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ELECTRON–ION COLLISIONAL IONIZATION CROSS SECTIONS FOR THE H AND He ISOELECTRONIC SEQUENCES

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In this work, we calculate the electron impact ionization cross sections for H-like and He-like isoelectronic-sequence ions by means of a distorted-wave Born exchange approximation method including a relativistic correction. A computer program has been developed and used to calculate these cross sections. Systematic study of the dependence of the cross sections on impact energies and nuclear charges is carried out. The results of calculations are fitted by empirical formulas to meet the requirements of applications. The fitted values are in good agreement with the calculated results. © 1995 Academic Press, Inc.

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CONTENTS

1. INTRODUCTION

Electron–ion collision is one of the fundamental processes in atomic physics. In astrophysics, plasmas, and x-ray laser studies, large amounts of atomic data are required, including ionization cross sections for electron–ion collisions. Electron impact ionization cross sections are important for modeling the structure and dynamics of high-temperature plasmas occurring both naturally in space and artificially in fusion devices.[1] In recent years, the study of soft x-ray lasers has made rapid progress.[2,3] The electron impact ionization cross sections for highly charged ions are very important atomic parameters in the study of plasma balance.

In many situations where electron impact ionization cross sections are used, it is necessary to obtain the data quickly and accurately. A suitable empirical formula for ionization is convenient and desirable for studies of x-ray lasers, fusion plasmas, and astrophysical plasmas.

In this paper, we use a distorted-wave Born exchange (DWBE) approximation method to calculate a series of electron impact ionization cross sections for H-like and He-like ions. The variations of the cross sections with impact energies and nuclear charges are studied systematically and some empirical formulas are used to fit the calculated results.

2. OUTLINE OF DWBE APPROXIMATION

The framework of our DWBE approximation was described and used in our previous works.[4] This approximation is a development of the Coulomb–Born (CB) approximation with the following four improvements: (1) we consider the distribution of target bound electrons rather than take the effect of these electrons as an equivalent point charge; (2) we consider the exchange effect between the two free electrons in the final state; (3) we consider the exchange effect between the free electron and bound electrons; (4) we use a relativistic correction in determining the target electron wave functions.[5] Atomic units are used in our calculation.

In the DWBE approximation, the direct ionization cross section (in units of πa_0^2) can be written as[6]

$$Q(E_i) = \int_0^{E/2} \sigma(E_e, E_i) dE_e, \qquad (1)$$

where E_i and E_e are the energies of the incident and ejected electrons, respectively. E is the sum of the ejected and scattered electron energies in the final state; $\sigma(E_e, E_i)$ is the differential cross section as a function of energy. By using partial wave expansion, the scattering amplitude can be divided into an angular factor and a Slater integral. To do this, we write

$$\sigma(E_e, E_i) = \frac{16}{\pi E_i} \sum_{l_i l_e l_f L} I_{l_i l_e l_f L}(E_e, E_i), \qquad (2)$$

where l_i, l_e, and l_f are the angular momenta of incident, ejected, and scattered electrons, respectively, L is the total angular momentum of the whole system, and

$$I_{l_i l_e l_f L}(E_e, E_i) = |f|^2 + |g|^2 - \alpha |f||g|; \qquad (3)$$

f and g are the direct and exchange partial wave scattering amplitudes, respectively. Here, we use the maximum interference approximation ($\alpha = 1$)[6,7] to treat the interaction between the direct and exchange terms, which are written as

$$f = \sum_\lambda f_\lambda(l_b l_i l_e l_f L)\left(P_b P_i \left|\frac{1}{r_{12}}\right| P_e P_f\right)_\lambda \qquad (4)$$

$$g = \sum_\lambda f_\lambda(l_b l_i l_f l_e L)\left(P_b P_i \left|\frac{1}{r_{12}}\right| P_f P_e\right)_\lambda, \qquad (5)$$

where f_λ is an angular factor in which l_b is the angular momentum of the bound electron, and $(P_b P_i|1/r_{12}|P_e P_f)_\lambda$ is the Slater integral. Here, P_b, P_i, P_e, and P_f are the wave functions of bound, incident, ejected, and scattered electrons, respectively. P_b is obtained from the atomic structure program of Cowan[5] in an HFR (Hartree–Fock approximation with relativistic correction) model. The calculations of P_i, P_e, and P_f are included in our own program. The effective integration method has been given in our previous work.[8] The total error introduced by the numerical calculation is estimated to be less than 0.5%.

3. CALCULATED IONIZATION CROSS SECTIONS

3.1. Scaled Cross Sections

In our calculations, we choose 11 H-like ions, He^+, C^{5+}, O^{7+}, F^{8+}, Mg^{11+}, Al^{12+}, Si^{13+}, S^{15+}, Cl^{16+}, Fe^{25+}, and Cu^{28+}, and 11 He-like ions, Li^+, C^{4+}, O^{6+}, F^{7+}, Mg^{10+}, Al^{11+}, Si^{12+}, S^{14+}, Cl^{15+}, Fe^{24+}, and Cu^{27+}. For incident energy, we take as the energy unit the reduced incident energy defined as

$$u = E_i/I, \qquad (6)$$

where E_i is the incident energy and I is the ionization potential of each ion. The values of I, also obtained by Cowan's program,[5] are listed in Table I. The energy range in our calculation is from $u = 1.01$ to $u = 15.0$ as required for practical applications. The calculated ionization cross sections for the above-mentioned ions are given in Tables II and III. In these tables, the choice of 26 incident energy points satisfies the needs of linear interpolation. Figures 1 and 2 are examples of the comparison of our results with available experimental data.[9–12] From these figures, it can be seen that the theoretical calculations are in good agreement with the experiments. It should be noted that the scaled cross sections uI^2Q are also given in the tables; the unit of scaled cross sections is $Ry^2\pi a_0^2$ (Ry is the Rydberg energy and a_0 is the Bohr radius). Figures 3 and 4 show the dependence of uI^2Q on $1/Z$ for H-like ions and on $1/(Z-1)$ for He-like ions, respectively. From Figs. 3 and 4, we can see two features: (1) uI^2Q varies only slightly and rather linearly with atomic number Z for an isoelectronic sequence of ions. Hence, it is simple to fit for Z and reasonable to extrapolate the fitting curve to larger Z values. (2) uI^2Q increases monotonically with u and changes more slowly at large u. Thus, fitting to u is relatively easy and appropriate extrapolation to larger u can also be justified.

3.2. Empirical Formulas and Fit Parameters for Individual H-like and He-like Ions

There are several methods to fit the variation of the cross sections depending on incident energies for a fixed ion. Here we list three empirical formulas:

(a) Lotz's formula,[13]

$$uI^2Q = a \ln u\{1 - b \exp[-c(u-1)]\}, \qquad (7)$$

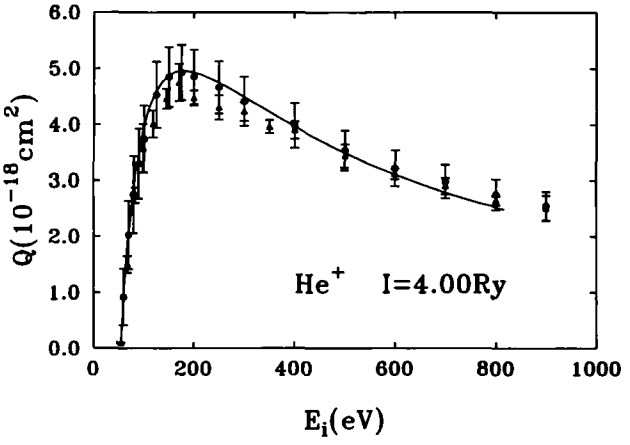

Figure 1. Ionization cross sections for He^+. Circles[9] and triangles[10], experimental data; solid line, theoretical result.

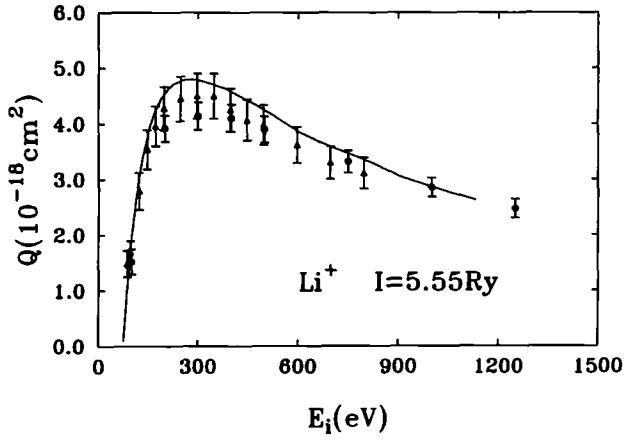

Figure 2. Ionization cross sections for Li^+. Circles[11] and triangles[12], experimental data; solid line, theoretical result.

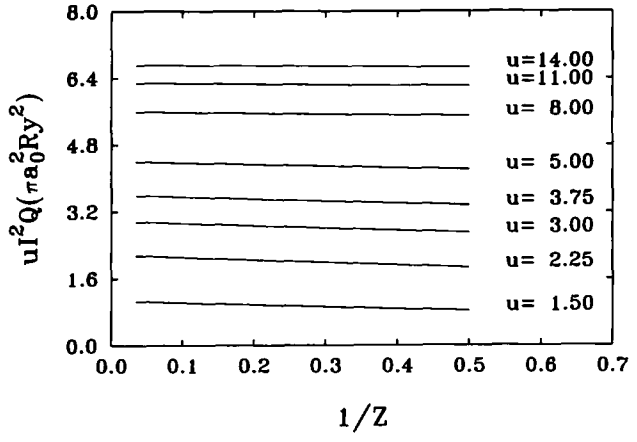

Figure 3. The dependence of scaled cross sections uI^2Q on $1/Z$ for H-like ions.

where a, b, and c are three adjustable parameters.

(b) Sampson's formula,[14]

$$uI^2Q = A \ln u + D\left(1 - \frac{1}{u}\right)^2 + \left(\frac{c}{u} + \frac{d}{u^2}\right)\left(1 - \frac{1}{u}\right), \quad (8)$$

where A, D, c, and d are four adjustable parameters.

(c) Younger's formula,[15]

$$uI^2Q = A\left(1 - \frac{1}{u}\right) + B\left(1 - \frac{1}{u}\right)^2 + C \ln u + D\frac{\ln u}{u}, \quad (9)$$

where A, B, C, and D are four adjustable parameters. All three formulas have the same tendency at the two limits, that is,

$$u \to 1, \quad Q \to 0, \quad (10)$$

$$u \to \infty, \quad Q \propto \frac{\ln u}{u}. \quad (11)$$

Equation (11) has the same form as the well-known Bethe formula.[16]

We use an "optimal calculation method"[17] to determine the values of the parameters. In a comparison among the three formulas, we found that Younger's formula [Eq. (9)] gives a smaller average deviation than the others. The average deviation F is defined as

$$F = \sqrt{\frac{1}{N}\sum_{i=1}^{N}\left(\frac{Q_{\text{fit}}(u) - Q_{\text{cal}}(u)}{Q_{\text{cal}}(u)}\right)^2}, \quad (12)$$

where Q_{cal} and Q_{fit} are calculated and fitted values, respectively, and N is the number of calculated points used in making the fit. The parameters and average deviations we give in Table IV for H-like ions and in Table V for He-like ions are those of Younger's formula.

3.3. Fit Parameters for the H and He Isoelectronic Sequences

Because the variation of uI^2Q with $1/Z$ for H-like ions is nearly a straight line, we can fit the scaled cross sections to the form

$$uI^2Q = a(u) + b(u)/Z, \quad (13)$$

where a and b are two parameters which depend on the scaled incident energy u only. A formula like Eq. (9) can

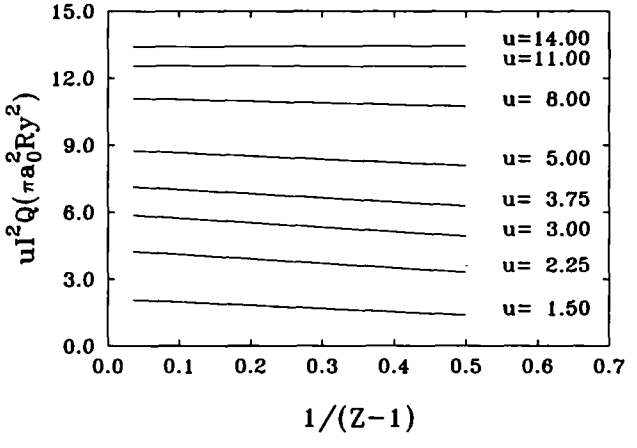

Figure 4. The dependence of scaled cross sections uI^2Q on $1/(Z-1)$ for He-like ions.

in turn be used to fit the variation of a and b with u, so that

$$a = A_1\left(1 - \frac{1}{u}\right) + B_1\left(1 - \frac{1}{u}\right)^2 + C_1 \ln u + D_1 \frac{\ln u}{u}, \quad (14)$$

$$b = A_2\left(1 - \frac{1}{u}\right) + B_2\left(1 - \frac{1}{u}\right)^2 + C_2 \ln u + D_2 \frac{\ln u}{u}, \quad (15)$$

where A_1, B_2, C_1, D_1, A_2, B_2, C_2, and D_2 are adjustable parameters. The fit parameters are given in Table VI.

For He-like ions, we can use the following equation to fit the scaled cross sections:

$$uI^2Q(Z, u) = a(u) + b(u)/(Z - 1). \quad (16)$$

For $a(u)$ and $b(u)$, the same formulas as Eqs. (14) and (15) would apply. The corresponding fit parameters are listed in Table VI as well.

As a test, we compared the cross sections for electron impact ionization of 11 H-like ions and 11 He-like ions obtained from formulas (13) and (16) using the fit parameters in Table VI with the DWBE values in Tables II and III. We found that the deviations between the fitted results and DWBE calculations are smaller than 1% in most cases and between 1% and 2% for the few other energy points.

Acknowledgments

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EXPLANATION OF TABLES

TABLE I. Ionization Potentials of H-like and He-like Ions

Z	Nuclear charge number
I_1	Ionization potential of H-like ions in Ry (1 Ry = 13.60 eV)
I_2	Ionization potential of He-like ions in Ry

TABLE II. Ionization Cross Sections for H-like Ions

TABLE III. Ionization Cross Sections for He-like Ions

Z	Nuclear charge number
u	Reduced incident energy (Eq. (6))
E	Incident energy in eV
uI^2Q	Scaled ionization cross section in $\pi a_0^2 \mathrm{Ry}^2$ ($a_0 = 0.5292 \times 10^{-8}$ cm)
Q	Ionization cross section in cm^2

TABLE IV. Fit Parameters for Individual H-like Ions

See Eq. (9)

TABLE V. Fit Parameters for Individual He-like Ions

See Eq. (9)

TABLE VI. Fit Parameters for the H and He Isoelectronic Sequences

See Eq. (13) or (16)

TABLE I. Ionization Potentials of H-like and He-like Ions

See page 96 for Explanation of Tables

Z	I_1	I_2	Z	I_1	I_2	Z	I_1	I_2
2	4.000		12	144.3	129.6	22	487.5	460.0
3	9.001	5.547	13	169.4	153.4	23	533.2	504.4
4	16.00	11.30	14	196.6	179.3	24	580.9	550.9
5	25.01	19.06	15	225.7	207.2	25	630.8	599.5
6	36.02	28.81	16	257.0	237.2	26	682.8	650.2
7	49.03	40.58	17	290.2	269.2	27	737.0	703.0
8	64.06	54.35	18	325.6	303.2	28	793.2	758.0
9	81.09	70.13	19	362.9	339.3	29	851.6	815.0
10	100.1	87.92	20	402.4	377.5			
11	121.2	107.7	21	443.9	417.7			

TABLE II. Ionization Cross Sections for H-like Ions

See page 96 for Explanation of Tables

Z	u	E(eV)	uI^2Q	Q(cm^2)	Z	u	E(eV)	uI^2Q	Q(cm^2)
2	1.010	5.494E01	0.019	1.043E-19	8	1.010	8.799E02	0.024	5.205E-22
	1.125	6.120E01	0.227	1.107E-18		1.125	9.801E02	0.290	5.527E-21
	1.250	6.800E01	0.436	1.918E-18		1.250	1.089E03	0.550	9.426E-21
	1.500	8.160E01	0.830	3.043E-18		1.500	1.307E03	1.007	1.439E-20
	1.750	9.520E01	1.202	3.776E-18		1.750	1.525E03	1.407	1.723E-20
	2.000	1.088E02	1.549	4.257E-18		2.000	1.742E03	1.769	1.896E-20
	2.250	1.224E02	1.867	4.563E-18		2.250	1.960E03	2.093	1.995E-20
	2.500	1.360E02	2.161	4.753E-18		2.500	2.178E03	2.386	2.046E-20
	2.750	1.496E02	2.438	4.874E-18		2.750	2.396E03	2.654	2.069E-20
	3.000	1.632E02	2.697	4.942E-18		3.000	2.614E03	2.907	2.077E-20
	3.250	1.768E02	2.930	4.957E-18		3.250	2.831E03	3.135	2.068E-20
	3.500	1.904E02	3.150	4.948E-18		3.500	3.049E03	3.345	2.049E-20
	3.750	2.040E02	3.355	4.920E-18		3.750	3.267E03	3.538	2.023E-20
	4.000	2.176E02	3.548	4.877E-18		4.000	3.485E03	3.718	1.993E-20
	4.500	2.448E02	3.899	4.764E-18		4.500	3.920E03	4.043	1.926E-20
	5.000	2.720E02	4.217	4.637E-18		5.000	4.356E03	4.337	1.860E-20
	6.000	3.264E02	4.746	4.349E-18		6.000	5.227E03	4.836	1.728E-20
	7.000	3.808E02	5.172	4.063E-18		7.000	6.099E03	5.260	1.611E-20
	8.000	4.352E02	5.504	3.783E-18		8.000	6.970E03	5.603	1.501E-20
	9.000	4.896E02	5.787	3.535E-18		9.000	7.841E03	5.901	1.406E-20
	10.00	5.440E02	6.025	3.313E-18		10.00	8.712E03	6.030	1.293E-20
	11.00	5.984E02	6.227	3.112E-18		11.00	9.583E03	6.233	1.215E-20
	12.00	6.528E02	6.396	2.931E-18		12.00	1.045E04	6.408	1.145E-20
	13.00	7.072E02	6.525	2.760E-18		13.00	1.133E04	6.556	1.081E-20
	14.00	7.616E02	6.658	2.615E-18		14.00	1.220E04	6.683	1.023E-20
	15.00	8.160E02	6.776	2.484E-18		15.00	1.307E04	6.804	9.724E-21
6	1.010	4.948E02	0.024	1.600E-21	9	1.010	1.114E03	0.025	3.266E-22
	1.125	5.511E02	0.282	1.702E-20		1.125	1.241E03	0.292	3.476E-21
	1.250	6.123E02	0.535	2.904E-20		1.250	1.379E03	0.553	5.920E-21
	1.500	7.348E02	0.984	4.455E-20		1.500	1.654E03	1.013	9.034E-21
	1.750	8.573E02	1.379	5.351E-20		1.750	1.930E03	1.415	1.081E-20
	2.000	9.797E02	1.739	5.902E-20		2.000	2.206E03	1.771	1.185E-20
	2.250	1.102E03	2.063	6.223E-20		2.250	2.481E03	2.097	1.247E-20
	2.500	1.225E03	2.355	6.393E-20		2.500	2.757E03	2.395	1.281E-20
	2.750	1.347E03	2.624	6.476E-20		2.750	3.033E03	2.666	1.297E-20
	3.000	1.470E03	2.877	6.510E-20		3.000	3.308E03	2.909	1.297E-20
	3.250	1.592E03	3.108	6.491E-20		3.250	3.584E03	3.136	1.291E-20
	3.500	1.715E03	3.322	6.443E-20		3.500	3.860E03	3.346	1.279E-20
	3.750	1.837E03	3.521	6.373E-20		3.750	4.136E03	3.542	1.264E-20
	4.000	1.959E03	3.706	6.288E-20		4.000	4.411E03	3.725	1.246E-20
	4.500	2.204E03	4.036	6.088E-20		4.500	4.963E03	4.059	1.207E-20
	5.000	2.449E03	4.331	5.880E-20		5.000	5.514E03	4.363	1.167E-20
	6.000	2.939E03	4.815	5.447E-20		6.000	6.617E03	4.870	1.086E-20
	7.000	3.429E03	5.211	5.053E-20		7.000	7.720E03	5.278	1.009E-20
	8.000	3.919E03	5.554	4.712E-20		8.000	8.823E03	5.553	9.286E-21
	9.000	4.409E03	5.825	4.393E-20		9.000	9.925E03	5.819	8.649E-21
	10.00	4.899E03	6.050	4.107E-20		10.00	1.103E04	6.046	8.087E-21
	11.00	5.389E03	6.248	3.855E-20		11.00	1.213E04	6.243	7.592E-21
	12.00	5.878E03	6.413	3.628E-20		12.00	1.323E04	6.410	7.145E-21
	13.00	6.368E03	6.534	3.412E-20		13.00	1.434E04	6.555	6.745E-21
	14.00	6.858E03	6.660	3.229E-20		14.00	1.544E04	6.683	6.385E-21
	15.00	7.348E03	6.768	3.063E-20		15.00	1.654E04	6.791	6.056E-21

TABLE II. Ionization Cross Sections for H-like Ions

See page 96 for Explanation of Tables

Z	u	E(eV)	uI^2Q	Q(cm^2)	Z	u	E(eV)	uI^2Q	Q(cm^2)
12	1.010	1.982E03	0.025	1.058E-22	14	1.010	2.700E03	0.025	5.715E-23
	1.125	2.208E03	0.297	1.117E-21		1.125	3.008E03	0.300	6.074E-22
	1.250	2.453E03	0.562	1.901E-21		1.250	3.342E03	0.566	1.031E-21
	1.500	2.944E03	1.027	2.892E-21		1.500	4.011E03	1.033	1.568E-21
	1.750	3.434E03	1.430	3.453E-21		1.750	4.679E03	1.438	1.871E-21
	2.000	3.925E03	1.790	3.782E-21		2.000	5.348E03	1.803	2.052E-21
	2.250	4.416E03	2.119	3.979E-21		2.250	6.016E03	2.132	2.157E-21
	2.500	4.906E03	2.417	4.084E-21		2.500	6.684E03	2.426	2.210E-21
	2.750	5.397E03	2.685	4.124E-21		2.750	7.353E03	2.692	2.229E-21
	3.000	5.887E03	2.928	4.124E-21		3.000	8.021E03	2.938	2.230E-21
	3.250	6.378E03	3.152	4.098E-21		3.250	8.690E03	3.160	2.214E-21
	3.500	6.869E03	3.362	4.058E-21		3.500	9.358E03	3.369	2.192E-21
	3.750	7.359E03	3.558	4.009E-21		3.750	1.003E04	3.566	2.165E-21
	4.000	7.850E03	3.741	3.951E-21		4.000	1.070E04	3.747	2.133E-21
	4.500	8.831E03	4.074	3.825E-21		4.500	1.203E04	4.081	2.065E-21
	5.000	9.812E03	4.377	3.699E-21		5.000	1.337E04	4.384	1.996E-21
	6.000	1.177E04	4.882	3.437E-21		6.000	1.604E04	4.888	1.855E-21
	7.000	1.374E04	5.288	3.192E-21		7.000	1.872E04	5.294	1.722E-21
	8.000	1.570E04	5.563	2.938E-21		8.000	2.139E04	5.552	1.580E-21
	9.000	1.766E04	5.829	2.736E-21		9.000	2.406E04	5.818	1.472E-21
	10.00	1.962E04	6.054	2.558E-21		10.00	2.674E04	6.045	1.376E-21
	11.00	2.159E04	6.252	2.401E-21		11.00	2.941E04	6.242	1.292E-21
	12.00	2.355E04	6.418	2.260E-21		12.00	3.209E04	6.410	1.216E-21
	13.00	2.551E04	6.560	2.132E-21		13.00	3.476E04	6.557	1.148E-21
	14.00	2.747E04	6.687	2.018E-21		14.00	3.743E04	6.682	1.087E-21
	15.00	2.944E04	6.796	1.914E-21		15.00	4.011E04	6.789	1.031E-21
13	1.010	2.327E03	0.025	7.658E-23	16	1.010	3.530E03	0.026	3.375E-23
	1.125	2.592E03	0.299	8.143E-22		1.125	3.932E03	0.302	3.574E-22
	1.250	2.880E03	0.565	1.384E-21		1.250	4.369E03	0.569	6.069E-22
	1.500	3.456E03	1.031	2.106E-21		1.500	5.243E03	1.037	9.211E-22
	1.750	4.032E03	1.437	2.516E-21		1.750	6.117E03	1.447	1.102E-21
	2.000	4.608E03	1.794	2.750E-21		2.000	6.990E03	1.809	1.205E-21
	2.250	5.184E03	2.119	2.887E-21		2.250	7.864E03	2.132	1.262E-21
	2.500	5.760E03	2.417	2.963E-21		2.500	8.738E03	2.425	1.292E-21
	2.750	6.336E03	2.688	2.996E-21		2.750	9.612E03	2.694	1.305E-21
	3.000	6.912E03	2.931	2.994E-21		3.000	1.049E04	2.943	1.307E-21
	3.250	7.487E03	3.158	2.978E-21		3.250	1.136E04	3.166	1.298E-21
	3.500	8.063E03	3.367	2.948E-21		3.500	1.223E04	3.376	1.285E-21
	3.750	8.639E03	3.562	2.911E-21		3.750	1.311E04	3.571	1.269E-21
	4.000	9.215E03	3.744	2.869E-21		4.000	1.398E04	3.754	1.250E-21
	4.500	1.037E04	4.077	2.777E-21		4.500	1.573E04	4.087	1.210E-21
	5.000	1.152E04	4.379	2.685E-21		5.000	1.748E04	4.389	1.169E-21
	6.000	1.382E04	4.884	2.495E-21		6.000	2.097E04	4.893	1.087E-21
	7.000	1.613E04	5.292	2.317E-21		7.000	2.447E04	5.299	1.009E-21
	8.000	1.843E04	5.557	2.129E-21		8.000	2.796E04	5.585	9.301E-22
	9.000	2.073E04	5.823	1.983E-21		9.000	3.146E04	5.855	8.667E-22
	10.00	2.304E04	6.050	1.854E-21		10.00	3.495E04	6.079	8.099E-22
	11.00	2.534E04	6.245	1.740E-21		11.00	3.845E04	6.275	7.601E-22
	12.00	2.765E04	6.411	1.637E-21		12.00	4.194E04	6.441	7.151E-22
	13.00	2.995E04	6.559	1.546E-21		13.00	4.544E04	6.571	6.734E-22
	14.00	3.225E04	6.684	1.463E-21		14.00	4.893E04	6.697	6.373E-22
	15.00	3.456E04	6.793	1.388E-21		15.00	5.243E04	6.805	6.044E-22

TABLE II. Ionization Cross Sections for H-like Ions

See page 96 for Explanation of Tables

Z	u	E(eV)	uf^2Q	Q(cm^2)	Z	u	E(eV)	uf^2Q	Q(cm^2)
17	1.010	3.986E03	0.026	2.659E-23	29	1.010	1.170E04	0.026	3.118E-24
	1.125	4.440E03	0.302	2.806E-22		1.125	1.303E04	0.307	3.314E-23
	1.250	4.933E03	0.571	4.770E-22		1.250	1.448E04	0.580	5.626E-23
	1.500	5.920E03	1.040	7.241E-22		1.500	1.737E04	1.055	8.530E-23
	1.750	6.907E03	1.446	8.630E-22		1.750	2.027E04	1.463	1.014E-22
	2.000	7.893E03	1.807	9.436E-22		2.000	2.316E04	1.829	1.109E-22
	2.250	8.880E03	2.137	9.917E-22		2.250	2.606E04	2.159	1.164E-22
	2.500	9.867E03	2.434	1.017E-21		2.500	2.895E04	2.454	1.190E-22
	2.750	1.085E04	2.702	1.026E-21		2.750	3.185E04	2.720	1.200E-22
	3.000	1.184E04	2.945	1.025E-21		3.000	3.475E04	2.973	1.202E-22
	3.250	1.283E04	3.168	1.018E-21		3.250	3.764E04	3.197	1.193E-22
	3.500	1.381E04	3.377	1.008E-21		3.500	4.054E04	3.406	1.180E-22
	3.750	1.480E04	3.574	9.952E-22		3.750	4.343E04	3.601	1.165E-22
	4.000	1.579E04	3.757	9.809E-22		4.000	4.633E04	3.783	1.147E-22
	4.500	1.776E04	4.090	9.493E-22		4.500	5.212E04	4.115	1.109E-22
	5.000	1.973E04	4.393	9.176E-22		5.000	5.791E04	4.417	1.072E-22
	6.000	2.368E04	4.896	8.522E-22		6.000	6.949E04	4.925	9.957E-23
	7.000	2.763E04	5.300	7.907E-22		7.000	8.107E04	5.339	9.251E-23
	8.000	3.157E04	5.584	7.289E-22		8.000	9.265E04	5.649	8.564E-23
	9.000	3.552E04	5.854	6.793E-22		9.000	1.042E05	5.923	7.982E-23
	10.00	3.947E04	6.079	6.349E-22		10.00	1.158E05	6.153	7.463E-23
	11.00	4.341E04	6.275	5.958E-22		11.00	1.274E05	6.351	7.003E-23
	12.00	4.736E04	6.442	5.607E-22		12.00	1.390E05	6.518	6.588E-23
	13.00	5.131E04	6.585	5.290E-22		13.00	1.506E05	6.612	6.169E-23
	14.00	5.525E04	6.714	5.008E-22		14.00	1.621E05	6.738	5.838E-23
	15.00	5.920E04	6.823	4.750E-22		15.00	1.737E05	6.845	5.535E-23
26	1.010	9.379E03	0.026	4.842E-24					
	1.125	1.045E04	0.307	5.142E-23					
	1.250	1.161E04	0.578	8.728E-23					
	1.500	1.393E04	1.052	1.323E-22					
	1.750	1.625E04	1.463	1.577E-22					
	2.000	1.857E04	1.823	1.720E-22					
	2.250	2.089E04	2.149	1.802E-22					
	2.500	2.322E04	2.447	1.847E-22					
	2.750	2.554E04	2.720	1.866E-22					
	3.000	2.786E04	2.962	1.863E-22					
	3.250	3.018E04	3.190	1.852E-22					
	3.500	3.250E04	3.398	1.832E-22					
	3.750	3.482E04	3.594	1.808E-22					
	4.000	3.714E04	3.776	1.781E-22					
	4.500	4.179E04	4.110	1.723E-22					
	5.000	4.643E04	4.413	1.665E-22					
	6.000	5.572E04	4.918	1.547E-22					
	7.000	6.500E04	5.327	1.436E-22					
	8.000	7.429E04	5.620	1.325E-22					
	9.000	8.357E04	5.892	1.235E-22					
	10.00	9.286E04	6.118	1.154E-22					
	11.00	1.021E05	6.315	1.083E-22					
	12.00	1.114E05	6.482	1.019E-22					
	13.00	1.207E05	6.599	9.578E-23					
	14.00	1.300E05	6.728	9.067E-23					
	15.00	1.393E05	6.836	8.598E-23					

TABLE III. Ionization Cross Sections for He-like Ions

See page 96 for Explanation of Tables

Z	u	E(eV)	uI^2Q	Q(cm^2)	Z	u	E(eV)	uI^2Q	Q(cm^2)
3	1.010	7.619E01	0.030	8.532E-20	8	1.010	7.466E02	0.046	1.349E-21
	1.125	8.487E01	0.364	9.243E-19		1.125	8.316E02	0.541	1.431E-20
	1.250	9.430E01	0.714	1.633E-18		1.250	9.240E02	1.028	2.449E-20
	1.500	1.132E02	1.399	2.666E-18		1.500	1.109E03	1.897	3.766E-20
	1.750	1.320E02	2.062	3.368E-18		1.750	1.294E03	2.665	4.535E-20
	2.000	1.509E02	2.711	3.876E-18		2.000	1.478E03	3.366	5.012E-20
	2.250	1.697E02	3.326	4.227E-18		2.250	1.663E03	4.017	5.317E-20
	2.500	1.886E02	3.904	4.465E-18		2.500	1.848E03	4.603	5.484E-20
	2.750	2.075E02	4.440	4.616E-18		2.750	2.033E03	5.137	5.564E-20
	3.000	2.263E02	4.951	4.719E-18		3.000	2.217E03	5.630	5.590E-20
	3.250	2.452E02	5.422	4.770E-18		3.250	2.402E03	6.078	5.570E-20
	3.500	2.640E02	5.872	4.797E-18		3.500	2.587E03	6.508	5.538E-20
	3.750	2.829E02	6.293	4.798E-18		3.750	2.772E03	6.908	5.487E-20
	4.000	3.018E02	6.690	4.782E-18		4.000	2.957E03	7.283	5.423E-20
	4.500	3.395E02	7.426	4.718E-18		4.500	3.326E03	7.963	5.270E-20
	5.000	3.772E02	8.122	4.645E-18		5.000	3.696E03	8.566	5.103E-20
	6.000	4.526E02	9.249	4.407E-18		6.000	4.435E03	9.599	4.765E-20
	7.000	5.281E02	10.15	4.146E-18		7.000	5.174E03	10.42	4.435E-20
	8.000	6.035E02	10.78	3.854E-18		8.000	5.913E03	10.98	4.088E-20
	9.000	6.790E02	11.44	3.633E-18		9.000	6.652E03	11.57	3.829E-20
	10.00	7.544E02	12.09	3.457E-18		10.00	7.392E03	12.08	3.597E-20
	11.00	8.298E02	12.60	3.275E-18		11.00	8.131E03	12.51	3.387E-20
	12.00	9.053E02	12.79	3.048E-18		12.00	8.870E03	12.89	3.201E-20
	13.00	9.807E02	13.21	2.904E-18		13.00	9.609E03	13.09	2.998E-20
	14.00	1.056E03	13.49	2.756E-18		14.00	1.035E04	13.35	2.841E-20
	15.00	1.132E03	13.74	2.620E-18		15.00	1.109E04	13.58	2.697E-20
6	1.010	3.957E02	0.043	4.537E-21	9	1.010	9.633E02	0.047	8.256E-22
	1.125	4.408E02	0.512	4.819E-20		1.125	1.073E03	0.551	8.755E-21
	1.250	4.898E02	0.974	8.252E-20		1.250	1.192E03	1.045	1.495E-20
	1.500	5.877E02	1.807	1.276E-19		1.500	1.431E03	1.925	2.296E-20
	1.750	6.857E02	2.565	1.552E-19		1.750	1.669E03	2.699	2.759E-20
	2.000	7.836E02	3.254	1.723E-19		2.000	1.908E03	3.408	3.048E-20
	2.250	8.816E02	3.883	1.828E-19		2.250	2.146E03	4.059	3.227E-20
	2.500	9.795E02	4.464	1.891E-19		2.500	2.384E03	4.645	3.323E-20
	2.750	1.077E03	5.006	1.928E-19		2.750	2.623E03	5.178	3.368E-20
	3.000	1.175E03	5.506	1.944E-19		3.000	2.861E03	5.672	3.382E-20
	3.250	1.273E03	5.973	1.946E-19		3.250	3.100E03	6.116	3.366E-20
	3.500	1.371E03	6.405	1.938E-19		3.500	3.338E03	6.544	3.344E-20
	3.750	1.469E03	6.811	1.924E-19		3.750	3.577E03	6.942	3.311E-20
	4.000	1.567E03	7.188	1.903E-19		4.000	3.815E03	7.315	3.271E-20
	4.500	1.763E03	7.875	1.853E-19		4.500	4.292E03	7.994	3.177E-20
	5.000	1.959E03	8.481	1.796E-19		5.000	4.769E03	8.596	3.075E-20
	6.000	2.351E03	9.494	1.676E-19		6.000	5.723E03	9.626	2.870E-20
	7.000	2.743E03	10.33	1.563E-19		7.000	6.676E03	10.45	2.670E-20
	8.000	3.135E03	10.93	1.446E-19		8.000	7.630E03	11.01	2.462E-20
	9.000	3.526E03	11.52	1.356E-19		9.000	8.584E03	11.61	2.307E-20
	10.00	3.918E03	12.04	1.275E-19		10.00	9.538E03	12.11	2.167E-20
	11.00	4.310E03	12.47	1.201E-19		11.00	1.049E04	12.55	2.040E-20
	12.00	4.702E03	12.85	1.134E-19		12.00	1.145E04	12.93	1.928E-20
	13.00	5.094E03	13.09	1.066E-19		13.00	1.240E04	13.12	1.805E-20
	14.00	5.485E03	13.37	1.012E-19		14.00	1.335E04	13.39	1.711E-20
	15.00	5.877E03	13.61	9.608E-20		15.00	1.431E04	13.63	1.625E-20

TABLE III. Ionization Cross Sections for He-like Ions

See page 96 for Explanation of Tables

Z	u	E(eV)	uI^2Q	Q(cm^2)	Z	u	E(eV)	uI^2Q	Q(cm^2)
12	1.010	1.780E03	0.048	2.502E-22	14	1.010	2.463E03	0.049	1.329E-22
	1.125	1.983E03	0.570	2.656E-21		1.125	2.743E03	0.579	1.409E-21
	1.250	2.203E03	1.080	4.528E-21		1.250	3.048E03	1.094	2.398E-21
	1.500	2.644E03	1.980	6.920E-21		1.500	3.658E03	2.002	3.656E-21
	1.750	3.084E03	2.771	8.298E-21		1.750	4.267E03	2.804	4.389E-21
	2.000	3.525E03	3.490	9.145E-21		2.000	4.877E03	3.517	4.817E-21
	2.250	3.966E03	4.133	9.627E-21		2.250	5.487E03	4.157	5.061E-21
	2.500	4.406E03	4.710	9.874E-21		2.500	6.096E03	4.740	5.194E-21
	2.750	4.847E03	5.244	9.994E-21		2.750	6.706E03	5.279	5.259E-21
	3.000	5.288E03	5.756	1.005E-20		3.000	7.315E03	5.776	5.274E-21
	3.250	5.728E03	6.199	9.996E-21		3.250	7.925E03	6.220	5.243E-21
	3.500	6.169E03	6.619	9.911E-21		3.500	8.535E03	6.644	5.200E-21
	3.750	6.610E03	7.012	9.800E-21		3.750	9.144E03	7.040	5.143E-21
	4.000	7.050E03	7.379	9.669E-21		4.000	9.754E03	7.410	5.075E-21
	4.500	7.932E03	8.050	9.375E-21		4.500	1.097E04	8.081	4.919E-21
	5.000	8.813E03	8.648	9.065E-21		5.000	1.219E04	8.677	4.754E-21
	6.000	1.058E04	9.683	8.458E-21		6.000	1.463E04	9.694	4.426E-21
	7.000	1.234E04	10.52	7.873E-21		7.000	1.707E04	10.50	4.110E-21
	8.000	1.410E04	11.02	7.222E-21		8.000	1.951E04	11.05	3.785E-21
	9.000	1.586E04	11.60	6.752E-21		9.000	2.195E04	11.64	3.542E-21
	10.00	1.763E04	12.09	6.336E-21		10.00	2.438E04	12.14	3.324E-21
	11.00	1.939E04	12.51	5.959E-21		11.00	2.682E04	12.56	3.129E-21
	12.00	2.115E04	12.89	5.628E-21		12.00	2.926E04	12.94	2.955E-21
	13.00	2.291E04	13.14	5.297E-21		13.00	3.170E04	13.11	2.763E-21
	14.00	2.468E04	13.42	5.023E-21		14.00	3.414E04	13.38	2.617E-21
	15.00	2.644E04	13.65	4.770E-21		15.00	3.658E04	13.60	2.484E-21
13	1.010	2.107E03	0.049	1.805E-22	16	1.010	3.258E03	0.050	7.682E-23
	1.125	2.347E03	0.574	1.908E-21		1.125	3.629E03	0.585	8.124E-22
	1.250	2.608E03	1.088	3.255E-21		1.250	4.032E03	1.106	1.384E-21
	1.500	3.129E03	1.994	4.970E-21		1.500	4.839E03	2.023	2.109E-21
	1.750	3.651E03	2.784	5.948E-21		1.750	5.645E03	2.820	2.520E-21
	2.000	4.172E03	3.495	6.533E-21		2.000	6.452E03	3.535	2.763E-21
	2.250	4.694E03	4.149	6.894E-21		2.250	7.258E03	4.190	2.912E-21
	2.500	5.216E03	4.740	7.088E-21		2.500	8.065E03	4.782	2.990E-21
	2.750	5.737E03	5.276	7.173E-21		2.750	8.871E03	5.320	3.025E-21
	3.000	6.259E03	5.763	7.182E-21		3.000	9.678E03	5.805	3.026E-21
	3.250	6.780E03	6.216	7.150E-21		3.250	1.048E04	6.251	3.007E-21
	3.500	7.302E03	6.642	7.095E-21		3.500	1.129E04	6.677	2.983E-21
	3.750	7.823E03	7.040	7.018E-21		3.750	1.210E04	7.074	2.950E-21
	4.000	8.345E03	7.410	6.925E-21		4.000	1.290E04	7.443	2.909E-21
	4.500	9.388E03	8.079	6.712E-21		4.500	1.452E04	8.112	2.819E-21
	5.000	1.043E04	8.669	6.482E-21		5.000	1.613E04	8.705	2.722E-21
	6.000	1.252E04	9.668	6.024E-21		6.000	1.936E04	9.712	2.531E-21
	7.000	1.460E04	10.46	5.588E-21		7.000	2.258E04	10.51	2.348E-21
	8.000	1.669E04	11.04	5.157E-21		8.000	2.581E04	11.06	2.161E-21
	9.000	1.878E04	11.61	4.823E-21		9.000	2.903E04	11.62	2.019E-21
	10.00	2.086E04	12.10	4.525E-21		10.00	3.226E04	12.11	1.893E-21
	11.00	2.295E04	12.53	4.258E-21		11.00	3.549E04	12.52	1.780E-21
	12.00	2.503E04	12.90	4.020E-21		12.00	3.871E04	12.89	1.680E-21
	13.00	2.712E04	13.10	3.768E-21		13.00	4.194E04	13.17	1.584E-21
	14.00	2.921E04	13.36	3.569E-21		14.00	4.516E04	13.44	1.501E-21
	15.00	3.129E04	13.59	3.387E-21		15.00	4.839E04	13.67	1.425E-21

TABLE III. Ionization Cross Sections for He-like Ions

See page 96 for Explanation of Tables

Z	u	E(eV)	uI^2Q	Q(cm^2)	Z	u	E(eV)	uI^2Q	Q(cm^2)
17	1.010	3.698E03	0.050	5.974E-23	29	1.010	1.119E04	0.051	6.688E-24
	1.125	4.119E03	0.588	6.343E-22		1.125	1.247E04	0.605	7.117E-23
	1.250	4.576E03	1.111	1.079E-21		1.250	1.386E04	1.142	1.209E-22
	1.500	5.492E03	2.029	1.642E-21		1.500	1.663E04	2.079	1.836E-22
	1.750	6.407E03	2.836	1.968E-21		1.750	1.940E04	2.897	2.192E-22
	2.000	7.322E03	3.551	2.156E-21		2.000	2.217E04	3.617	2.395E-22
	2.250	8.238E03	4.191	2.262E-21		2.250	2.494E04	4.263	2.509E-22
	2.500	9.153E03	4.780	2.322E-21		2.500	2.771E04	4.858	2.573E-22
	2.750	1.007E04	5.323	2.350E-21		2.750	3.048E04	5.403	2.602E-22
	3.000	1.098E04	5.812	2.353E-21		3.000	3.325E04	5.890	2.600E-22
	3.250	1.190E04	6.259	2.339E-21		3.250	3.602E04	6.337	2.582E-22
	3.500	1.281E04	6.684	2.319E-21		3.500	3.879E04	6.762	2.559E-22
	3.750	1.373E04	7.079	2.292E-21		3.750	4.157E04	7.159	2.528E-22
	4.000	1.464E04	7.448	2.261E-21		4.000	4.434E04	7.528	2.492E-22
	4.500	1.648E04	8.119	2.191E-21		4.500	4.988E04	8.199	2.413E-22
	5.000	1.831E04	8.712	2.116E-21		5.000	5.542E04	8.809	2.333E-22
	6.000	2.197E04	9.723	1.968E-21		6.000	6.650E04	9.809	2.165E-22
	7.000	2.563E04	10.53	1.826E-21		7.000	7.759E04	10.62	2.009E-22
	8.000	2.929E04	11.08	1.681E-21		8.000	8.867E04	11.17	1.849E-22
	9.000	3.295E04	11.65	1.573E-21		9.000	9.976E04	11.75	1.729E-22
	10.00	3.661E04	12.15	1.476E-21		10.00	1.108E05	12.26	1.623E-22
	11.00	4.027E04	12.57	1.388E-21		11.00	1.219E05	12.69	1.528E-22
	12.00	4.393E04	12.95	1.311E-21		12.00	1.330E05	13.11	1.447E-22
	13.00	4.759E04	13.13	1.226E-21		13.00	1.441E05	13.20	1.345E-22
	14.00	5.126E04	13.39	1.161E-21		14.00	1.552E05	13.46	1.273E-22
	15.00	5.492E04	13.61	1.101E-21		15.00	1.663E05	13.68	1.208E-22
26	1.010	8.931E03	0.051	1.046E-23					
	1.125	9.948E03	0.602	1.113E-22					
	1.250	1.105E04	1.137	1.892E-22					
	1.500	1.326E04	2.071	2.874E-22					
	1.750	1.547E04	2.885	3.431E-22					
	2.000	1.769E04	3.602	3.748E-22					
	2.250	1.990E04	4.250	3.931E-22					
	2.500	2.211E04	4.845	4.033E-22					
	2.750	2.432E04	5.390	4.079E-22					
	3.000	2.653E04	5.874	4.075E-22					
	3.250	2.874E04	6.324	4.049E-22					
	3.500	3.095E04	6.748	4.012E-22					
	3.750	3.316E04	7.145	3.965E-22					
	4.000	3.537E04	7.513	3.909E-22					
	4.500	3.979E04	8.184	3.785E-22					
	5.000	4.421E04	8.775	3.652E-22					
	6.000	5.306E04	9.786	3.394E-22					
	7.000	6.190E04	10.59	3.149E-22					
	8.000	7.074E04	11.12	2.894E-22					
	9.000	7.958E04	11.68	2.702E-22					
	10.00	8.843E04	12.17	2.532E-22					
	11.00	9.727E04	12.58	2.379E-22					
	12.00	1.061E05	12.94	2.243E-22					
	13.00	1.150E05	13.18	2.109E-22					
	14.00	1.238E05	13.43	1.997E-22					
	15.00	1.326E05	13.65	1.894E-22					

TABLE IV. Fit Parameters for Individual H-like Ions

See page 96 for Explanation of Tables

Z	A	B	C	D	$F(\%)$
2	16.43	-6.417	-0.1220	-14.38	0.38
6	13.79	-5.146	0.1916	-11.55	0.35
8	12.64	-4.642	0.3651	-10.53	0.56
9	12.77	-4.675	0.3325	-10.60	0.49
12	12.82	-4.698	0.3246	-10.58	0.44
13	12.65	-4.605	0.3456	-10.43	0.49
14	12.61	-4.566	0.3371	-10.37	0.48
16	12.61	-4.622	0.3642	-10.38	0.50
17	12.65	-4.656	0.3688	-10.49	0.44
26	12.34	-4.515	0.4208	-10.13	0.56
29	12.27	-4.496	0.4463	-10.07	0.63

TABLE V. Fit Parameters for Individual He-like Ions

See page 96 for Explanation of Tables

Z	A	B	C	D	$F(\%)$
3	29.20	-12.56	0.9088	-27.06	0.60
6	28.11	-11.10	0.5525	-24.28	0.37
8	26.37	-10.14	0.7307	-22.46	0.46
9	25.37	-9.711	0.8921	-21.54	0.46
12	25.91	-9.772	0.7218	-21.74	0.45
13	25.87	-9.697	0.6999	-21.62	0.40
14	25.91	-9.754	0.7134	-21.64	0.50
16	25.94	-9.711	0.6871	-21.59	0.38
17	25.84	-9.648	0.6932	-21.48	0.52
26	25.62	-9.426	0.6845	-21.13	0.51
29	25.75	-9.565	0.7196	-21.27	0.63

TABLE VI. Fit Parameters for the H and He Isoelectronic Sequences

See page 96 for Explanation of Tables

$a(u)$	A_1	B_1	C_1	D_1
H-like	11.93	-4.295	0.4516	-9.700
He-like	24.08	-8.728	0.8835	-19.65
$b(u)$	A_2	B_2	C_2	D_2
H-like	5.819	-2.553	-0.8306	-6.567
He-like	17.81	-10.80	-1.239	-21.07