

ELECTRON IMPACT ON ATMOSPHERIC GASES
I. UPDATED CROSS SECTIONS

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Abstract. We update the analytic characterizations of electron impact cross sections for important atmospheric gases (namely, O₂, N₂, O, CO, CO₂, and He). With these cross sections it is simple to communicate massive quantities of experimental and theoretical results. In addition, these forms are convenient for applications in energy degradation calculations, including a new approach described in a companion paper.

1. Introduction

Because of the energy-depositional aspects of auroral and dayglow phenomena, attempts to obtain a detailed understanding of these phenomena involve two major tasks: first, the assembly of comprehensive sets of cross sections for excitation, ionization, and dissociation of the involved atmospheric species by electrons and, second, the use of an energy apportionment method to determine the distribution of the electron energy among the various loss processes. In this first paper of a two-paper sequence we attempt to deal with the former task.

Following the approach of Green and Barth [1965] and subsequently Green and Dutta [1967] we will present the relevant electron impact cross sections by analytic forms. Communication of cross sections in this manner removes any doubts about the actual cross sections used and eliminates the need for extensive tables or graphs to convey the cross sections.

The steady appearance of new experimental results requires a periodic reevaluation of cross sections used in energy-deposition calculations. The major part of the present work consists of an extensive revision of the cross sections of O and He. In addition, we also present minor revisions of CO, CO₂, O₂, and N₂.

2. Cross Sections

a. Discrete States

We use two different formulae for the representation of the cross sections for discrete states. One form due to Green and Dutta [1967] can be used for either forbidden or allowed states and is given by:

$$\sigma_j(E) = (q_0 F/W^2) [1 - (W/E)^\alpha]^\beta (W/E)^\Omega \quad (1)$$

where $q_0 = 4\pi a_0^2 R^2$ and has the numerical value $6.513 \times 10^{-14} \text{ eV}^2 \text{ cm}^2$, a_0 being the Bohr radius and R the Rydberg energy. W is the parameter for the low-energy shape of the cross section and, in most cases, is close to the energy loss \bar{W}_j associated with excitation of the j^{th} state. F

is the strength parameter, and α , β , and Ω are three other adjustable parameters.

The second form, which is used to represent the cross sections of allowed states only, is adapted from Porter et al. [1976] (hereafter referred to as PJG) and is more consistent with the asymptotic form of Born-Bethe theory. For the nonrelativistic energies that we are considering this form can be written as:

$$\sigma_j(E) = \frac{q_0 F [1 - (W/E)^\alpha]^\beta}{EW} \ln \left(\frac{4EC}{W} + e \right) \quad (2)$$

Here q_0 and W are the same as in (1), F is the optical oscillator strength, C is a factor determined by the falloff of the cross section with higher energy, and e is the base of the natural logarithm.

We treat Rydberg series the same in both forms by using the simple rule $F = F^*/n^{*3}$, where $n^* = n - \delta$, F^* is a constant for a given series, n is the principal quantum number of the state in question, and δ is the quantum defect for the series. For the contribution to all higher-lying members above and including a certain principal quantum number n we replace n^{*3} by $2(n - \delta - \frac{1}{2})^2$. The energy for excitation in either scheme is found by using the usual Rydberg equation [Green and Dutta, 1967, equation (28)].

b. Continuum States

We use only one representation for the differential ionization cross section $S(E, T)$ and, ultimately, the ionization cross section $\sigma_i(E)$. This form, which was initially developed by Green and Sawada [1972] (hereafter referred to as GS) and is basically a Lorentzian or Breit-Wigner form, is given by the following:

$$S_i(E, T) = \frac{A(E)\Gamma^2(E)}{[T - T_0(E)]^2 + \Gamma^2(E)} \quad (3)$$

with

$$A(E) = \left(\frac{K}{E} + K_B \right) \ln \left(\frac{E}{J} + J_B + \frac{J_C}{E} \right) \quad (4)$$

$$\Gamma(E) = \Gamma_S E / (E + \Gamma_B) \quad (5)$$

$$T_0(E) = T_S - [T_A / (E + T_B)] \quad (6)$$

In these equations, K , K_B , J , J_B , J_C , Γ_S , Γ_B , T_S , T_A , and T_B are adjustable parameters and may be different for different ionization continua of a gas. T is the energy of the secondary electron, and E is the energy of the primary electron before the ionizing event. The secondary electron will always be defined as the electron with the least energy leaving an ionization event.

TABLE 1. Parameters for the Ionization States of Molecular Oxygen

Ionization State	I_i	K	K_B	J	J_B	J_C	Γ_S	Γ_B	T_S	T_A	T_B
X $2\Pi_g$	12.1	0.475	0.0	3.760	0.0	0.0	18.50	12.10	1.860	1000.0	24.20
a $4\Pi_u$	16.1	1.129	0.0	3.760	0.0	0.0	18.50	16.10	1.860	1000.0	32.20
A $2\Pi_u$	16.9	1.129	0.0	3.760	0.0	0.0	18.50	16.90	1.860	1000.0	33.80
b $4\Sigma_g^-$	18.2	1.010	0.0	3.760	0.0	0.0	18.50	18.20	1.860	1000.0	36.40
B $2\Sigma_g^-$	20.0	0.653	0.0	3.760	0.0	0.0	18.50	20.30	1.860	1000.0	40.60
c $4\Sigma_u^-, 2\Pi$ (III)	23.0	0.950	0.0	3.760	0.0	0.0	18.50	23.00	1.860	1000.0	46.00
37-eV state	37.0	0.594	0.0	3.760	0.0	0.0	18.50	37.00	1.860	1000.0	74.00

c. Cross Section Parameters for the Six Gases

Molecular oxygen (O_2) was recently studied by PJG, who give the parameters for the discrete states. We used the S(E, T) parameters from GS, which are given as fits to the Kieffer and Dunn [1966] data. The parameter K was divided fractionally between the various ionization continua (as given by PJG), and we set $T_B = 2I_i$ and $\Gamma_B = I_i$ for each i^{th} ionization continuum given. These ionization states and their representations are given in Table 1.

Molecular nitrogen (N_2) has also been reexamined recently by PJG, and we refer to them for the discrete state parameters. The N_2 ionization parameters given in Table 2 were derived in a manner similar to the method used for O_2 ionization states.

Atomic oxygen (O), one of the major species in the terrestrial, Martian, and Venusian upper atmospheres, has interested scientists for many years. Green and Barth [1967] (hereafter referred to as GB) were the first workers to try to coalesce the knowledge about atomic oxygen in a workable form for use in electron degradation. We have tried to update and improve these cross sections that describe O in this work.

Experimentally, little work has been done with atomic oxygen. The substance is quite reactive and therefore difficult to work with in

the laboratory. Measurements of the ionization cross section have been made by Fite and Brackmann [1959] (hereafter referred to as FB), Rothe et al. [1962], and Boksenberg [1961]. The discrete excitation states have been almost neglected, and we were able to find only the work of Stone and Zipf [1971, 1974] (hereafter referred to as SZ) in this area of experimentation. Here they observed the 1304-Å and 1356-Å emissions corresponding to the transitions from the $(4s^0)3s\ 3s^0$ and $(4s^0)3s\ 5s^0$ states of oxygen. Unfortunately, direct excitation processes by electron impact are not the only means for production of these states, and consequently, cascading mechanisms must be understood before accurate cross sections for the excitation of individual states are realized. Julienne and Davis [1976] have, in fact, attempted to utilize some of their own theoretical cross sections, including cascading, and, upon comparing them with the SZ experimental values, found their results to be lower than those of the laboratory efforts.

The SZ paper of 1971 shows a peak of 1.2×10^{-16} cm² for the $3s^0$ excitation cross section, whereas the SZ 1974 paper gives a peak of 5.3×10^{-17} cm² \pm 40% in an updated cross section measurement. Not only are absolute experimental values of cross sections difficult to measure at low energies, but there are problems with theoretical calculations in this energy re-

TABLE 2. Parameters for the Ionization States of Molecular Nitrogen

Ionization State	I_i	K	K_B	J	J_B	J_C	Γ_S	Γ_B	T_S	T_A	T_B
X $2\Sigma_g^+$	15.58	2.420	0.0	1.74	0.0	0.0	13.8	15.58	4.71	1000.0	31.16
A $2\Pi_u$	16.73	1.060	0.0	1.74	0.0	0.0	13.8	16.73	4.71	1000.0	33.46
B $2\Sigma_u^+$	18.75	0.551	0.0	1.74	0.0	0.0	13.8	18.75	4.71	1000.0	37.50
D $2\Pi_g$	22.00	0.371	0.0	1.74	0.0	0.0	13.8	22.00	4.71	1000.0	44.00
C $2\Sigma_u^+$	23.60	0.371	0.0	1.74	0.0	0.0	13.8	23.60	4.71	1000.0	47.20
40-eV state	40.00	0.530	0.0	1.74	0.0	0.0	13.8	40.00	4.71	1000.0	80.00

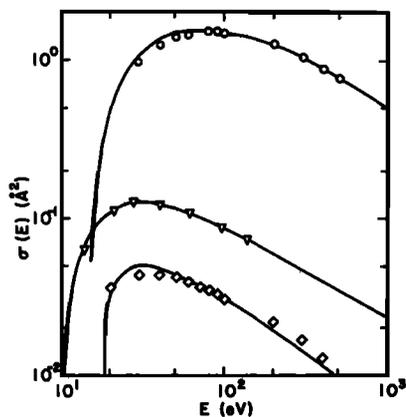


Fig. 1. Cross sections for atomic oxygen. Data from Fite and Brackmann [1959] for the ionization cross section (circles), Sawada and Ganas [1973] for the $(4s^0)3s\ 3s^0$ state (triangles), and Kazaks et al. [1972] for the $(4s^0)3d\ 3d^0$ state (squares) are shown. The solid lines represent our fit to the data.

gime as well. After weighing the experimental and theoretical results together we decided to use the following approach.

With the cross section for the transition from the $1s^2\ 2s^2\ 2p^4\ 3p$ ground state to the $1s^2\ 2s^2\ 2p^3(4s^0)3s\ 3s^0$ excited state and optical oscillator strength given by Sawada and Ganas [1973] (hereafter referred to as SG) it was possible to gain an excellent fit to this cross section by varying the parameters C, W, α , and β . The optical oscillator strength and cross section for the transition to the $(3s^0)3d\ 3d^0$ state were found by Kazaks et al. [1972]. It was possible to fit these values also, and the cross sections and fits are both shown in Figure 1.

With these two fits we have parameters for the transitions to the ns or nd type configurations. It seems reasonable to assume that the shapes of the other ns or nd state cross sections should not change appreciably. We will thus postulate that the only two parameters to change in the fitting of the cross sections for other allowed states will be their optical os-

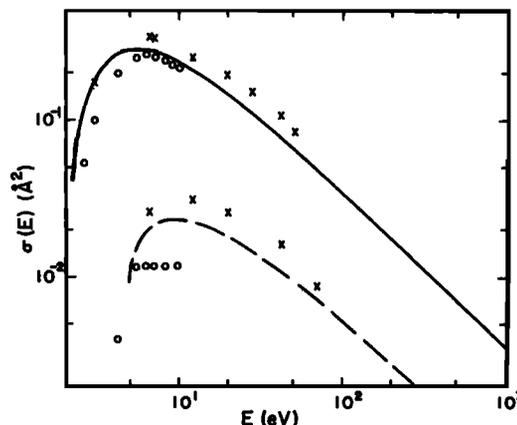


Fig. 2. Cross sections for atomic oxygen. Data from Thomas and Nesbet [1975] (circles) and Smith et al. [1967] (crosses) are shown. The solid line represents the fit to the $1D$ state, and the dashed line represents the fit to the $1S$ state.

cillator strengths and their threshold energy of excitation.

Optical oscillator strengths for three other allowed transitions (namely, to the $(2d^0)3s\ 3p^0$, $(2d^0)3d\ 3p^0$, and $(2p^0)3s\ 3p^0$ states) were found in the study by Wiese et al. [1966]. The four remaining states allowed from the ground state to the $n = 3$ level (namely, the $(2p^0)3d\ 3s^0$, $(2d^0)3d\ 3p^0$, $(2p^0)3d\ 3p^0$, and $(2p^0)3d\ 3d^0$ states) were assigned reasonable optical oscillator strengths deduced from the values of the other five states. The thresholds for all these states were taken from GB. The tenth prominent allowed transition, with which we deal, is the excitation to the $1s^2\ 2s\ 2p^5\ 3p^0$ configuration and has an optical oscillator strength and threshold given by Dehmer et al. [1973]. This transition was given the ns shape parameters.

We compare cross sections for the three states $(4s^0)3s\ 3s^0$, $(4s^0)3d\ 3d^0$, and $(2d^0)3s\ 3p^0$ from Dalgarno and Lejeune [1971] (hereafter referred to as DL) and from this work (JGG) in Table 3. The only significant differences between the two sets of allowed cross sections at high energies occur when the optical oscillator strengths differ. This is seen in the $(4s^0)3d\ 3d^0$ cross section comparison.

The autoionization factor given for each discrete state is the fraction of excitations of that state which results in the formation of an ionized atom and an electron via the autoionization channel. We have used the data of van Tassal et al. [1973], Dehmer and Chupka [1975], Huffman et al. [1967], and Cermak [1975] to come up with reasonable values for the autoionization factors both here and in the Rydberg states.

We next consider forbidden-state excitations and use (1) for their description. Excitation of the $1D$ and the $1S$ states (very important states in aeronomy) can be characterized by using the parameters of GB, the resulting cross sections agreeing closely with the theory of Smith et al. [1967] and Thomas and Nesbet [1975]. A plot of these cross sections is given in Figure 2.

The SG theoretical data were used again, this time for the cross sections of the transitions

TABLE 3. Comparison of Cross Sections for Three States in Atomic Oxygen From Dalgarno and This Work at Three Energies

State	E, eV	Cross Section, $\times 10^{-16}\ \text{cm}^{-2}$	
		DL	JGG
$(4s^0)3s\ 3s^0$	20	0.059	0.109
	100	0.075	0.087
	1000	0.019	0.018
$(4s^0)3d\ 3d^0$	20	0.0046	0.035
	100	0.011	0.030
	1000	0.0029	0.0056
$(2d^0)3s\ 3p^0$	20	0.022	0.046
	100	0.058	0.057
	1000	0.016	0.013

TABLE 4. Parameters for the Excitation, Rydberg, and Ionization States of Atomic Oxygen

Excited States	W	α	β	W_j	C	F	A.F.
(⁴ S ⁰)3s ³ S ⁰	9.53	0.86	1.440	9.53	0.320	0.0560	0.0
(⁴ S ⁰)3d ³ D ⁰	17.90	1.26	0.490	12.10	0.610	0.0310	0.0
(² D ⁰)3s ³ D ⁰	12.50	0.86	1.440	12.50	0.320	0.0560	0.0
(² D ⁰)3d ³ S ⁰	15.35	1.26	0.490	15.35	0.610	0.0065	0.50
(² D ⁰)3d ³ P ⁰	15.35	1.26	0.490	15.35	0.610	0.0077	1.00
(² D ⁰)3d ³ D ⁰	15.35	1.26	0.490	15.35	0.610	0.0052	0.50
(² P ⁰)3s ³ P ⁰	14.10	0.86	1.440	14.10	0.320	0.0370	0.70
(² P ⁰)3d ³ P ⁰	16.94	1.26	0.490	16.94	0.610	0.0080	0.30
(² P ⁰)3d ³ D ⁰	16.94	1.26	0.490	16.94	0.610	0.0060	0.50
2p ⁵ ³ P ⁰	15.50	0.86	1.440	15.50	0.320	0.0423	0.30
				Ω			
2p ⁴ ¹ D	1.96	1.00	2.000	1.85	1.000	0.0100	0.0
2p ⁴ ¹ S	4.18	0.50	1.000	4.18	1.000	0.0042	0.0
(⁴ S ⁰)3s ⁵ S ⁰	10.60	19.20	10.500	9.29	2.690	0.0130	0.0
(⁴ S ⁰)3p ³ P	10.74	1.17	0.753	10.74	1.600	0.0234	0.0
(⁴ S ⁰)3p ³ P	11.64	18.20	5.600	11.00	0.855	0.0578	0.0
Rydberg States	I _i	α	β	δ	C	F*	A.F. n = 4 n = 5
(⁴ S ⁰)nd ³ D ⁰	13.60	1.26	0.490	0.01	0.610	0.8290	0.0 0.0
(⁴ S ⁰)ns ³ S ⁰	13.60	0.86	1.440	1.16	0.320	0.3490	0.0 0.0
(² D ⁰)ns ³ D ⁰	16.90	0.86	1.440	1.21	0.320	0.3210	1.00 1.00
(² D ⁰)nd ³ SPD ⁰	16.90	1.26	0.490	0.04	0.610	0.5030	0.70 1.00
(² P ⁰)ns ³ P ⁰	18.50	0.86	1.440	1.25	0.320	0.1980	1.00 1.00
(² P ⁰)nd ³ PD ⁰	18.50	1.26	0.490	0.05	0.610	0.3600	0.75 0.75

TABLE 4. (continued)

Rydberg States	I_1	α	β	δ	Ω	F*	A.F.		
							$n = 3$	$n = 4$	$n = 5$
$(^4S^0)ns$	13.60	19.20	10.500	1.24	2.690	0.0710	0.0	0.0	0.0
$(^4S^0)np$	13.60	18.20	5.600	0.69	0.855	0.7130	0.0	0.0	0.0
$(^4S^0)np$	13.60	1.17	0.753	0.81	1.600	0.2460	0.0	0.0	0.0
$(^4S^0)nd$	13.60	1.00	2.000	0.01	3.000	0.2000	0.0	0.0	0.0
$(^2D^0)ns$	16.90	1.00	2.000	1.18	3.000	0.2000	0.0	0.0	0.0
$(^2D^0)nd$	16.90	2.00	1.000	0.84	1.000	0.1000	0.0	0.0	0.0
$(^2D^0)np$	16.90	1.00	1.000	0.83	3.000	0.0400	0.0	0.0	0.0
$(^2D^0)np$	16.90	2.00	1.000	0.04	1.000	0.1000	0.0	0.0	0.0
$(^2D^0)nd$	16.90	2.00	2.000	0.04	3.000	0.2000	0.0	0.0	0.0
$(^2P^0)ns$	18.50	1.00	2.000	1.19	3.000	0.2000	0.0	0.0	0.0
$(^2P^0)np$	18.50	2.00	1.000	0.86	1.000	0.1000	0.0	0.0	0.0
$(^2P^0)np$	18.50	1.00	1.000	0.85	3.000	0.0400	0.0	0.0	0.0
$(^2P^0)nd$	18.50	2.00	1.000	0.05	1.000	0.1000	0.0	0.0	0.0
$(^2P^0)nd$	18.50	1.00	2.000	0.05	3.000	0.2000	0.0	0.0	0.0

Ionization States	I_1	K	K_B	J	J_B	J_C	Γ_S	Γ_B	T_S	T_A	T_B
$^4S^0$	13.60	1.03	0.0	1.81	0.0	0.0	13.0	-0.815	6.41	3450.0	162.0
$^2D^0$	16.90	0.78	0.0	1.79	0.0	0.0	13.0	-0.815	6.41	3450.0	162.0
$^2P^0$	18.50	1.31	0.0	1.78	0.0	0.0	13.0	-0.815	6.41	3450.0	162.0

A.F. refers to the autoionization factor (or branching ratio for ionization). The n is the principal quantum number of the state. If (1) is used, we have a column for Ω ; if (2) is used, we have a column for C.

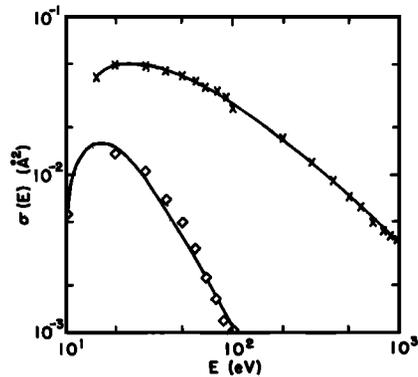


Fig. 3. Cross sections for carbon monoxide. Data from the $d\ 3\Delta$ (squares) and $D\ 1\Delta$ states (crosses) are shown [from Chung and Lin, 1974]. The analytic fits are represented as solid lines for these states.

to the $(4s0)3s\ 5s0$ and $(4s0)3p\ 3p$ states. For the $(4s0)3p\ 5p$ state we took a mean of the cross sections used for that state from the source of SG, Christensen [1975], and Dalgarno and Lejeune [1971]. These three states were then fit with (1).

Now, a look at the higher-lying transitions in atomic oxygen is in order. These states can be lumped together under the title of Rydberg series. Since there are three ionization continua (at 13.6 eV, 16.9 eV, and 18.5 eV) and there will be a Rydberg series for each of these, we will again make the distinction between the optically allowed states and fifteen that are forbidden.

The Rydberg states are treated as discussed in section 2a. From these equations it is observed that if we know the δ , n , and F for some state, then we can calculate the F^* for that series. We do know these parameters for $n = 3$ of the several states already discussed, when we take the quantum defects δ from the Green and Barth [1967] paper and the F from our previous discussion. Using these values, we are able to calculate F^* for most of the series, and, further, we force the shape parameters to be the same as those in the $n = 3$ transition.

Help for parameters of forbidden Rydberg states was obtained from the data of GB. One exception is the falloff of the np triplet states with increasing energy. We assume that forbidden-state cross sections falloff with increasing energy faster than allowed states in their energy dependence and thus have supposed that $\Omega = 1$ instead of 0.75.

We will now review the direct ionization cross section of O. It was decided to fit the experimental ionization cross section data from FB and Rothe et al. [1962], since these two groups agreed quite well. Several authors in the past have used one half of the ionization cross section of O_2 as the O ionization cross section; thus a good starting point appeared to be the use of the $S(E, T)$ parameters for O_2 with the amplitude parameter halved. Using the FB data apportioned among our three ionization continua, we employed a nonlinear least square fitting procedure. Variation on the $K, J, T_S, T_A, T_B, \Gamma_B,$ and Γ_S gave quite a nice fit to the data of FB. This fit can be seen in Figure 1.

We have used these cross sections in the continuous-slowing-down approximation (CSDA) energy degradation scheme (described by Peterson et al. [1973]) in order to get a loss function $L(E)$ for any energy E . From the theoretical Bethe formula for $L(E)$ taken from Henry and McElroy [1968] we calculated $L(E)$ to be $29\ eV\ \text{\AA}^2$ at 500 eV. The CSDA gives us $32\ eV\ \text{\AA}^2$ at 500 eV, so it appears that our cross sections used are fairly valid. All the parameters of atomic oxygen for the discrete and continuum states are now given in Table 4.

The cross sections of carbon monoxide (CO), like O, have been coalesced before. The work of Sawada et al. [1972a] (hereafter referred to as SSG) is used as a basis for a few updated cross sections, since they based their paper, in part, on electron impact excitation cross sections and generalized oscillator strengths measured in the laboratory.

The C II (1335 A) state of SSG appears to be misplaced. The excitation of this state involves the removal of an electron and the dissociation of CO; therefore it is probably already included in the dissociative ionization process.

TABLE 5. Parameters for the Excitation States of Carbon Monoxide

Excited States	W	α	β	\bar{w}_j	Ω	F	A.F.
a' $3\Sigma^+$	9.350	10.300	1.870	6.910	2.600	0.874000	0.0
c 3Π	18.600	14.700	1.550	11.400	2.590	0.116000	0.0
d 3Δ	2.320	2.550	111.000	7.500	1.860	0.010600	0.0
j $3\Sigma^+$	8.000	10.000	17.700	11.270	2.630	0.026400	0.0
D 1Δ	5.150	0.714	3.000	8.070	1.000	0.032500	0.0
O I (8447 \AA)	36.000	0.400	1.000	22.000	0.886	0.087300	0.500

A.F. refers to the autoionization factor (or branching ratio for ionization). Equation (1) used here.

TABLE 6. Parameters for the Excitation States of Carbon Dioxide

Excited States	W	α	β	\bar{W}_j	Ω	F	A.F.
O I (1356 Å)	16.400	0.600	3.000	20.400	0.944	0.168000	0.500
O I (1279 Å)	15.700	1.000	3.000	26.200	0.643	0.010400	0.500
O I (1329 Å)	21.800	1.000	3.000	20.900	1.040	0.020200	0.500
O I (1561 Å)	22.400	1.000	3.000	24.500	0.982	0.053800	0.500
O I (1657 Å)	21.100	1.000	3.000	24.100	0.947	0.087200	0.500

A.F. refers to the autoionization factor (or branching ratio for ionization). Equation (1) used here.

We thus omit this state from further consideration.

We used the theoretical work of Chung and Lin [1974] to add five new states (namely, a $^3\Sigma^+$, c $^3\Pi$, d $^3\Delta$, j $^3\Sigma^+$, and D $^1\Delta$). Sample fits to two of these forbidden states are given in Figure 3.

Lawrence [1970] gives a cross section for the production of O I (8447 Å) emission from CO by electron impact. The emission of a photon at 8447 Å will result in the excitation of the $(4S^0)3s\ 3S^0$ state of O, the consequence being the emission of a 1304-Å photon. Including this emission cross section will result in double counting, if we also use the full cross section of the O I (1304 Å) excitation from the SSG paper. At 100 eV the O I (8447 Å) cross section is about 71% of the O I (1304 Å) cross section, and by reducing the F value of the O I (1304 Å) state by that much we should produce a sensible representation of the two excited states. We then fit the O I (8447 Å) cross section with (1).

The six new states of CO and their parameters are given in Table 5.

Carbon dioxide (CO₂), the most abundant molecule in the atmospheres of Mars and Venus, will now be discussed. Our starting point will be the paper of Sawada et al. [1972b] (hereafter referred to as SStG). This work, like the work on CO, is based primarily on experimental gener-

alized oscillator strengths, with some emphasis on laboratory electron impact excitation cross sections. We have added some new excitation states and have also changed some of those that already existed in SStG.

Let us look at the discrete excitation states. Additional excitations of O I (1356 Å) and C I (1279 Å) were found in the work by Ajello [1971] and fit with (1), as were the states of C I (1329 Å), C I (1561 Å), and C I (1657 Å) from Mumma [1970]. An autoionization factor was assumed to be 0.5 for these states.

We then deleted the C II (1335 Å) state (for the same reasons pointed out in the discussion of CO states). The C I (composite) was discarded also, when the four individual C I states described above were used.

In SStG a discrepancy between their total cross section and the total inelastic cross section of Hake and Phelps [1967] was pointed out. We have attempted to alleviate some of this difference by increasing the F parameters by a factor of 2.6 for the 8.6-, 9.3-, 11.1-, 12.4-, and 13.6-eV levels. This resulted in an energy per ion pair much closer to the experimental values than that found in SStG [see Green et al., 1977, Table 4].

The new states of CO₂ and their parameters are given in Table 6.

Jusick et al. [1967] compiled a complete set of analytic electron impact cross sections for helium. However, in the time since this work was published a considerable new body of experimental data and theoretical results has become available concerning the cross sections of helium. These new experimental results generally agree with one another concerning the energy dependence for the cross section of a given state. There is usually considerable disagreement concerning the maximum value of a given cross section, however. We have used this new body of data to update the work of Jusick et al. by choosing from this data those results for which the most care was taken to eliminate or correct unwanted pressure, cascade, and polarization effects. Once we chose a particular set of data for a given singlet state, we then renormalized the experimental results at 1000 eV to the corresponding theoretical cross section calculated by Inokuti and Kim [1969]. These theoretical cross sections were calculated with highly accurate, correlated Weiss wave functions consisting of over 50 terms for each state, and they yield practically identical results in both the length and the velocity 'formulas' and are generally regarded as very reliable cross sections.

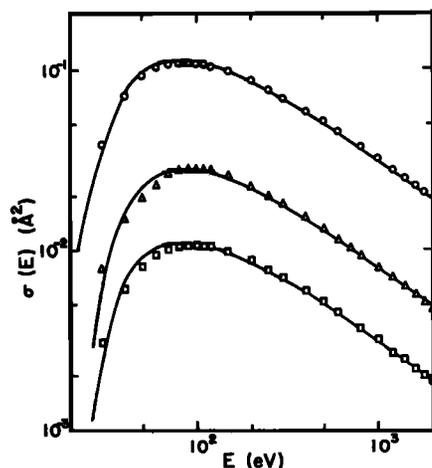


Fig. 4. Cross sections for the $n\ 1P$ states of helium plotted against incident energy E . The 2^1P (circles), 3^1P (triangles), and 4^1P (squares) are the renormalized data of Donaldson et al. [1972]. The solid lines are our fits to this data using the parameters listed in Table 7.

TABLE 7. Parameters for the Excitation and Ionization States of Helium

Excited States	W	α	β	\bar{W}_j	Ω	F	A.F.
2 ¹ P	21.220	1.000	2.100	21.220	0.750	0.405400	0.0
3 ¹ P	23.090	1.000	2.000	23.090	0.750	0.114600	0.0
4 ¹ P	23.740	1.000	1.850	23.740	0.750	0.045760	0.0
n > 4 ¹ P	23.900	1.000	1.850	23.900	0.750	0.072000	0.0
2 ¹ S	9.500	1.000	3.000	20.610	1.000	0.032360	0.0
3 ¹ S	9.500	1.000	3.000	22.920	1.000	0.007324	0.0
4 ¹ S	9.510	1.000	3.000	23.670	1.000	0.002830	0.0
5 ¹ S	9.630	1.000	3.000	24.010	1.000	0.001450	0.0
n > 5 ¹ S	9.630	1.000	3.000	24.150	1.000	0.003100	0.0
3 ¹ D	21.000	2.000	1.000	23.020	1.000	0.003774	0.0
4 ¹ D	21.590	2.000	1.000	23.730	1.000	0.001630	0.0
5 ¹ D	22.200	2.000	1.000	24.040	1.000	0.000862	0.0
n > 5 ¹ D	24.130	2.000	1.000	24.130	1.000	0.001780	0.0
2 ³ S	19.820	0.785	1.000	19.820	3.000	0.137300	0.0
3 ³ S	20.100	1.060	1.000	22.720	3.000	0.038680	0.0
4 ³ S	20.460	1.280	1.000	23.590	3.000	0.016320	0.0
n > 4 ³ S	23.910	1.280	1.000	23.910	3.000	0.025800	0.0
2 ³ P	20.960	0.124	1.000	20.960	3.000	1.200000	0.0
3 ³ P	23.010	0.133	1.000	23.010	3.000	0.317000	0.0
4 ³ P	23.710	0.133	1.000	23.710	3.000	0.134000	0.0
n > 4 ³ P	23.910	0.133	1.000	23.910	3.000	0.212000	0.0

Ionization State	I _i	K	K _B	J	J _B	J _C	Γ _S	Γ _B	T _S	T _A	T _B
He ⁺	24.580	1.190	0.0	10.200	0.0	0.0	15.000	0.0	2.050	1310.0	101.000

A.F. refers to the autoionization factor (or branching ratio for ionization). Equation (1) used here.

Following the philosophy outlined above, we represent the cross sections for the dominant ¹P states of helium by fitting (1) to the renormalized data of Donaldson et al. [1972] for the cross sections of the 2¹P, 3¹P, and 4¹P states. We present the renormalized data and our fits to it in Figure 4. To represent the ¹S states, we fit (1) to the results of Dillon and Lassetre

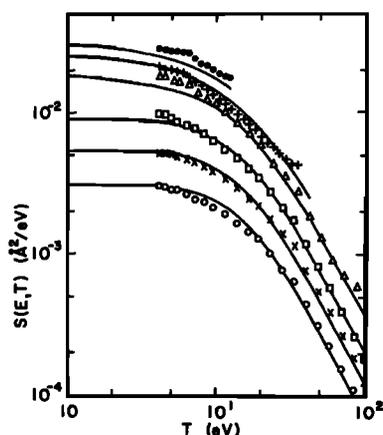


Fig. 5. The differential cross section $S(E, T)$ for helium plotted against the secondary energy T for selected incident energies E . The solid circles represent values at 50 eV; pluses, 100 eV; triangles, 200 eV; squares, 500 eV; crosses, 1000 eV; and open circles, 2000 eV. These are the renormalized data of Opal et al. [1972]. The solid lines are our fits to this data using the parameters listed in Table 7.

[1975] for the 2¹S state and to the renormalized 4¹S, 5¹S, and 6¹S data of van Raan et al. [1971]. The 3¹S state cross section was obtained by assuming that the dependence of this cross section on energy is the same as that of the 4¹S state but that W and F of (1) are different. We obtained the amplitude F for the 3¹S state from the F value for the 4¹S state by using the rule $F = F^*/(n-\delta)^3$ discussed previously. We represent the cross sections for the ¹D states by fitting the renormalized data of van Raan et al. for the 4¹D, 5¹D, and 6¹D parameters in the manner described above for the 3¹S state.

For the triplet state cross sections there are no theoretical calculations with the accuracy of the Inokuti-Kim singlet cross section calculations. Consequently, the data we chose were not renormalized as the singlet data were. Since the triplet cross sections are negligible except at energies below 100 eV, we do not feel that this lack of a reliable standard for the magnitude of these cross sections will have any significant effect on most degradation calculations involving these cross sections. We used the data of Jobe and St. John [1967] as corrected for cascade by F. J. de Heer and R. H. J. Jansen (unpublished manuscript, 1975) as the basis of our analytic representation of the 2³S state, and we used the data of van Raan et al. [1971] to obtain our representation of the 4³S state. We used this latter fit to obtain the 3³S state cross section in the manner discussed above for the 3¹S cross section.

Last, we represent the cross sections of the 3³P states by using the data of van Raan et al. for the 4³P state; we obtained the 3³P cross section from the fit to the 4³P state.

For each of the series discussed above, whether singlet or triplet, we summed the contribution from the higher Rydberg members by representing them as a single state whose cross section is given by (1) with an amplitude given by $F^*/[2(n - \frac{1}{2} - \delta)^2]$. The quantum defects were obtained from calculations of Seaton [1966]. The parameters which, with (1), characterize each of the cross sections discussed above are presented in Table 7.

The principal data for the differential ionization cross section $S(E, T)$ of helium is that of Opal et al. [1972]. We have renormalized this data to the total ionization cross section obtained by F. J. De Heer and R. H. J. Jansen (unpublished manuscript, 1975) by averaging the results of five experimental groups (see de Heer and Jansen for the details of this averaging procedure). We then fit this renormalized $S(E, T)$ data with (3). The renormalized data and our fits to them are presented in Figure 5, and the parameters characterizing our fit are presented in Table 7.

4. Conclusion

In this work we have presented revised sets of inelastic electron impact cross sections for the six gases which are principal constituents of planetary atmospheres. These cross sections describe all the relevant excitations produced by electron impact on these gases in the energy range from threshold to 10 keV. The characterizations of the cross sections of these gases are revised to varying degrees and incorporate the most recent and accurate data. All the cross sections are represented by simple analytic forms, which makes their communication direct and unambiguous and facilitates their use in any energy degradation calculation. A complete set of parameters for cross sections for nine gases including H_2 , Ar, and H_2O is available upon request.

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References

- Ajello, J. M., Emission cross sections of CO_2 by electron impact in the interval 1260-4500Å, II, J. Chem. Phys., **55**, 3169, 1971.
- Boksenberg, A., Electron collision processes in dissociated molecular gases, Ph.D. thesis, Univ. of London, London, 1961.
- Cermak, V., Electron spectroscopy of autoionizing states of oxygen, chlorine, and bromine atoms, J. Electron. Spectrosc. Relat. Phenomena, **6**, 135, 1975.
- Christensen, A. B., Observations of O I 7774Å emission excited by conjugate photoelectrons, Planet. Space Sci., **23**, 831, 1975.
- Chung, S., and C. C. Lin, Electron excitation of electronic states of the CO molecule, Phys. Rev. Sect. A, **9**, 1954, 1974.
- Dalgarno, A., and G. Lejeune, The absorption of electrons in atomic oxygen, Planet. Space Sci., **19**, 1653, 1971.
- Dehmer, P. M., and W. A. Chupka, Nonstatistical emission from metastable autoionizing states of O I*, J. Chem. Phys., **62**, 584, 1975.
- Dehmer, P. M., J. Berkowitz, and W. A. Chupka, Photo-ionization of atomic oxygen from 920-650Å, J. Chem. Phys., **59**, 5777, 1973.
- Dillon, M. A., and E. N. Lassette, A collision cross section study of the $1^1S \rightarrow 2^1P$ and $1^1S \rightarrow 2^1S$ transitions in helium at kinetic energies from 200-700 eV. Failure of the Born approximation at large momentum changes, J. Chem. Phys., **62**, 2373, 1975.
- Donaldson, F. G., M. A. Hender, and J. W. McConkey, Vacuum ultraviolet measurements of the electron impact excitation of helium, Proc. Phys. Soc. London, Sect. B, **5**, 1192, 1972.
- Fite, W. L., and R. T. Brackmann, Ionization of atomic oxygen on electron impact, Phys. Rev., **113**, 815, 1959.
- Green, A. E. S., and C. A. Barth, Calculations of ultraviolet molecular nitrogen emissions from the aurora, J. Geophys. Res., **70**, 1083, 1965.
- Green, A. E. S., and C. A. Barth, Calculations of the photoelectron excitation of the day-glow, J. Geophys. Res., **72**, 3975, 1967.
- Green, A. E. S., and T. Sawada, Ionization cross sections and secondary electron distributions, J. Atmos. Terr. Phys., **34**, 1719, 1972.
- Green, A. E. S., C. H. Jackman, and R. H. Garvey, Electron impact on atmospheric gases, 2, Yield spectra, J. Geophys. Res., **82**, in press, 1977.
- Hake, R. D., Jr., and A. V. Phelps, Momentum-transfer and inelastic collision cross sections for electrons in O_2 , CO and CO_2 , Phys. Rev., **158**, 70, 1967.
- Henry, R. J. W., and M. B. McElroy, Photoelectrons in planetary atmospheres, in Atmospheres of Venus and Mars, pp. 251-285, Gordon and Breach, New York, 1968.
- Huffman, R. E., J. C. Larrabee, and Y. Tanaka, New absorption spectra of atomic and molecular oxygen in the vacuum ultraviolet, I, Rydberg series from O I ground state and new excited O_2 bands, J. Chem. Phys., **46**, 2213, 1967.
- Inokuti, M., and Y. K. Kim, Total cross sections for inelastic scattering of charged particles by atoms and molecules, III, Accurate Bethe cross sections for ionization of helium, Phys. Rev., **186**, 100, 1969.
- Jobe, J. D., and R. M. St. Johns, Absolute measurements of the 2^1P and 2^3P electron excitation cross sections of helium atoms, Phys. Rev., **164**, 117, 1967.
- Julienne, P. S., and J. Davis, Cascade and radiation trapping effects on atmospheric atomic oxygen emission excited by electron impact, J. Geophys. Res., **81**, 1397, 1976.
- Jusick, A. T., C. E. Watson, L. R. Peterson, and A. E. S. Green, Electron impact cross sections for atmospheric species, 1, Helium, J. Geophys. Res., **72**, 3943, 1967.
- Kazaks, P. A., P. S. Ganas, and A. E. S. Green, Electron-impact excitation and ionization of atomic oxygen, Phys. Rev. Sect. A, **6**, 2169, 1972.
- Kieffer, L. J., and G. H. Dunn, Electron impact ionization cross section data for atoms, atomic ions and diatomic molecules: I. Experimental data, Rev. Mod. Phys., **38**, 1, 1966.
- Lawrence, G. M., Dissociative excitation of some oxygen-containing molecules: Lifetimes and electron-impact cross sections, Phys. Rev. Sect. A, **2**, 397, 1970.

- Mumma, M. J., Dissociative excitation of atmospheric gases, Ph.D. thesis, Univ. of Pittsburgh, Pittsburgh, Pa., 1970.
- Opal, C. B., E. C. Beaty, and W. K. Peterson, Tables of secondary electron-production cross sections, At. Data, 4, 209, 1972.
- Peterson, L. R., T. Sawada, J. N. Bass, and A. E. S. Green, Electron energy deposition in a gaseous mixture, Comp. Phys. Com., 5, 239, 1973.
- Porter, H. S., C. H. Jackman, and A. E. S. Green, Efficiencies for production of atomic nitrogen and oxygen by relativistic proton impact in air, J. Chem. Phys., 65, 154, 1976.
- Rothe, E. W., L. L. Marino, R. H. Neynaber, and S. M. Trujillo, Electron impact ionization of atomic hydrogen and atomic oxygen, Phys. Rev., 125, 582, 1962.
- Sawada, T., and P. S. Ganas, Distorted-wave calculations of electron-impact excitation of atomic oxygen, Phys. Rev. Sect. A., 7, 617, 1973.
- Sawada, T., D. L. Sellin, and A. E. S. Green, Electron impact excitation cross sections and energy degradation in CO, J. Geophys. Res., 77, 4819, 1972.
- Sawada, T., D. J. Strickland, and A. E. S. Green, Electron energy deposition of CO₂, J. Geophys. Res., 77, 4812, 1972.
- Seaton, M. J., Quantum defect theory, II, Illustrative one-channel and two-channel problems, Proc. Phys. Soc. London, 88, 815, 1966.
- Smith, K., R. J. W. Henry, and P. G. Burke, Calculations on the scattering of electrons by atomic systems with configurations 2p⁴, Phys. Rev., 157, 51, 1967.
- Stone, E. J., and E. C. Zipf, Excitation of the O I(³S) and N I(⁴P) resonance states by electron impact on O and N, Phys. Rev. Sect. A, 4, 610, 1971.
- Stone, E. J., and E. C. Zipf, Electron-impact excitation of the 3s⁰ and 5s⁰ states of atomic oxygen, J. Chem. Phys., 60, 4237, 1974.
- Thomas, L. D., and R. K. Nesbet, Low-energy electron scattering by atomic oxygen, Phys. Rev. Sect. A., 11, 170, 1975.
- van Raan, A. F. J., J. P. deJongh, J. van Eck, and H. G. M. Heideman, Absolute cross sections for excitation of helium by electrons (20-2000 eV) and the polarization of the emitted radiation, Physica, 53, 45, 1971.
- van Tassal, R. A., R. E. Huffman, and J. L. Roebber, Atomic oxygen oscillator strengths in the autoionization region, I, The absolute strength of the 5s' lines, J. Chem. Phys., 59, 5926, 1973.
- Wiese, W. L., M. W. Smith, and B. M. Glennon, Atomic transition probabilities, vol. 1, Hydrogen through neon, Nat. Stand. Ref. Data Ser. Nat. Bur. Stand., 1966.

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