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EFFECTS OF METASTABLE ATOMS ON VOLUME ION PRODUCTION IN A TENUOUS HELIUM PLASMA

by Ronald J. Sovie and John V. Dugan, Jr.

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ERRATA

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Because of an error in the integration subroutine used in calculating the Maxwell averaged ionization cross sections, some incorrect results were presented in NASA TN D-3121. The corrected curves and tables are presented herein.

Including the electron - metastable-atom interactions in the volume ion production calculation does not cause an increase in this cost for electron temperatures above 20 electron volts, as was concluded in the report. The qualitative conclusion that the cost is not appreciably reduced by including these interactions in the volume ion production cost calculations is still valid, however.

The following corrections should be made to the report:

Page 1, paragraph 2: The second and third sentences should be replaced with The ion production cost was reduced by about 25 percent at an electron kinetic temperature of 6 electron volts and by 14 percent at 20 electron volts. For electron kinetic temperatures above 20 electron volts the cost is reduced by about 10 percent.

Page 7: Equation (20) should read

$$g_Q = \frac{U_i}{E_2}\left(\frac{E_2}{E_2 + U_i}\right)^{3/2}\left[\frac{U}{U_i} + \frac{2}{3}\left(1 - \frac{U}{2E_2}\right)\ln\left(2.7 + \sqrt{\frac{E_2 - U}{U_i}}\right)\right]\left(1 - \frac{U}{E_2}\right)^{\frac{2U_i+U}{U_i+U}}$$

Page 10, paragraph 1: The fourth sentence should be deleted.

Pages 10 and 26: Tables I and IV should be replaced by the corrected tables attached.

Pages 11 and 12: Figures 1, 2, 3, and 4 should be replaced by the corrected figures attached.

Page 13, paragraph 1 under CONCLUDING REMARKS: The second sentence should be deleted.

Page 19: Equation (B1b) should read

$$\left\langle Q_{2^3S}^{2^1S}(V_e)V_e \right\rangle + \sum_{n=2}^{8} \left\langle Q_{2^3S}^{n^1P}(V_e)V_e \right\rangle A_{n^1P}^{2^1S} + \sum_{n=3}^{8} \left\langle Q_{2^3S}^{n^1S}(V_e)V_e \right\rangle C_{n^1S}^{2^1S}$$

$$+ \sum_{n=3}^{8} \left\langle Q_{2^3S}^{n^1D}(V_e)V_e \right\rangle C_{n^1D}^{2^1S} = \beta(kT_e)$$

Page 21: Equation (B7) should read

$$N_{2^1S} = \frac{N_o\left[\alpha(kT_e) + \delta(kT_e)\beta(kT_e)\right]}{\sum_i \left\langle Q_{2^1S}^{i}(V_e)V_e \right\rangle - \left[\beta(kT_e)\xi(kT_e) + \gamma(kT_e)\right]} = B(kT_e)N_o \qquad cm^{-3}$$

Page 21: Equation (B8) should read

$$N_{2^3S} = N_o\left[\delta(kT_e) + \xi(kT_e)B(kT_e)\right] = D(kT_e)N_o \qquad cm^{-3}$$

TABLE I. - VOLUME ION PRODUCTION RESULTS

Electron kinetic temperature, eV	Ion production cost for ground state, φ_{gs}, eV/ion	Ion production cost for 2^1S state, φ_{2^1S}, eV/ion	Ion production cost for 2^3S state, φ_{2^3S}, eV/ion	Volume ion production cost including electron - metastable-atom interactions, φ, eV/ion	Ion production rate parameter, $\mathring{N}_{ion}/N_oN_e$, $\frac{(ions)(cm^3)}{sec}$	Power consumption rate parameter w', (W)(cm^3)	Ion production cost considering ground-state - metastable-atom collisions for a neutral temperature of 1 eV and 1 percent ionization, eV/ion	Ratio of steady-state 2^1S density to ground-state density, $B(kT_e)$	Ratio of steady-state 2^3S density to ground-state density, $D(kT_e)$
6	77.8	46.8	39.0	57.8	2.8×10^{-10}	2.6×10^{-27}	68.0	5.4×10^{-6}	2.3×10^{-3}
8	68.8	40.1	32.1	51.6	8.1	6.7	59.4	12.3	4.5
12	59.7	33.4	28.3	47.9	23.3	17.9	53.1	29.5	7.8
16	55.1	29.4	25.5	45.9	40.4	29.7	49.9	47.8	9.6
20	52.1	26.3	23.4	44.6	56.7	40.6	47.9	66.3	10.5
24	50.0	23.9	21.8	43.7	71.9	50.4	46.5	84.7	10.9
28	48.5	21.9	20.4	43.1	85.6	59.1	45.3	101.1	11.0
32	47.4	20.3	19.2	42.6	97.8	66.7	44.8	118.9	10.9
36	46.4	18.9	18.1	42.0	109.3	73.4	43.9	140.6	10.8
40	45.7	17.7	17.1	41.8	119.5	79.9	43.6	159.6	10.6

TABLE VI. - ELECTRON - METASTABLE-ATOM IONIZATION CROSS SECTIONS FOR 2^3S AND 2^1S STATES

(a) Monoenergetic cross sections

Electron energy, eV	$Q^+_{2^1S}$, cm^2	$Q^+_{2^3S}$, cm^2
2.5	----------	----------
5	1.78×10^{-16}	0.11×10^{-16}
7.5	5.99	2.93
10	7.96	4.75
12.5	8.72	5.66
15	8.91	6.06
17.5	8.83	6.18
20	8.61	6.16
22.5	8.33	6.06
25	8.03	5.91
27.5	7.72	5.75
30	7.43	5.76
35	6.87	5.23
40	6.38	4.9
45	5.94	4.6
50	5.56	4.32
55	5.22	4.08
60	4.92	3.86
70	4.42	3.49
80	4.0	3.18
90	3.67	2.92
100	3.38	2.70

(b) Maxwell average cross sections

Electron kinetic temperature, eV	$\langle Q^+_{2^1S}(V_e)V_e \rangle$, cm^3/sec	$\langle Q^+_{2^3S}(V_e)V_e \rangle$, cm^3/sec
2	1.53×10^{-8}	0.71×10^{-8}
4	6.00	3.50
6	9.78	6.21
8	12.55	8.34
10	14.57	9.97
12	16.06	11.22
14	17.17	12.20
16	18.02	12.96
18	18.67	13.56
20	19.16	14.04
24	19.84	14.74
30	20.37	15.34
34	20.52	15.57
40	20.58	15.75
44	20.55	15.80
50	20.43	15.80
60	20.13	15.68
70	19.78	15.49
80	19.40	15.27
90	19.03	15.03
100	18.67	14.79

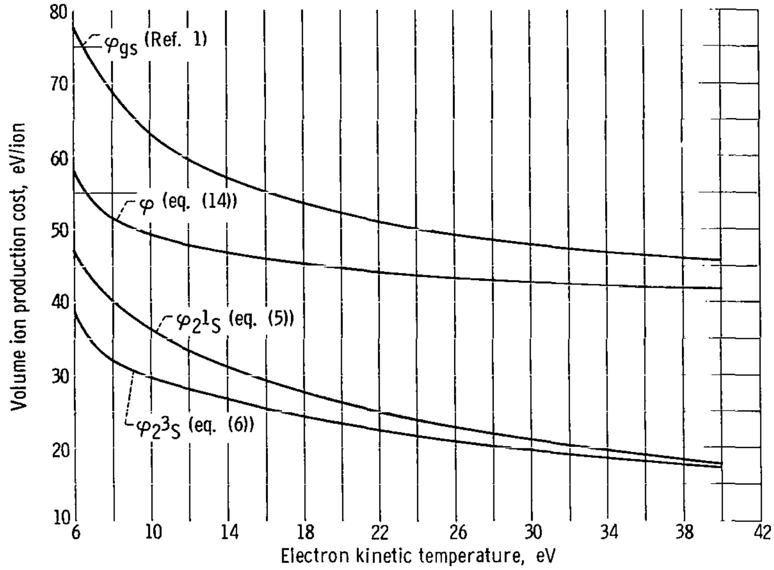

Figure 1. - Volume ion production cost as function of electron kinetic temperature.

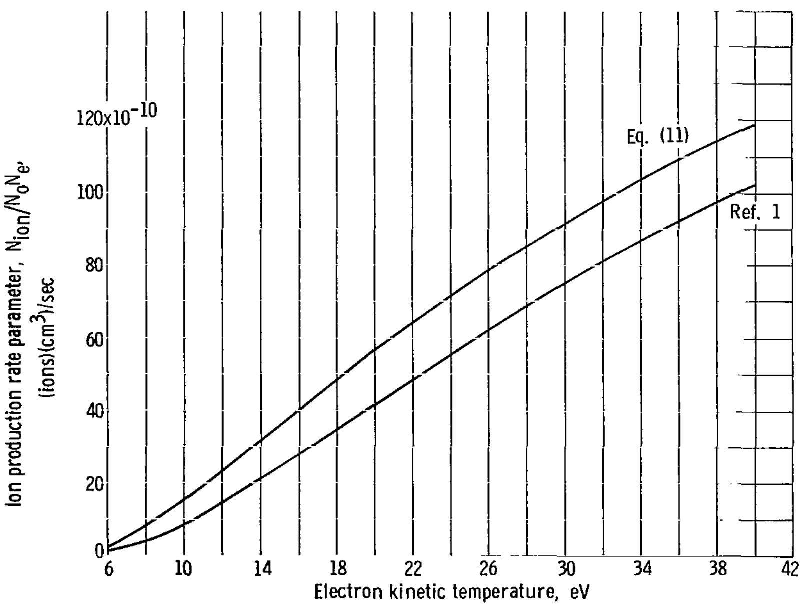

Figure 2. - Ion production rate parameter as function of electron kinetic temperature.

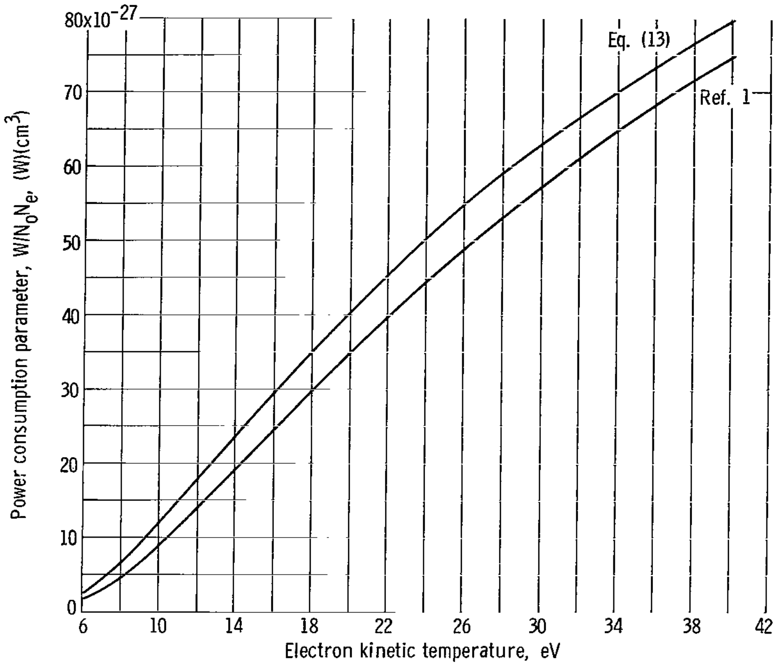

Figure 3. - Power consumption parameter as function of electron kinetic temperature.

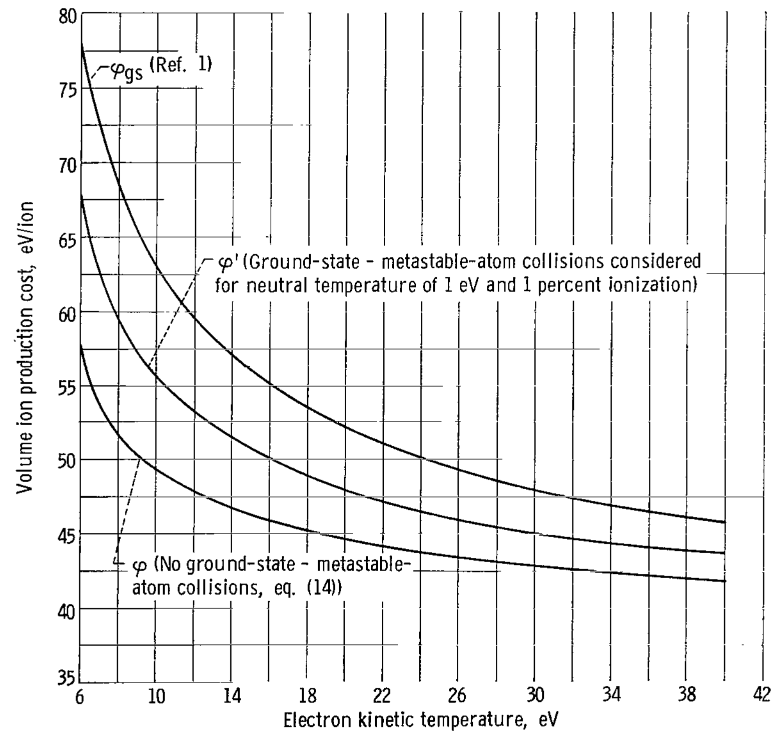

Figure 4. - Effect of ground-state - metastable-atom collisions on volume ion production cost.

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SUMMARY

The semiclassical Gryzinski method was used to theoretically calculate the excitation and ionization cross sections for interactions between electrons and the metastable 2^1S and 2^3S states of helium. These cross sections were used to calculate the effect of electron-metastable atom interactions on volume ion production processes in a steady-state tenuous helium plasma. The effects of neutral-metastable atom collisions were also considered. Experimentally obtained excitation functions were used for ground-state excitations and a Maxwellian distribution of free electron energies was assumed.

Including the metastable atom interactions in the calculated volume ion production cost (defined as the net energy required for each ion produced) yielded a surprisingly small effect. Instead of the anticipated substantial reduction, the ion production cost was reduced by only about 12 percent at an electron kinetic temperature of 6 electron volts. Reductions in cost were obtained for electron kinetic temperatures up to 20 electron volts, and slight increases for higher temperatures. The unexpectedly high ion production costs occurred because the cross sections for the allowed excitations $2^1S \rightarrow 2^1P$, $2^3S \rightarrow 2^3P$ are very much greater than the ionization cross sections for the metastable states.

The volume ion production cost, ion production rate and power consumed in ion production are presented as functions of electron kinetic temperature. The electron-metastable atom inelastic cross sections are also given as functions of electron energy.

INTRODUCTION

In plasma production and heating devices, it is advantageous to know the net energy cost for each ion produced, the ion production rate, and the product of these terms which is the net power consumed in ion production. These quantities are needed to perform calculations on power balance and species continuity. Sovie and Klein (ref. 1) have calculated these quantities for the case of a tenuous, optically thin helium plasma in which a Maxwellian distribution of free electron energies prevails. The effects of electron-metastable atom interactions were not considered in this earlier report since the analysis was made for the case where the metastable atoms were assumed to have very short lifetimes due to neutral collisions and wall effects.

The metastable states could be important in an analysis of the type just mentioned since the cross sections for exciting these states are large and the population of the 2^3S state is considerably enhanced by cascading effects from the various triplet series in helium. A lower limit to the ion production cost was calculated using the data from reference 1 with the assumption that all the metastable states produced were ionized. In this approximation the ion production cost was reduced by as much as a factor of 2.4.

Experimental metastable excitation cross sections are not presently available. However, good agreement is obtained between the theoretical cross sections calculated by using the semiclassical Gryzinski method (ref. 2) and the available experimental cross-section data. Indeed, Sovie and Dugan (ref. 3) have obtained excellent agreement (within 8 percent) with the results of reference 1 by using these theoretical cross sections to calculate the volume ion production cost for the ground-state atom. Therefore, it is expected that a good approximation of the electron-metastable atom cross sections may be obtained by using this technique.

In this study the cross sections for excitation and ionization of the metastable 2^1S and 2^3S states of helium are calculated using the semiclassical Gryzinski method. These cross sections are then used to determine the effects of electron-metastable atom interactions on the volume ion production calculations presented in reference 1. Results are obtained for the case where the metastable lifetimes are controlled by electron-metastable atom and neutral-metastable atom collisions.

THEORY

Assumptions and Limitations

The ion production cost is calculated by assuming that the only important losses of free electron energy occur by inelastic collisions, that is, by excitation and ionization of bound electrons. In the range of electron temperatures of interest (6 to 40 eV) the energy loss in elastic collisions is clearly negligible since the average energy loss per encounter is very small. Furthermore, all electron-atom collisions are assumed to occur with either ground-state or metastable atoms. The results presented are applicable to low-pressure, optically thin, partially ionized, so-called tenuous plasmas (ref. 4) for which cumulative inelastic impacts are improbable for excited states other than metastable states due to the short lifetimes of these excited states. According to Wilson (ref. 4) a plasma is tenuous if the criterion $N_e \leq 1.5\times10^{10} X_i^{-1/2}(kT_e)^4$ is satisfied (where X_i is the ionization energy and kT_e is the electron kinetic temperature).

The processes by which charged particles recombine may be considered separately in the ultimate power balance calculations. For low-pressure discharges recombination occurs primarily at the walls, and for wall recombination or radiative recombination the energy is considered as being lost from the plasma. Although there may be an energy feedback to the electrons in three-body recombination, this process is not the dominant one for the number densities and electron temperatures considered in this treatment (ref. 5). Inelastic electron-ion interactions are not considered in this study since it was shown in reference 1 that these interactions were not important even for fairly highly ionized plasmas having electron temperatures below about 40 electron volts.

Development of Equations

The theory for the ion production cost calculations is developed in the same manner as was presented in reference 1. The number of j^{th} excited states produced per unit volume per second by inelastic collisions between a monoenergetic beam of electrons with velocity V_e and ground-state atoms is

$$\dot{N}_j = N_o N_e Q_{gs}^j(V_e)V_e \qquad (cm^{-3})(sec^{-1}) \tag{1}$$

where the cross sections employed are expressed as functions of electron velocity V_e. (All symbols are defined in appendix A.) The usual nomenclature used to describe the excitation cross section will be modified slightly in this treatment in order to minimize confusion. The cross section for electron excitation from a state A to a state B will be represented by the symbol Q_A^B. The subscript will denote the initial state of the atom and the superscript the final state of the atom $\left(\text{e.g., the cross section for exciting the } 2^1P \text{ state from the } 2^1S \text{ metastable state is written as } Q_{2^1S}^{2^1P}\right)$. The symbols n and L used in describing certain excitation processes denote the principal quantum number and the total angular momentum of the atom. If there is a distribution of free electron energies, equation (1) becomes

$$\dot{N}_j = N_o N_e \left\langle Q_{gs}^j(V_e)V_e \right\rangle \qquad (cm^{-3})(sec^{-1}) \tag{2}$$

where the brackets indicate an average value over the distribution function. The total energy expended in inelastic ground-state excitation processes including ionization per unit volume per second is, therefore

$$\dot{E}_{j,\,TOT} = \sum_j \dot{N}_j E_j = N_o N_e \sum_j \left\langle Q^j_{gs}(V_e)V_e \right\rangle E_j \qquad eV/(cm^3)(sec) \qquad (3)$$

The net energy cost for producing singly ionized atoms by electron collisions with ground-state atoms (i. e., the volume ion production cost) is, therefore

$$\varphi_{gs} = \frac{\sum_j \left\langle Q^j_{gs}(V_e)V_e \right\rangle E_j}{\left\langle Q^+(V_e)V_e \right\rangle} \qquad eV/ion \qquad (4)$$

Similarly the volume ion production costs for producing ions from the 2^1S and 2^3S metastable states are given by

$$\varphi_{2^1S} = \frac{\sum_i \left\langle Q^i_{2^1S}(V_e)V_e \right\rangle E_i}{\left\langle Q^+_{2^1S}(V_e)V_e \right\rangle} \qquad eV/ion \qquad (5)$$

and

$$\varphi_{2^3S} = \frac{\sum_k \left\langle Q^k_{2^3S}(V_e)V_e \right\rangle E_k}{\left\langle Q^+_{2^3S}(V_e)V_e \right\rangle} \qquad eV/ion \qquad (6)$$

The i summation is over all inelastic collision processes between electrons and the 2^1S state, the k summation is over all inelastic electron -2^3S state interactions.

The steady-state ion production rate is given by

$$\dot{N}_{ion} = N_o N_e \left\langle Q^+_{gs}(V_e)V_e \right\rangle + N_{2^1S} N_e \left\langle Q^+_{2^1S}(V_e)V_e \right\rangle + N_{2^3S} N_e \left\langle Q^+_{2^3S}(V_e)V_e \right\rangle \qquad (cm^{-3})(sec^{-1}) \tag{10}$$

where N_o, N_{2^1S}, and N_{2^3S} represent the steady-state number densities of the ground state, 2^1S state, and 2^3S state, respectively. The expression for the steady-state number densities of the 2^1S and 2^3S state are derived in appendix B by considering all excitation and de-excitation processes for these states. These steady-state densities may be represented as

$$N_{2^1S} = B(kT_e)N_o \qquad cm^{-3}$$

and

$$N_{2^3S} = D(kT_e)N_o \qquad cm^{-3}$$

where $B(kT_e)$ and $D(kT_e)$ represent the ratios of the steady-state metastable densities to the ground-state densities and are given by equations (B7) and (B8).

The ion production rate is, therefore,

$$\dot{N}_{ion} = N_o N_e \left[\left\langle Q^+_{gs}(V_e)V_e \right\rangle + B(kT_e) \left\langle Q^+_{2^1S}(V_e)V_e \right\rangle + D(kT_e) \left\langle Q^+_{2^3S}(V_e)V_e \right\rangle \right] \qquad (cm^{-3})(sec^{-1}) \tag{11}$$

The power consumed in ion production is simply the sum of the products of the ion production rate and ion production cost for the ground-state and the 2^1S and 2^3S metastable states. The power consumed in ion production is, therefore,

$$W = N_o N_e \left[\left\langle Q^+_{gs}(V_e)V_e \right\rangle \varphi_{gs} + B(kT_e) \left\langle Q^+_{2^1S}(V_e)V_e \right\rangle \varphi_{2^1S} + D(kT_e) \left\langle Q^+_{2^3S}(V_e)V_e \right\rangle \varphi_{2^3S} \right] \qquad eV/(cm^3)(sec) \tag{12}$$

The power converted to watts per cubic centimeter is

$$w' = 1.602\times10^{-19} W \qquad W/cm^3 \tag{13}$$

The volume ion production cost for the helium atom including electron metastable atom interactions is $W/\dot{N}_{ion}$ and from equations (11) and (12) one has

$$\varphi = \frac{\left\langle Q^+_{gs}(V_e)V_e\right\rangle \varphi_{gs} + B(kT_e)\left\langle Q^+_{2^1S}(V_e)V_e\right\rangle \varphi_{2^1S} + D(kT_e)\left\langle Q^+_{2^3S}(V_e)V_e\right\rangle \varphi_{2^3S}}{\left\langle Q^+_{gs}(V_e)V_e\right\rangle + B(kT_e)\left\langle Q^+_{2^1S}(V_e)V_e\right\rangle + D(kT_e)\left\langle Q^+_{2^3S}(V_e)V_e\right\rangle} \quad \text{eV/ion} \tag{14}$$

The above equations have been derived by neglecting the effects of ground-state-metastable atom collisions. In laboratory plasmas these ground-state-metastable atom collisions could be a mechanism for destroying metastable populations. These collisions will have a larger effect on the 2^3S state population since this population is enhanced by the cascading effects mentioned. In this treatment the effect of these ground-state-metastable atom collisions is approximated by assuming that these collisions will induce radiation from the metastable state (ref. 6) (i.e., there is no energy feedback to the free electron gas). The collision coefficient for ground-state-metastable atom collisions is obtained by looking at the atoms as hard spheres of radius σ and assuming a Maxwellian distribution of neutral and metastable velocities and equal ground-state and metastable temperatures. The collision coefficient for ground-state-metastable collisions is (ref. 7)

$$\theta' = \sqrt{2\pi}\,\overline{V}_n\sigma^2 = 1.54\times10^{-9}(kT_n)^{1/2} \qquad \text{cm}^3/\text{sec} \tag{15}$$

where kT_n is the kinetic temperature of ground-state and metastable atoms.

The collision rate for destroying the 2^3S state by ground-state collisions may be written as

$$\nu_{2^3S} = N_{2^3S} N_e \frac{\theta'}{f_i} \tag{16}$$

where f_i is the fraction ionized for the plasma.

The collision rate for destroying the 2^1S state may be written as

$$\nu_{2^1S} = N_{2^1S} N_e \frac{\theta'}{f_i} \tag{17}$$

The effect of ground-state-metastable atom collisions on the volume ion production cost is calculated by including the ν terms from equations (16) and (17) into the right-hand sides of equations (B1) and (B3), respectively, yielding the quantities $B'(kT_e)$ and

$D'(kT_e)$. The expression for the volume ion production cost including neutral-metastable atom collisions is, therefore

$$\varphi = \frac{\left\langle Q^{+}_{gs}(V_e)V_e\right\rangle \varphi_{gs} + B'\left(kT_e, \frac{\theta'}{f_i}\right)\left\langle Q^{+}_{2^1S}(V_e)V_e\right\rangle \varphi_{2^1S} + D'\left(kT_e, \frac{\theta'}{f_i}\right)\left\langle Q^{+}_{2^3S}(V_e)V_e\right\rangle \varphi_{2^3S}}{\left\langle Q^{+}_{gs}(V_e)V_e\right\rangle + B'\left(kT_e, \frac{\theta'}{f_i}\right)\left\langle Q^{+}_{2^1S}(V_e)V_e\right\rangle + D'\left(kT_e, \frac{\theta'}{f_i}\right)\left\langle Q^{+}_{2^3S}(V_e)V_e\right\rangle} \quad \text{eV/ion} \tag{18}$$

where the θ'/f_i values used depend upon the neutral temperature and percentage ionization in the plasma.

Cross Sections

The cross sections used for ground-state excitations were those previously employed in reference 1, where the results of a number of individual investigations of helium excitation cross sections were combined to yield a credible, self-consistent set of helium excitation functions. These excitation functions were represented by empirical equations describing the cross sections as functions of electron velocity, multiplied by the electron velocity and averaged over a Maxwellian distribution of free electron velocities to obtain the $\langle Q^j(V_e)V_e\rangle$ quantities mentioned in the previous section.

The electron-metastable atom cross sections were calculated by using the semiclassical Gryzinski method (ref. 2). Discussions of the theory and application of this method are presented in references 2, 3, 8, 9, and 10.

According to the Gryzinski formulation, the cross sections for an inelastic electron-atom collision with an energy loss equal to or greater than a value U is given by

$$Q(U) = \frac{M\sigma_o}{U^2}\, g_Q\left(\frac{U_i}{U}, \frac{E_2}{U}\right) \qquad \text{cm}^2 \tag{19}$$

where

$$g_Q = \frac{U_i}{E_2}\left(\frac{E_2}{E_2 + U_i}\right)^{3/2}\left[\frac{U}{U_i} + \frac{2}{3}\left(1 - \frac{U}{2E_2}\right)\ln\left(2.7 + \frac{\sqrt{E_2 - U}}{U_i}\right)\right]\left(1 - \frac{U}{E_2}\right)^{\frac{2U_i+U}{U_i+U}} \tag{20}$$

U_i is the kinetic energy of the bound electron and E_2 is the energy of the incident electron. The symbol M denotes the number of equivalent electrons in the outer shell of the target atoms and serves as an effective probability factor that accounts for the number of bound electrons available for collision. For the electron-metastable atom cross sections calculated in this treatment, U_i is equal to the ionization potential of the metastable state and $M = 1$. In the special case of ionization where $U = U_i$ equation (15) becomes

$$Q^{+}_{MS}(U_i) = \frac{\sigma_o}{U_i^2}\,\frac{1}{X}\left(\frac{X-1}{X+1}\right)^{3/2}\left[1 + \frac{2}{3}\left(1 - \frac{1}{2X}\right)\ln\left(2.7 + \sqrt{X-1}\right)\right] \qquad \text{cm}^2 \tag{21}$$

where $X = E_2/U_i$.

In the calculation of the excitation cross sections for discrete states the arrangement of the energy levels in the atom must be considered. The cross section for excitation from a metastable state to a higher excited state is defined as the cross section for an energy loss restricted to the range U_n to U_{n+1}. The symbol U_n represents the energy difference between the state to be excited and the metastable state and U_{n+1} represents the energy difference between the metastable state and the next higher excited state above U_n.

Using the formulation of equation (19), the expression for the excitation cross section of a level at energy U_n above the metastable state is simply

$$Q_{exc}(U_n) = Q(U_n) - Q(U_{n+1}) \qquad \text{cm}^2 \tag{22}$$

In the special case of electron exchange collisions (i.e., $2^1S \rightarrow 3^3S$, $2^1S \rightarrow 3^3P$, $2^3S \rightarrow 2^1S$, etc.) one must use the Gryzinski exchange cross section

$$Q_{exch}(U_n) = \frac{\sigma_o}{U_n^2}\left(\frac{U_{n+1} - U_n}{U_n}\right) g_{exch} \qquad \text{cm}^2 \tag{23}$$

where

$$g_{exch} = \frac{U_n^2}{(E_2 + U_i)(E_2 + U_i - U_n)}\begin{cases} \dfrac{U_n}{U_i}\,\dfrac{E_2 - U_n}{U_{n+1} - U_n} & \text{if } E_2 < U_{n+1} \\[2ex] \dfrac{U_n}{E_2 + U_i - U_{n+1}} & \text{if } E_2 > U_{n+1} \end{cases} \tag{24}$$

The mean product of the theoretical cross sections and the electron velocity integrated over a Maxwellian free electron velocity distribution at kinetic temperature kT_e is

$$\left\langle Q(V_e)V_e \right\rangle = \frac{8\pi}{C_o} \int_0^{\infty} Q_{exc}(E_2)\exp(-E_2/kT_e)E_2 \, dE_2 \qquad (cm^{-3})(sec^{-1}) \tag{25}$$

where C_o is a normalization factor equal to $(2\pi kT_e)^{3/2}(m_e)^{1/2}$.

Atomic Model for Calculations

It was shown in reference 1 that only the energy levels with principal quantum number up to $n = 8$ need be considered in the calculation of the volume ion production cost for the ground state. In the electron-metastable atom interactions the cross sections were calculated for discrete states up to $n = 6$. In the region of highly excited states $(n > 6)$, the energy differences between excited states are very small, and the total cross section for these states can be very well approximated as that for one equivalent level (ref. 3). In this case U_n would be the energy difference between the metastable state and the $n = 7$ level and U_{n+1} would be the ionization energy of the metastable state. The energy loss in this case is taken to be the mean energy between the $n = 7$ level and the ionization limit.

The ionization cross sections for the 2^1S and 2^3S states were calculated using equation (21) with $U_i = 4$ electron volts for the 2^1S state and 4.77 electron volts for the 2^3S state. The cross sections for the allowed excitations $2^1S \rightarrow 2^1P$, $2^3S \rightarrow 2^3P$ were calculated using equation (22) with U_n equal to the excitation energies of the 2^1P and 2^3P states and U_{n+1} the excitation energy of the next higher n^1P and n^3P series members, respectively. When using the exchange cross section equation (23) for levels with nearly identical energies (e.g., 4^3P, 4^3S, and 4^3D states of helium), the cross section is best approximated by considering the levels as one with an energy equal to the mean energy of the three and the next higher level serves as a limit to the cross section. Sheldon and Dugan (ref. 10) have used this procedure and have obtained apparently satisfactory agreement with experiment for cesium. Following Gryzinski the exchange cross sections for the $2^1S \rightarrow n^3P + n^3D + n^3S (n \geq 4)$ excitations and the $2^3S \rightarrow n^1P + n^1D + n^1S$ $(n \geq 3)$ excitations were calculated in this manner using equation (23).

RESULTS AND DISCUSSION

Tables and plots of the excitation functions for the 2^1S and 2^3S metastable states are presented in appendix C. The $B(kT_e)$ and $D(kT_e)$ quantities have been calculated using these excitation functions.

The volume ion production results and the values of $B(kT_e)$ and $D(kT_e)$ are presented in table I and the ion production results are plotted against electron kinetic temperature in figures 1 to 4. As was expected the electron-metastable atom interactions increased the ion production rate (fig. 2), and consequently the power consumption parameter (fig. 3). The surprising result of these calculations is that inclusion of the electron-metastable atom interactions does not appreciably reduce the volume ion production cost (fig. 1). These interactions actually increase this cost for electron kinetic temperatures above 20 electron volts. The calculations of the volume ion production costs for the 2^1S and 2^3S states show that one does not obtain "cheap" ions by ionizing these states. The reasons for these high metastable ion production costs become apparent upon examination of the excitation functions listed in tables II to VI (appendix C). The cross sections for the optically allowed excitations $2^1S \rightarrow 2^1P$ and $2^3S \rightarrow 2^3P$ are very much greater than the ionization cross sections for the 2^1S and 2^3S states. Furthermore, the $2^1S \rightarrow 3^1P$ and $2^3S \rightarrow 3^3P$ excitations are approximately equal to the ionization cross sections. The very large cross sections for these allowed excitations are obtained because the energy losses required to excite these states are small compared to the ionization potentials of the metastable states (e.g., $U_n = 0.6$ eV for $2^1S \rightarrow 2^1P$, $U_i = 4$ eV for 2^1S). This effect is not merely a result of the semiclassical method used to calculate these cross sec-

TABLE I. - VOLUME ION PRODUCTION RESULTS

Electron kinetic temperature, eV	Ion production cost for ground state, φ_{gs}, eV/ion	Ion production cost for 2^1S state, φ_{2^1S}, eV/ion	Ion production cost for 2^3S state, φ_{2^3S}, eV/ion	Volume ion production cost including electron metastable atom interactions, φ, eV/ion	Ion production rate parameter, $\dot{N}_{ion}/N_oN_e$, $\frac{(ions)(cm^3)}{sec}$	Power consumption rate parameter, w', W/cm^3	Ion production cost considering ground-state metastable atom collisions for a neutral temperature of 1 electron volt and an ionization of 1 percent, φ', eV/ion	Ratio of steady-state 2^1S density to ground-state density, $B(kT_e)$	Ratio of steady-state 2^3S density to ground-state density, $D(kT_e)$
6	77.8	55.2	45.7	61.8	2.7×10^{-10}	2.68×10^{-27}	70.7	5.58×10^{-6}	2.69×10^{-3}
8	68.8	54.8	45.2	58.1	7.8	7.29	63.8	12.83	5.94
12	59.7	56.2	47.0	55.2	22.7	20.1	57.9	29.9	12.93
16	55.1	57.2	48.7	53.3	39.6	30.6	54.5	45.6	18.5
20	52.1	58.3	49.9	51.7	55.8	42.2	52.0	58.5	22.3
24	50	59.0	50.7	50.3	71.0	57.3	50.2	69.2	24.8
28	48.5	60.0	52.3	49.4	84.8	67	48.9	76.3	26.6
32	47.4	60.7	52.7	48.5	96.9	75.3	47.9	83	27.6
36	46.4	61.3	53.5	47.5	108.4	82.5	46.7	91.3	28.3
40	45.7	62.1	54.3	47	118.7	89.4	46.2	96.7	28.6

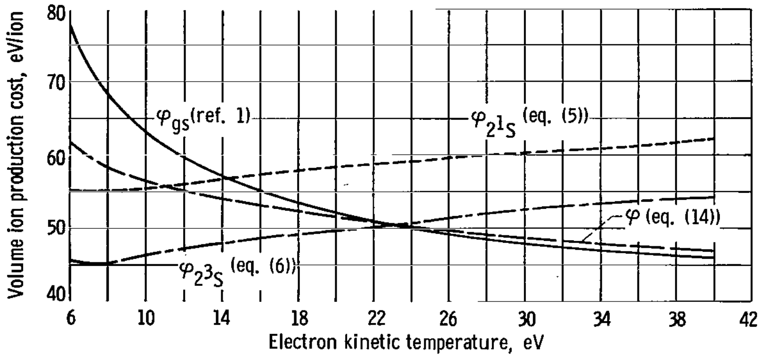


Figure 1. - Volume ion production cost as function of electron kinetic temperature.

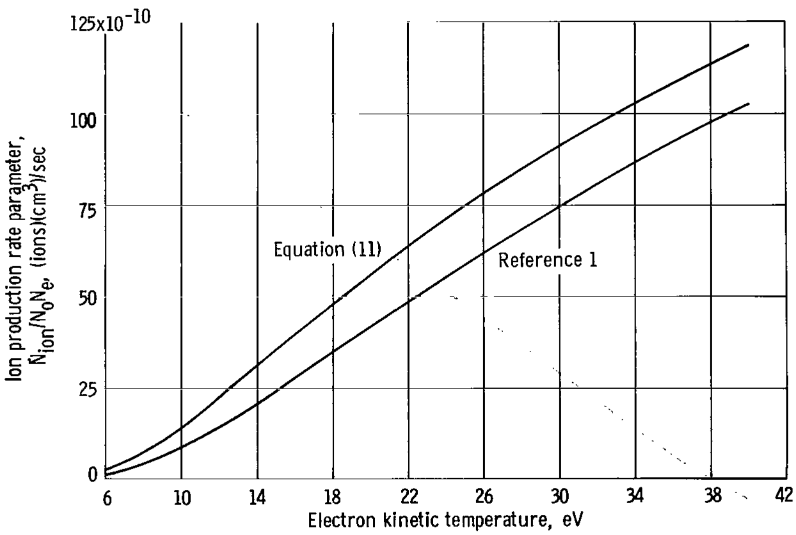


Figure 2. - Ion production rate parameter as function of electron kinetic temperature.

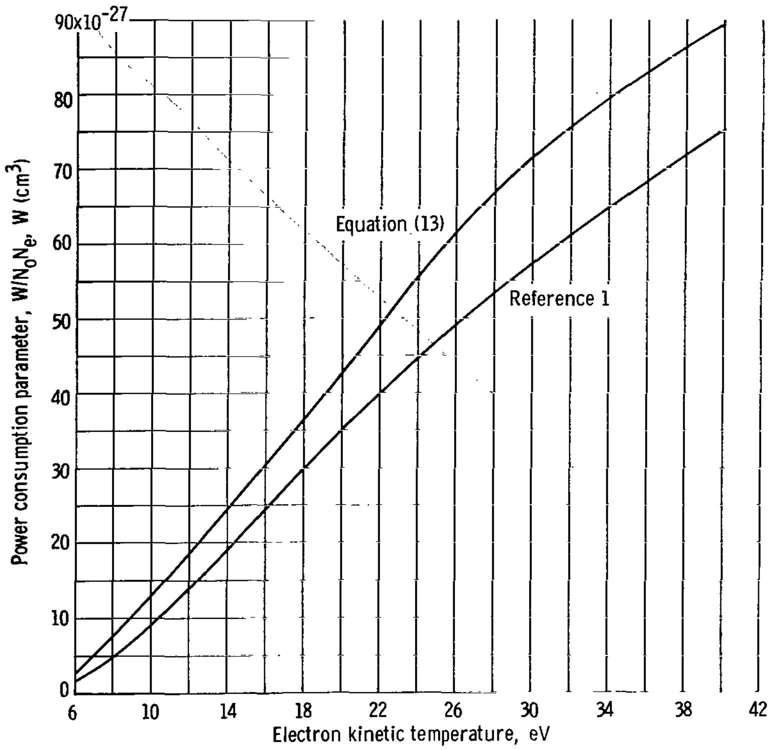


Figure 3. - Power consumption parameter against electron kinetic temperature.

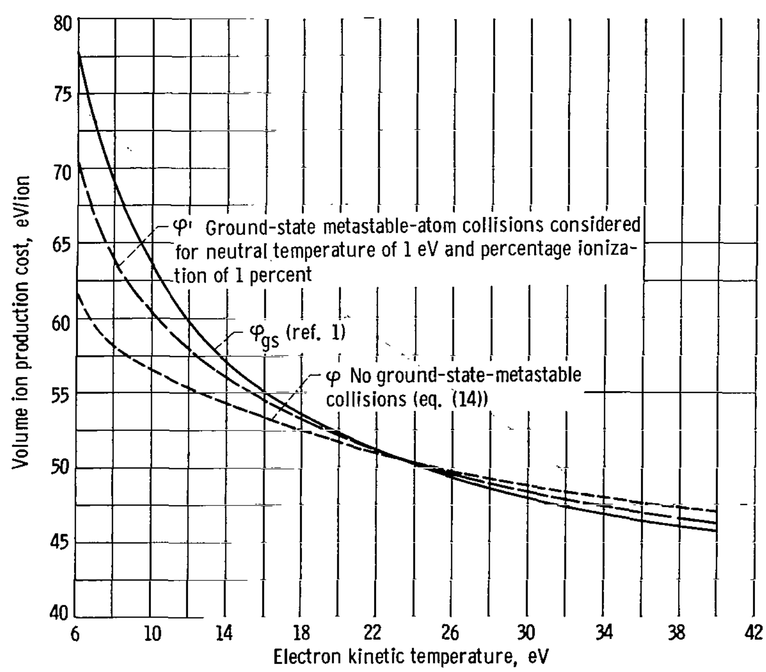


Figure 4. - Effect of ground-state atom-metastable-atom collisions on the volume ion production cost.

tions. The $2^1S - 3^1P$ excitation $\left[U_n = 2.47 \text{ eV}, (U_n/U_i) = 0.6\right]$ is approximately equal to the ionization cross section for the 2^1S state. A calculation, performed by C. F. Monnin of the Lewis Research Center, of the excitation and ionization cross sections for the 2s state in hydrogen using the Born approximation shows that the $2s \rightarrow 3p$ excitation cross section $\left[U_n = 1.9 \text{ eV}, (U_n/U_i) = 0.57\right]$ is also approximately equal to the ionization cross section for the 2s state.

The very large $2^1S \rightarrow 2^1P$, $2^1S \rightarrow 3^1P$ cross sections (appendix C) indicate that the majority of the 2^1S metastable states will be excited to these states and will then cascade to the ground state. The majority of the 2^3S state excitations will be trapped in the helium triplet series since this state acts as a ground state for these series. In this case essentially all of the 2^3S states will eventually be ionized but only after repeated cycles of being excited to higher triplet states and cascading back to the 2^3S state.

The effects of ground-state-metastable atom collisions on the ion production cost calculations are shown in table I for a neutral temperature of 1 electron volt and a 1 percent ionized plasma. This cost per ion is compared in figure 4 with the costs per ion when ground-state-metastable collisions are neglected (eq. (14)) and when neutrals and metastables are neglected (ref. 1). The latter two curves are actually the upper and lower limits to the true ion production cost. If neutral collisions become very important, the ion production cost will approach the results of reference 1 and if they are unimportant, the results will approach those given by equation (14).

CONCLUDING REMARKS

The calculations herein yield the surprising result that the electron-metastable atom interactions do not appreciably reduce the volume ion production cost. This cost was actually increased slightly by these interactions for electron kinetic temperatures above 20 electron volts.

It should be reemphasized that these calculations are valid only for a sufficiently tenuous plasma such that the criteria $N_e \leq 1.5 \times 10^{10} X_i^{-1/2} (kT_e)^4$ is satisfied. Furthermore, if the electron density and temperature are such that the appropriate steady-state ionization equation (corrected Saha or coronal equation) predicts an appreciable degree of ionization, the presented results are valid only if the ionization and excitation are reduced by enhanced recombination and deexcitation effects (e. g., at the walls of a discharge chamber, or by plasma flow or diffusion effects).

The results presented represent only a portion of the power consumption rate or species-production rate in an actual experiment. There are additional terms to account for recombination or wall losses, but these depend strongly on the experimental configurations. There are also additional terms if the plasma is heated, accelerated, or does work.

Lewis Research Center,
National Aeronautics and Space Administration,
Cleveland, Ohio, August 18, 1965.

APPENDIX A

SYMBOLS

A	relative transition probability
$B(kT_e)$	ratio of 2^1S steady-state population to ground-state population defined by eq. (B7)
C	relative transition probability for indirect cascading $\left(\text{e.g.,}\ C_{n^1S}^{2^1S} = \sum_{\bar{n}} A_{n^1S}^{\bar{n}^1P} A_{\bar{n}^1P}^{2^1S}\right)$
C_o	normalization factor, $(2\pi kT_e)^{3/2}(m_e)^{1/2}$, $(eV)^{3/2}(g)^{1/2}$
$D(kT_e)$	ratio of steady-state population of 2^3S state to ground state defined by eq. (B8)
E	energy, eV
E_i	energy difference between the i^{th} excited state and the 2^1S state, eV
$\dot{E}_{j,TOT}$	total energy expended in excitation processes from ground-state atoms, $eV/(cm^3)(sec)$
E_k	energy difference between the k^{th} excited state and the 2^3S state, eV
E_2	energy of incident electrons in Gryzinski formulas, eV
f_i	fraction ionized in the plasma
IL	ionization limit
kT_e	electron kinetic temperature, eV
kT_n	neutral kinetic temperature, eV
M	number of equivalent electrons in outer shell of target atom in Gryzinski formulas
m_e	electron mass, 9.11×10^{-28} g
N_e	electron number density, cm^{-3}
$\dot{N}_{ion}$	volume ion production rate, $(cm^{-3})(sec^{-1})$
$\dot{N}_j$	production rate of excited states from the ground state, $(cm^{-3})(sec^{-1})$
N_o	neutral particle density, cm^{-3}
Q	inelastic cross section, cm^2

Q_{exc}	excitation cross section in Gryzinski formulas, cm^2
Q_{exch}	exchange cross sections in Gryzinski formulas, cm^2
U	energy loss in Gryzinski formulas, eV
U_i	kinetic energy of bound electron, eV
V	velocity, cm/sec
$\overline{V}_n$	Maxwellian averaged neutral velocity, cm/sec
W	power consumed in ion production, $eV/(cm^3)(sec)$
w'	power consumed in ion production, W/cm^3
X	E_2/U_i
X_i	ionization energy of helium atom, 24.58 eV
α	defined by eq. (B1)
β	defined by eq. (B1)
γ	defined by eq. (B1)
δ	defined by eq. (B4)
θ	ground-state-metastable collision frequency, 1/sec
θ'	ground-state-metastable collision coefficient, cm^3/sec
ξ	defined by eq. (B4)
σ	hard sphere radius of helium atom, 2.1×10^{-8} cm
σ_o	constant in Gryzinski calculations, 6.63×10^{-14} $(cm^2)(eV)$
φ	volume ion production cost considering electron-metastable and electron-ground-state interactions
φ'	volume ion production cost considering electron-metastable, electron-ground-state, and ground-state-metastable interactions

Subscripts:

e	electron
gs	ground state
i	dummy index
k	dummy index
2^1S	metastable 2^1S state
2^3S	metastable 2^3S state

n^1S	member of the singlet S series
n^1P	member of the singlet P series
n^1D	member of the singlet D series
MS	metastable state

Superscripts:

2^1S	metastable 2^1S state
2^3S	metastable 2^3S state
n^1S	member of singlet S series
n^1P	member of singlet P series
n^1D	member of singlet D series
n^1L	any member of the singlet system
n^3L	any member of the triplet system
+	ionization
1	singlet state
3	triplet state

APPENDIX B

STEADY-STATE METASTABLE NUMBER DENSITIES

The steady-state number densities for the 2^1S and 2^3S states are obtained from the steady-state population balance equations for these states. In these equations the population mechanisms considered are direct excitation and indirect and direct cascading effects. In this treatment the cascading effects are considered only for principal quantum numbers up to 8. The steady-state equation for the 2^1S state is

$$
\begin{aligned}
& N_o N_e \left\langle Q_{gs}^{2^1S}(V_e)V_e \right\rangle + N_o N_e \sum_{n=2}^{8} \left\langle Q_{gs}^{n^1P}(V_e)V_e \right\rangle A_{n^1P}^{2^1S} + N_o N_e \sum_{n=3}^{8} \left\langle Q_{gs}^{n^1S}(V_e)V_e \right\rangle C_{n^1S}^{2^1S} \\
& + N_o N_e \sum_{n=3}^{8} \left\langle Q_{gs}^{n^1D}(V_e)V_e \right\rangle C_{n^1D}^{2^1S} + N_{2^3S} N_e \left\langle Q_{2^3S}^{2^1S}(V_e)V_e \right\rangle \\
& + N_{2^3S} N_e \sum_{n=3}^{8} \left\langle Q_{2^3S}^{n^1P}(V_e)V_e \right\rangle A_{n^1P}^{2^1S} + N_{2^3S} N_e \sum_{n=3}^{8} \left\langle Q_{2^3S}^{n^1S}(V_e)V_e \right\rangle C_{n^1S}^{2^1S} \\
& + N_{2^3S} N_e \sum_{n=3}^{8} \left\langle Q_{2^3S}^{n^1D}(V_e)V_e \right\rangle C_{n^1D}^{2^1S} + N_{2^1S} N_e \sum_{n=2}^{8} \left\langle Q_{2^1S}^{n^1P}(V_e)V_e \right\rangle A_{n^1P}^{2^1S} \\
& + N_{2^1S} N_e \sum_{n=3}^{8} \left\langle Q_{2^1S}^{n^1S}(V_e)V_e \right\rangle C_{n^1S}^{2^1S} + N_{2^1S} N_e \sum_{n=3}^{8} \left\langle Q_{2^1S}^{n^1D}(V_e)V_e \right\rangle C_{n^1D}^{2^1S} \\
& = N_{2^1S} N_e \sum_{i} \left\langle Q_{2^1S}^{i}(V_e)V_e \right\rangle \qquad \text{(B1)}
\end{aligned}
$$

In this equation the symbol $A_{n^1P}^{2^1S}$ represents the relative transition probability for direct cascading from an n^1P state to the 2^1S state. The symbol C represents the relative transition probabilities for indirect cascading to the 2^1S state from the n^1S and n^1D series. These relative transition probabilities are given by

$$C_{n^1S}^{2^1S} = \sum_{\bar{n}} A_{n^1S}^{\bar{n}^1P} A_{\bar{n}^1P}^{2^1S}$$

All A values are obtained from the values presented by Gabriel and Heddle (ref. 11).

The first four terms on the left-hand side of equation (B1) represent the population of the 2^1S state from the ground state by direct excitation and cascade effects, the next four represent the direct excitation and cascade contributions from the 2^3S state and the last three terms are the cascade contributions from states excited from the 2^1S state. Letting

$$\left\langle Q_{gs}^{2^1S}(V_e)V_e \right\rangle + \sum_{n=2}^{8} \left\langle Q_{gs}^{n^1P}(V_e)V_e \right\rangle A_{n^1P}^{2^1S} + \sum_{n=3}^{8} \left\langle Q_{gs}^{n^1S}(V_e)V_e \right\rangle C_{n^1S}^{2^1S}$$

$$+ \sum_{n=3}^{8} \left\langle Q_{gs}^{n^1D}(V_e)V_e \right\rangle C_{n^1D}^{2^1S} = \alpha(kT_e) \qquad \text{(B1a)}$$

$$\left\langle Q_{2^3S}^{2^1S}(V_e)V_e \right\rangle + \sum_{n=2}^{8} \left\langle Q_{2^3S}^{n^1P}(V_e)V_e \right\rangle A_{n^1P}^{2^1S} + \sum_{n=3}^{8} \left\langle Q_{2^3S}^{n^1S}(V_e)V_e \right\rangle C_{n^1S}^{2^1S}$$

$$+ \sum_{n=3}^{8} \left\langle Q_{2^1S}^{n^1D}(V_e)V_e \right\rangle C_{n^1D}^{2^1S} = \beta(kT_e) \qquad \text{(B1b)}$$

and

$$\sum_{n=2}^{8} \left\langle Q_{2^1S}^{n^1P}(V_e)V_e \right\rangle A_{n^1P}^{2^1S} + \sum_{n=3}^{8} \left\langle Q_{2^1S}^{n^1S}(V_e)V_e \right\rangle C_{n^1S}^{2^1S} + \sum_{n=3}^{8} \left\langle Q_{2^1S}^{n^1D}(V_e)V_e \right\rangle C_{n^1D}^{2^1S} = \gamma(kT_e)$$

(B1c)

equation (B1) becomes

$$N_o N_e \alpha(kT_e) + N_{2^3S} N_e \beta(kT_e) + N_{2^1S} N_e \gamma(kT_e) = N_{2^1S} N_e \sum_i \left\langle Q^i_{2^1S}(V_e)V_e \right\rangle \tag{B2}$$

Since the 2^3S state acts as an effective ground state for the entire triplet system any member of the entire triplet system that is excited will cascade either directly or indirectly to the 2^3S state. The relative transition probabilities from the triplet series members to the 2^3S state are therefore considered to be unity and the steady-state population balance for the 2^3S state is given by

$$N_o N_e \left[\left\langle Q^{2^3S}_{gs}(V_e)V_e \right\rangle + \sum_n \sum_L \left\langle Q^{n^3L}_{gs}(V_e)V_e \right\rangle \right] + N_{2^3S} N_e \sum_n \sum_L \left\langle Q^{n^3L}_{2^3S}(V_e)V_e \right\rangle$$

$$+ N_{2^1S} N_e \sum_n \sum_L \left\langle Q^{n^3L}_{2^1S}(V_e)V_e \right\rangle = N_{2^3S} N_e \sum_k \left\langle Q^k_{2^3S}(V_e)V_e \right\rangle \tag{B3}$$

or

$$N_{2^3S} = N_o \frac{\left[\left\langle Q^{2^3S}_{gs}(V_e)V_e \right\rangle + \sum_n \sum_L \left\langle Q^{n^3L}_{gs}(V_e)V_e \right\rangle \right]}{\sum_k \left\langle Q^k_{2^3S}(V_e)V_e \right\rangle - \sum_n \sum_L \left\langle Q^{n^3L}_{2^3S}(V_e)V_e \right\rangle}$$

$$+ \frac{N_{2^1S} \sum_n \sum_L \left\langle Q^{n^3L}_{2^1S}(V_e)V_e \right\rangle}{\sum_k \left\langle Q^k_{2^3S}(V_e)V_e \right\rangle - \sum_n \sum_L \left\langle Q^{n^3L}_{2^3S}(V_e)V_e \right\rangle} \ \mathrm{cm}^{-3} \tag{B4}$$

Letting the coefficient of N_o be $\delta(kT_e)$ and that of $N_{2^1S} = \xi(kT_e)$ equation (B4) becomes

$$N_{2^3S} = N_o \delta(kT_e) + N_{2^1S} \xi(kT_e) \tag{B5}$$

substituting (B5) into (B1) yields

$$N_o N_e \alpha(kT_e) + N_o N_e \delta(kT_e)\beta(kT_e) + N_{2^1S} N_e \beta(kT_e)\xi(kT_e) + N_{2^1S} N_e \gamma(kT_e)$$

$$= N_{2^1S} N_e \sum_i \left\langle Q^i_{2^1S}(V_e)V_e \right\rangle \tag{B6}$$

Solving for N_{2^1S} one has

$$N_{2^1S} = \frac{N_o\left[\alpha(kT_e) + \delta(kT_e)\beta(kT_e)\right]}{\sum_i \left\langle Q^i_{2^1S}(V_e)V_e \right\rangle - \left[\beta(kT_e)\xi(kT_e) + \delta(kT_e)\right]} = B(kT_e)N_o \qquad cm^{-3} \tag{B7}$$

and, substituting (B7) into (B5), the steady-state density of 2^3S states is given by

$$N_{2^3S} = N_o\left[\delta(kT_e) + \xi(kT_e)\beta(kT_e)\right] = D(kT_e)N_o \qquad cm^{-3} \tag{B8}$$

APPENDIX C

METASTABLE EXCITATION FUNCTIONS

The excitation functions for the 2^1S and 2^3S metastable states are presented in tables II to VI and are plotted in figures 5 to 7. The exchange cross section has been calculated by assuming that after an exchange collision it is equally probable that the final state will be a singlet or a triplet state. The exchange cross section from the 2^1S state to the various helium spectral series for $n \geq 3$ (e.g., $2^1S \rightarrow 3^1S + 3^1D$, $2^1S \rightarrow 3^3S + 3^3P + 3^3D$) will essentially be identical since the U_n and U_{n+1} values are essentially the same. Consequently, these cross sections are not listed separately but are all listed in table III. The exchange cross sections from the 2^3S state to levels with $n \geq 4$ are presented in a similar manner for the same reason.

TABLE II. - ELECTRON-METASTABLE ATOM CROSS SECTIONS

FOR $2^1S \rightarrow n^1P$ EXCITATIONS

Electron energy, eV	$Q_{2^1S}^{2^1P}$, cm^2	$Q_{2^1S}^{3^1P}$, cm^2	$Q_{2^1S}^{4^1P}$, cm^2	$Q_{2^1S}^{5^1P}$, cm^2	$Q_{2^1S}^{6^1P}$, cm^2	$Q_{2^1S}^{7^1P \rightarrow IL}$, cm^2
1	7.9×10^{-15}	---------	---------	---------	---------	---------
2	30	---------	---------	---------	---------	---------
3	40.4	2.8×10^{-16}	---------	---------	---------	---------
4	44.4	6.71	15.7×10^{-17}	5.4×10^{-17}	2.64×10^{-17}	---------
5	45.5	8.36	22.4	8.76	4.76	11.9×10^{-17}
6	44.9	9.0	25.0	10.27	5.63	14.7
7	44.4	9.56	27.3	11.0	6.0	16
8	43.1	9.68	28	11.4	6.32	16.72
9	41.9	9.66	28.2	11.51	6.41	17
10	40.5	9.56	28.02	11.5	6.40	17.05
11	39.1	9.35	27.4	11.3	6.30	16.94
12	38	9.2	27.2	11.2	6.25	16.72
15	34.3	8.57	25.5	10.54	5.88	15.8
20	29.4	7.55	22.6	9.37	5.26	14.1
25	25.8	6.71	20.2	8.36	4.68	12.6
35	20.8	5.47	16.5	6.85	3.84	10.34
50	16.2	4.28	13	5.38	3.02	8.14
75	12	3.28	9.6	4.0	2.24	6.04
100	9.52	2.54	7.68	3.19	1.79	4.84
150	6.9	1.84	5.54	2.3	1.30	3.48
200	5.5	1.45	4.37	1.83	1.03	2.75

TABLE III. - EXCHANGE CROSS SECTIONS FROM 2^1S STATE

Electron energy, eV	$Q_{2^1S}^{2^3P}$, cm^2	$Q_{2^1S}^{3^1S+3^1D}$ or $Q_{2^1S}^{3^3S+3^3P+3^3D}$, cm^2	$Q_{2^1S}^{4^1S+4^1D}$ or $Q_{2^1S}^{4^3P+4^3S+4^3D}$, cm^2	$Q_{2^1S}^{5^1S+5^1D}$ or $Q_{2^1S}^{5^3S+5^3P+5^3D}$, cm^2	$Q_{2^1S}^{6^1S+6^1D}$ or $Q_{2^1S}^{6^3S+6^3P+6^3D}$, cm^2	$Q_{2^1S}^{7^1S+7^1D \to IL}$ or $Q_{2^1S}^{7^3S+7^3P+7^3D \to IL}$, cm^2
3	2537×10^{-19}	177×10^{-18}	----------	----------	----------	----------
4	1603	119	53.3×10^{-18}	36.4×10^{-18}	237.5×10^{-19}	690.5×10^{-19}
5	1077	74.5	32.3	21.65	140	399.5
6	760	49.9	21.1	14	89.5	252.5
7	555	35.1	14.55	9.55	61	170
8	418	25.6	10.45	6.6	43.25	120
9	323	19.3	7.8	5.05	31.85	88
10	255	14.9	5.95	3.85	24.15	66.5
11	204	11.7	4.65	3.0	18.75	51.5
12	166	9.4	3.7	2.35	14.85	40.5
15	97	5.25	2.05	1.3	8.2	22
17	70.5	3.78	1.45	.92	5.75	15.5
20	46.5	2.45	.95	.585	3.65	9.85
25	26	1.3	.5	.315	1.95	5.25
30	16	.8	.3	.19	1.15	3.1
40	7.2	.35	.13	.08	.5	1.35
50	3.8	.19	.07	.045	.27	.7
60	2.3	.11	.04	.025	.15	.415
80	1.0	.05	.02	.01	.065	.18
100	.5	.025	.01	.005	.04	.10
150	.16	.01	.0025	.0015	.010	.03
200	----------	.003	.001	.0005	.005	.01
	Q_{max} 4125×10^{-19} at 2.1 eV	Q_{max} 194.5×10^{-18} at 3.1 eV	Q_{max} 75.8×10^{-18} at 3.39 eV	Q_{max} 46.9×10^{-18} at 3.57 eV	Q_{max} 288×10^{-19} at 3.68 eV	Q_{max} 703×10^{-19} at 3.97 eV

TABLE IV. - ELECTRON-METASTABLE CROSS SECTIONS FOR

$2^3S - n^3P$ EXCITATIONS

Electron energy, eV	$Q_{2^3S}^{2^3P}$, cm^2	$Q_{2^3S}^{3^3P}$, cm^2	$Q_{2^3S}^{4^3P}$, cm^2	$Q_{2^3S}^{5^3P}$, cm^2	$Q_{2^3S}^{6^3P}$, cm^2	$Q_{2^3S}^{7^3P \to IL}$, cm^2
3	70.7×10^{-16}	----------	----------	----------	----------	----------
4	92.8	19.9×10^{-17}	----------	----------	----------	----------
5	103.3	35.2	9.17×10^{-17}	34.1×10^{-18}	16.7×10^{-18}	34.7×10^{-18}
7	109.5	46.8	13.95	50.5	30.0	75.0
9	108.2	50.2	15.4	64.5	34.5	85.4
10	106.4	50.5	15.66	66	35	88
11	104.0	50.4	15.7	66.2	35.5	88.4
12	101.6	50	15.65	66.1	35.5	88.4
15	94	47.7	15.06	63.8	34.4	85.8
20	82.8	43.1	13.7	58.4	31.5	78.8
25	73.6	38.9	12.4	52.9	28.5	71.7
35	60.3	32.2	10.3	44.1	23.8	59.8
50	47.5	25.6	8.22	35.2	19	47.8
75	35.4	19.2	6.18	26.4	14.3	35.9
100	28.5	15.5	4.97	21.2	11.5	28.8
150	20.7	11.2	3.60	15.40	8.35	21
200	16.5	8.84	2.85	12.2	6.6	16.5

TABLE V. - EXCHANGE CROSS SECTIONS FROM 2^3S STATE

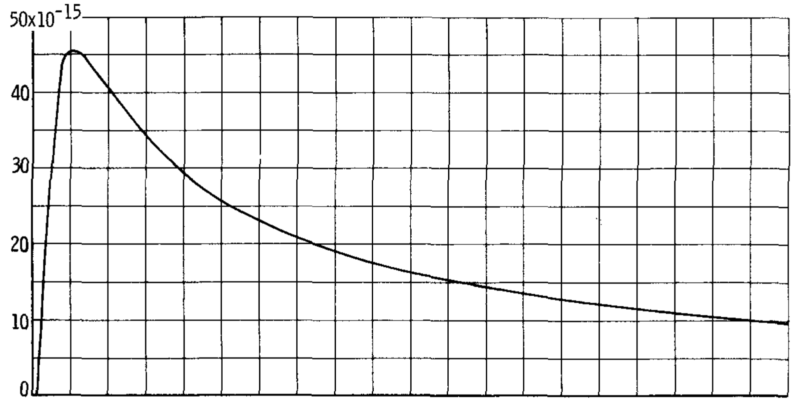
Electron energy, eV	$Q^{2^1S}_{2^3S}$, cm^2	$Q^{2^1P}_{2^3S}$, cm^2	$Q^{3^3S+3^3D}_{2^3S}$, cm^2	$Q^{3^1S+3^1P+3^1D}_{2^3S}$, cm^2	$Q^{4^3S+4^3D}_{2^3S}$ or $Q^{4^1S+4^1P+4^1D}_{2^3S}$, cm^2	$Q^{5^3S+5^3D}_{2^3S}$ or $Q^{5^1S+5^1P+5^1D}_{2^3S}$, cm^2	$Q^{6^3S+6^3D}_{2^3S}$ or $Q^{6^1S+6^1P+6^1D}_{2^3S}$, cm^2	$Q^{7^3S+7^3D \to IL}_{2^3S}$ or $Q^{7^1S+7^1P+7^1D \to IL}_{2^3S}$, cm^2
2	915×10^{-19}	1150×10^{-19}	---------	---------	---------	---------	---------	---------
3	576	2252	184×10^{-19}	---------	---------	---------	---------	---------
4	386	1660	1135	977×10^{-19}	257×10^{-19}	---------	---------	---------
5	271	1113	726	616	348	223.5×10^{-19}	107×10^{-19}	372×10^{-19}
6	198	783	492	414	229	145	69	236.5
7	148	572	350	293	159	99.5	47	160
8	114	431	257	214	115	72.5	33.5	113.5
9	90	332	195	161	86	53	24.8	83.5
10	72	261	151	145	66	40.45	18.9	63.5
11	59	210	119	99	51.5	31.6	14.7	49
12	48	171	97	79	41.3	25.15	11.65	38.9
15	29	99.5	55	44.6	22.9	13.85	6.4	21.25
17	21.4	72.5	39.5	32	16.4	9.9	4.55	15.05
20	14.3	48	25.6	20.8	10.55	6.3	2.9	9.55
25	8.1	26.6	14	11.3	5.7	3.4	1.55	5.1
30	5	16.3	8.5	6.9	3.45	2.05	.95	3.04
50	1.25	4.0	2.0	2.6	.8	.45	.215	.69
75	.4	1.25	.6	.5	.25	.15	.065	.21
100	.18	.54	.27	.2	.10	.06	.03	.09
200	.02	.07	.035	.025	.015	.01	.005	.02
	Q_{max} 1270×10^{-19} at 1.4 eV	Q_{max} 2400×10^{-19} at 3.2 eV	Q_{max} 1270×10^{-19} at 3.7 eV	Q_{max} 1020×10^{-19} at 3.9 eV	Q_{max} 516×10^{-19} at 4.18 eV	Q_{max} 300×10^{-19} at 4.4 eV	Q_{max} 140×10^{-19} at 4.5 eV	Q_{max} 420×10^{-19} at 4.77 eV

TABLE VI. - ELECTRON-METASTABLE IONIZATION

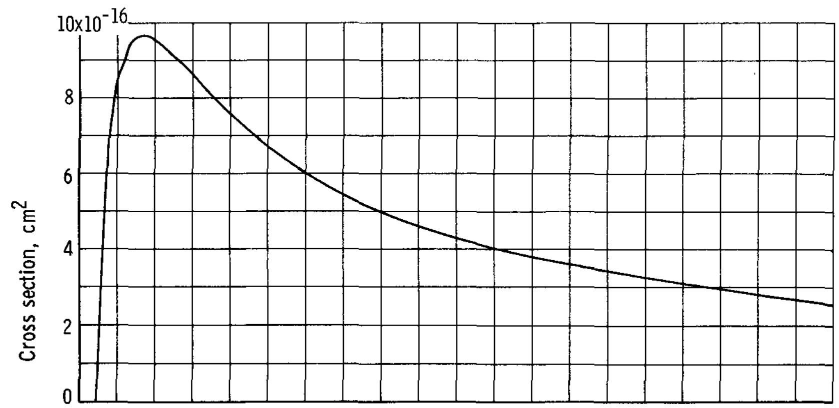
CROSS SECTIONS AND $\langle Q^{+}(V_e)V_e \rangle$ VALUES

FOR 2^3S AND 2^1S STATES

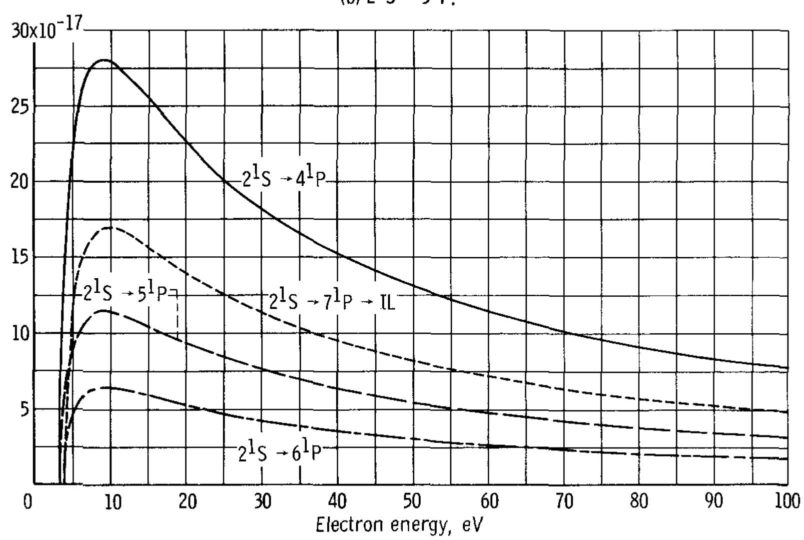
Electron energy, eV	$Q^{+}_{2^1S}$, cm^2	$\langle Q^{+}_{2^1S}(V_e)V_e \rangle$, cm^3/sec	$Q^{+}_{2^3S}$, cm^2	$\langle Q^{+}_{2^3S}(V_e)V_e \rangle$, cm^3/sec
2.5	----------	4.2×10^{-8}	----------	2.29×10^{-8}
5	1.78×10^{-16}	7.6	0.11×10^{-16}	4.75
7.5	5.99	8.83	2.93	5.75
10	7.96	9.29	4.75	6.16
12.5	8.72	9.43	5.66	6.32
15	8.91	9.42	6.06	6.36
17.5	8.83	9.35	6.18	6.34
20	8.61	9.24	6.16	6.28
22.5	8.33	9.11	6.06	6.21
25	8.03	8.97	5.91	6.13
27.5	7.72	8.83	5.75	6.05
30	7.43	8.69	5.76	5.96
35	6.87	8.43	5.23	5.79
40	6.38	8.19	4.9	5.63
45	5.94	7.96	4.6	5.49
50	5.56	7.75	4.32	5.35
55	5.22	7.56	4.08	5.22
60	4.92	7.39	3.86	5.1
70	4.42	7.07	3.49	4.89
80	4.0	6.8	3.18	4.70
90	3.67	6.56	2.92	4.54
100	3.38	6.34	2.70	4.39



(a) $2^1S \rightarrow 2^1P$.

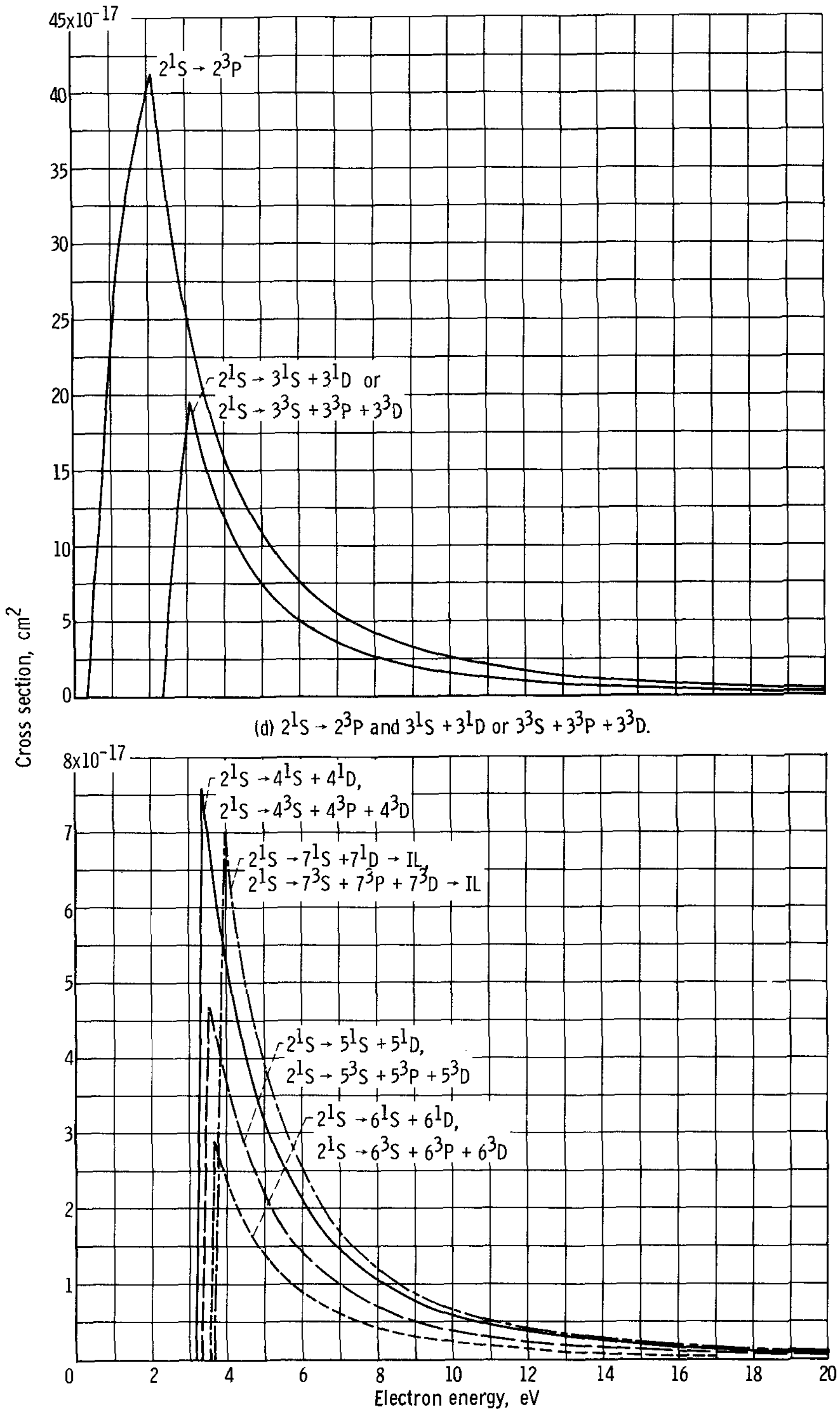


(b) $2^1S \rightarrow 3^1P$.



(c) $2^1S \rightarrow n^1P$.

Figure 5. - Excitation functions for 2^1S state.



(d) $2^1S \rightarrow 2^3P$ and $3^1S + 3^1D$ or $3^3S + 3^3P + 3^3D$.

(e) $2^1S \rightarrow n^1S + n^1D$ and $n^3S + n^3P + n^3D$.

Figure 5. - Concluded.

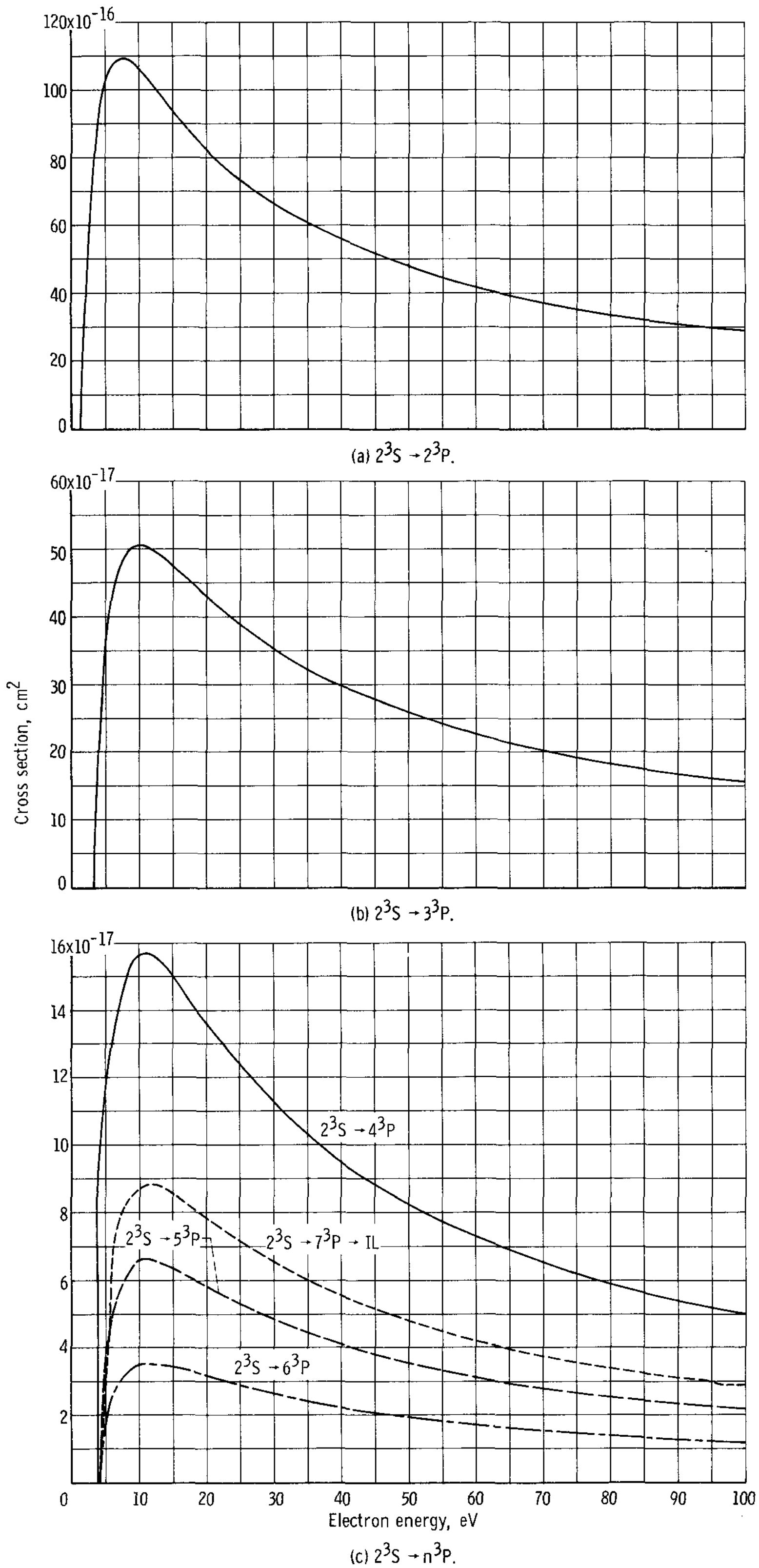
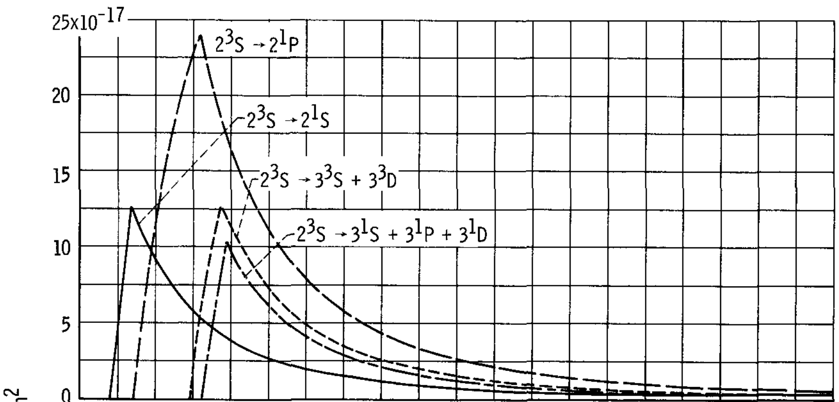
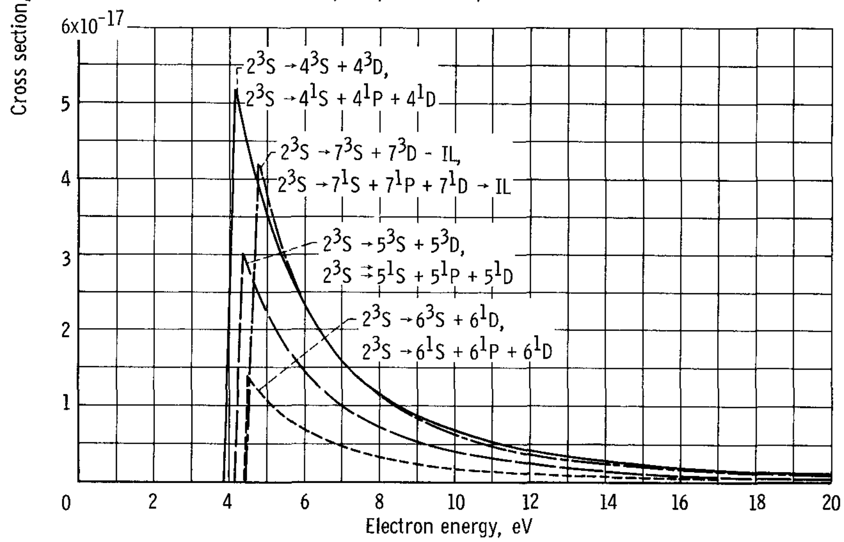


Figure 6. - Excitation functions for 2^3S state.



(d) $2^3S \rightarrow 2^1S$, 2^1P, $3^3S + 3^3D$, and $3^1S + 3^1P + 3^1D$.



(e) $2^3S \rightarrow n^3S + n^3D$ and $n^1S + n^1P + n^1D$.

Figure 6. - Concluded.

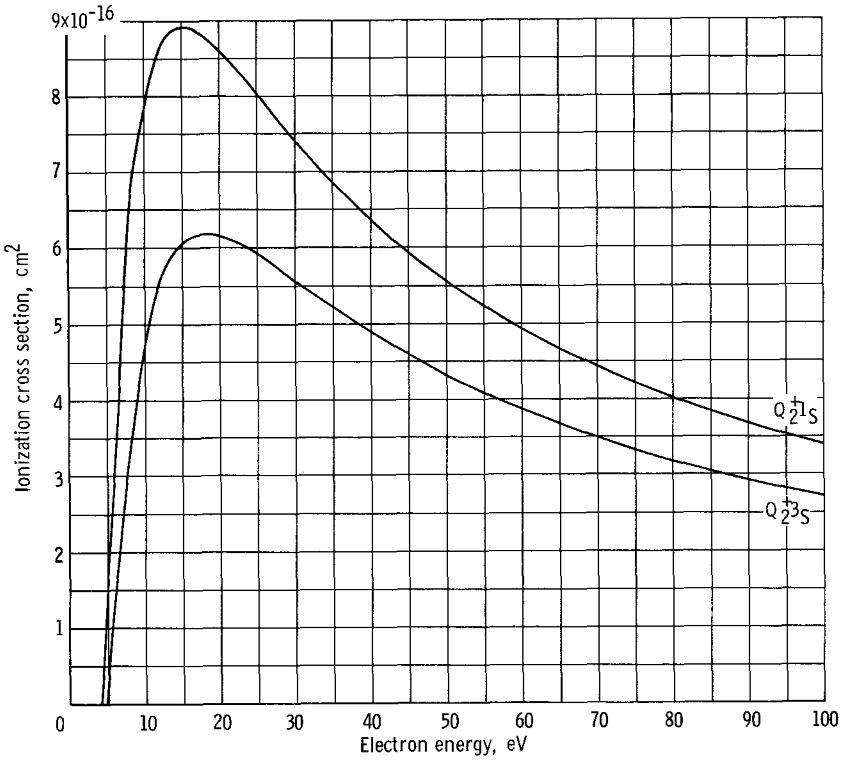


Figure 7. - Ionization cross sections for 2^1S and 2^3S metastable states.

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