20.0
Fe XI	290	4.46	3.74	1		0	1.45	395	0.57	0.44	6.26
				2	34.6	2	0	358	1.86	1.58	16.4
				1	35.4	2		350	0.62	0.54	9.79
				2		1	1.57	376	0.62	0.50	4.72
				1		1		367	0.37	0.31	5.11
Co XII	337	3.92	3.54	0	36.0	1		360	0.49	0.41	21.1
				1		0	1.79	369	0.49	0.40	6.52
				2	37.2	2	0	333	1.63	1.49	17.9
				1	38.1	2		325	0.54	0.50	10.5
				2		1	1.96	352	0.54	0.47	5.06
Ni XIII	385	3.47	3.33	1		1		343	0.33	0.29	5.48
				0	38.8	1		337	0.44	0.40	23.5
				1		0	2.12	344	0.44	0.39	7.32
				2	39.7	2	0	312	1.45	1.41	19.3
				1	40.8	2		304	0.48	0.48	11.5
				2		1	2.42	332	0.48	0.44	5.32
				1		1		323	0.29	0.27	5.75
				0	41.5	1		317	0.39	0.37	24.5
				1		0	2.50	324	0.39	0.36	7.62

TABLE 15  
Chlorine Sequence

$1s^2 2s^2 2p^6 3s^2 3p^5 \left( {}^2P^o_{1/2, 3/2} \right) - 3s 3p^6 \left( {}^2S_{1/2} \right)$									
Ion	I. P.	$S_M$	$(\tilde{\omega}f)_M$	(E. P.) <sub>u</sub>	J	(E. P.)	$\lambda$	$S_L$	$(\tilde{\omega}f)_L$ A x 10 <sup>-9</sup>
Cl I	13.01	11.53	3.01?	10.7?	3/2	0	1160?	7.69	2.01?
A II	27.62	8.30	2.73	13.42	1/2	0.11	1170?	3.84	1.00?
K III	46	6.23	2.46	16.12	3/2	0	919.8	5.53	1.83
					1/2	0.18	932.0	2.77	0.90
Ca IV	67	4.84	2.23	18.89	3/2	0	765.6	4.15	1.65
					1/2	0.27	778.5	2.08	0.81
Sc V	92	3.85	2.02	21.62	3/2	0	656.0	3.23	1.50
					1/2	0.39	669.7	1.61	0.73
Ti VI	120	3.15	1.86	24.37	3/2	0	573.4	2.57	1.36
					1/2	0.54	587.9	1.28	0.66
V VII	151	2.62	1.72	27.17	3/2	0	508.6	2.10	1.25
					1/2	0.72	524.2	1.05	0.61
Cr VIII	185	2.21	1.60	30.01	3/2	0	456.2	1.75	1.16
					1/2	0.95	472.8	0.87	0.56
Mn IX	222	1.88	1.49	32.88	3/2	0	413.0	1.47	1.08
					1/2	1.23	430.6	0.74	0.52
Fe X	262	1.63	1.40	35.7	3/2	0	376.9	1.25	1.01
					1/2	1.55	395.6	0.63	0.48
Co XI	305	1.42	1.32	38.5	3/2	0	347	1.09	0.95
					1/2	1.94	367	0.54	0.45
Ni XII	352	1.25	1.24	41.4	3/2	0	322	0.95	0.90
					1/2	2.39	343	0.47	0.42
					3/2	0	299	0.83	0.84
					1/2	2.93	322	0.42	0.40



TABLE 16  
Excitation Cross-sections by Electronic Impact

Ion	Transition	Q (E) in units of $\pi a_0^2$		Ion	Transition	Q (E) in units of $\pi a_0^2$	
		150 ev	300 ev			150 ev	300 ev
O VI	$2s^2 S-2p^2 P^o$	0.28	0.17	Mg VIII	$2s^2 2p^2 P^o-2s^2 2p^2 D$	<u>0.031</u>	0.020
F VII		0.19	0.12	Al IX			0.016
Ne VIII		0.14	0.087	Si X			0.013
Na IX		0.11	0.068	P XI			0.010
Mg X		0.085	0.053	S XII			0.008
Al XI		0.068	0.043	Cl XIII			0.007
Si XII		0.055	0.035	A XIV			0.006
P XIII		<u>0.048</u>	0.029	Na VI	$2s^2 2p^2 3P-2s^2 2p^3 3D^o$	<u>0.050</u>	0.032
F VI	$2s^2 1S-2s2p^1 P^o$	0.20	0.13	Mg VII		<u>0.037</u>	0.024
Ne VII		<u>0.14</u>	0.091	Al VIII			0.018
Na VIII		<u>0.10</u>	0.068	Si IX			0.014
Mg IX			0.052	P X			0.012
Al X			0.041	S XI			0.009
Si XI			0.033	Cl XII			0.008
P XII			0.027	A XIII			<u>0.006</u>
Ne VI		0.058	0.037	K XIV			<u>0.0055</u>
Na VII		<u>0.042</u>	0.027	Ca XV			<u>0.005</u>
	$2s^2 2p^2 P^o-2s^2 2p^2 D$						

TABLE 16 (Cont.)

Ion	Transition	Q (E) in units of $\pi a_0^2$		Ion	Transition	Q (E) in units of $\pi a_0^2$	
		150 ev	300 ev			150 ev	300 ev
Na V	$2s^2 2p^3 4s^0 - 2s^2 2p^4 4p$	<u>0.18</u>	0.12	Ca X	$3s^2 S-3p^2 P^0$	0.37	0.23
Mg VI			0.085	Sc XI		0.30	0.19
Al VII			0.063	Ti XII		<u>0.25</u>	0.16
Si VIII			0.049	V XIII		<u>0.21</u>	0.14
P IX			0.039	Cr XIV			0.12
S X			0.031	Mn XV			0.10
Cl XI			<u>0.025</u>	Fe XVI			0.087
A XII			<u>0.021</u>	Co XVII			0.077
K XIII			<u>0.018</u>	Ni XVIII			0.067
Mg V	$2s^2 2p^4 3P-2s^2 2p^5 3P^0$		0.033	K VIII	$3s^2 1S-3s^2 3p^1 P^0$	0.49	0.31
Al VI			0.024	Ca IX		<u>0.39</u>	0.25
Si VII			0.018	Sc X		<u>0.31</u>	0.20
P VIII			<u>0.014</u>	Ti XI			0.17
S IX			<u>0.011</u>	V XII			0.14
Al V	$2s^2 2p^5 2P^0-2s^2 2p^6 2S$		0.027	Cr XIII			0.12
Si VI			<u>0.020</u>	Mn XIV			0.10
P VII			<u>0.015</u>	Fe XV			0.089
A VIII	$3s^2 S-3p^2 P^0$	0.58	0.36	Co XVI			0.078
K IX		0.46	0.29	Ni XVII			0.067

TABLE 16 (Cont.)

Ion	Transition	Q (E) in units of $\pi a_0^2$		Ion	Transition	Q (E) in units of $\pi a_0^2$	
		150 ev	300 ev			150 ev	300 ev
Ca VIII	$3s^2 3p^2 P^O-3s 3p^2 D$	0.15	0.096	V IX	$3s^2 3p^3 4S^O-3s 3p^4 P$	<u>0.31</u>	0.20
Sc IX		0.12	0.078	Cr X		<u>0.26</u>	0.17
Ti X		0.10	0.064	Mn XI			0.14
V XI		<u>0.082</u>	0.053	Fe XII			0.12
Cr XII			0.045	Co XIII			0.10
Mn XIII			0.038	Ni XIV			0.09
Fe XIV			0.033	Ti VII	$3s^2 3p^4 3P-3s 3p^5 3P^O$	0.14	0.088
Co XV			0.029	V VIII		<u>0.11</u>	0.072
Ni XVI			0.025	Cr IX		<u>0.092</u>	0.060
Sc VIII	$3s^2 3p^2 3P-3s 3p^3 D^O$	0.14	0.087	Mn X			0.050
Ti IX		0.11	0.071	Fe XI			0.042
V X		<u>0.092</u>	0.059	Co XII			0.036
Cr XI		<u>0.076</u>	0.049	Ni XIII			0.031
Mn XII			0.042	V VII	$3s^2 3p^5 2P^O-3s 3p^6 2S$	<u>0.13</u>	0.081
Fe XIII			0.036	Cr VIII		<u>0.10</u>	0.066
Co XIV			0.031	Mn IX			0.055
Ni XV			0.027	Fe X			0.046
Sc VII	$3s^2 3p^3 4S^O-3s 3p^4 P$	0.47	0.30	Co XI			0.039
Ti VIII		0.38	0.24	Ni XII			0.033

## NOTES TO TABLES

*Extrapolation.*—The experimental data listed by Moore (1949, 1952) do not cover the entire range of our tables. To obviate the lack of such data, we have made use of extrapolations. When the ground state splits into two or more levels, the magnitude of the splitting was computed by Rohrlich (1959), who kindly put his results at our disposal. The excitation potential of the upper state was calculated in two ways: (1) by linear extrapolation of the experimental data and (2) by applying the method described by Layzer (1959). Discrepancies greater than 3 per cent were very seldom observed. We should point out, however, that both methods neglect those relativistic corrections that shift the position of the center of gravity of the entire term; as a result, our predicted wave lengths are always too long. The relativistic corrections were not applied for two reasons: (1) our primary interest was the computation of  $f$ -values, where errors of a few per cent are negligible; (2) Dr. C. Pecker, of the Institut d'Astrophysique in Paris, is carrying out a detailed calculation that we did not wish to duplicate. In addition, from a practical point of view, the neglect of the relativistic corrections has the advantage of assuring us that the error is always in the same direction, as indicated above.

*Line blending.*—Sometimes the splitting between two or more levels with different values of  $J$  is so small that lines originating from these levels have wave lengths differing by less than 1 Å. It is likely that such lines will be observed as a blend, and hence we decided to give the strength,  $\omega f$ -value, and  $\omega A$  for the blend; to derive the individual intensities of each line we simply need to remember that

$$\omega A (1 + 2) = \omega A (1) + \omega A (2)$$

(the same relationship applies to  $\omega f$ ), where 1 and 2 refer to the two lines in the blend, and also we must know the ratio of the strengths of the two lines. Consider the following examples:

In Table 2 we combine the transitions  $J_u = 2 \rightarrow J_l = 1$  and  $J_u = 1 \rightarrow J_l = 1$  into a blend. For Si I we list  $S_L = 15.69$ ,  $\omega f = 2.31$ , and  $\omega A = 36 \times 10^8 \text{ sec}^{-1}$ . In the note to Table 12 we remark that  $S (2 \rightarrow 1)/S (1 \rightarrow 1) = 3$ . This means that  $S_L (2 \rightarrow 1) = 11.77$  and  $S_L (1 \rightarrow 1) = 3.92$ ; furthermore,  $\omega f (2 \rightarrow 1) = 1.73$ ,  $\omega f (1 \rightarrow 1) = 0.58$ ;  $\omega A (2 \rightarrow 1) = 27 \times 10^8$ ,  $\omega A (1 \rightarrow 1) = 9 \times 10^8$ .

Notes to the individual tables:

Table 4: extrapolation begins at S XII;  $S (5/2 \rightarrow 3/2)/S (3/2 \rightarrow 3/2) = 9$ .

Table 5: extrapolation begins at S XI;  $S (2 \rightarrow 2)/S (1 \rightarrow 2) = 15$ ,  $S (2 \rightarrow 1)/S (1 \rightarrow 1) = 3$ .

Table 6: extrapolation begins at S X.

Table 7: extrapolation begins at S IX.

Table 8: extrapolation begins at A X.

Table 10: extrapolation begins at Sc X.

Table 11: extrapolation begins at Ti X;  $S (5/2 \rightarrow 3/2)/S (3/2 \rightarrow 3/2) = 9$ .

Table 12: extrapolation begins at Sc VIII;  $S (2 \rightarrow 2)/S (1 \rightarrow 2) = 15$ ,  $S (2 \rightarrow 1)/S (1 \rightarrow 1) = 3$ .

Table 13: extrapolation begins at Ti VIII.

Table 14: extrapolation begins at V VIII.

Table 15: extrapolation begins at Fe X.

Table 16: numbers in italics indicate that  $5E_0 \leq W \leq 6E_0$ ; in all other cases  $W > 6E_0$ .