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Electron Energy Loss Rates in N_2 , O_2 and Air

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Plasma Physics Division

August 28, 1984

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The rate of energy loss by low energy electrons in N₂, O₂ and air are calculated for an Electron Maxwellian velocity distribution. For each species the rate coefficients for energy loss to specific inelastic processes are presented. These processes are the vibrational excitation, dissociation, electronic excitations and ionization of the species.				
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ELECTRON ENERGY LOSS RATES IN N_2 , O_2 AND AIR

I. INTRODUCTION

For discharge modeling in N_2 , O_2 and air one needs to know the rates of electron energy loss to various inelastic processes. To obtain these rates one requires a set of established electron-molecule scattering cross sections for the inelastic processes in N_2 and O_2 . These cross sections are then utilized with the appropriate electron velocity distribution to generate the collision rate coefficients and the energy loss rate coefficients to each individual inelastic process.

In this report we provide the electron energy loss rate coefficients in N_2 , O_2 and air for a Maxwellian electron velocity distribution.

II. ELECTRON ENERGY LOSS RATE COEFFICIENTS IN N_2

A set of cross sections for the electron nitrogen collisions was given recently¹ which was a revision of a previous set². These cross sections have been utilized³ to obtain the rate coefficients for the various inelastic processes in N_2 for a Maxwellian electron velocity distribution. Using these data with the appropriate threshold energies^{4,5} the rate coefficients of the electron energy loss in N_2 , O_2 and air were developed and some results⁶ were given in graphical forms in Ref. (4). However, the detailed account of these energy loss processes are provided in this report.

Table I gives the coefficients for the electron energy loss rate to the important triplet states of N_2 i.e. $A^3\Pi$, $B^3\Pi$, $C^3\Pi$, $W^3\Delta$ and $B^3\Sigma$. The coefficients are also shown in Figures 1a and 1b.

Table II gives the electron energy loss rate coefficients to several singlet states ($W^1\Delta$, $a'^1\Sigma$ and $a^1\Pi$) whose excitation energies are below 12 eV. These rate coefficients are shown graphically in Figures 2a and 2b. All other singlet states and triplets above 12 eV and a fraction of $a^1\Pi$ (18%) are

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assumed to predissociate and are included⁷ in the total dissociation rate of N_2 .

Table III shows the electron energy loss rate coefficients to the dissociation and ionization of N_2 (Columns 3 and 4, respectively). These rates are also shown in Figure 3.

The rate coefficient for energy loss to eight vibrational levels is given in Table III (Column 5) and is shown graphically in Figure 4.

The total rate coefficient for energy loss in N_2 is given in Table III (Column 6) and is shown in Figure 5 along with the contributions of various processes discussed above.

III. ELECTRON ENERGY LOSS RATE COEFFICIENTS IN O_2

The rate coefficients for the electron energy loss in O_2 are presented in Table IV. Columns 1 and 2 of this table give the coefficients for energy loss to the lowest lying metastable states $a^1\Delta$ and $b^1\Sigma$. Two dissociation channels for O_2 are presented through the $B^3\Sigma$ state and the sum of $A^3\Sigma + C^3\Delta + C^1\Sigma$ states with different dissociation thresholds. The rate coefficients for energy loss to these dissociations are shown in Columns 3 and 4 of Table IV.

The coefficient for energy loss to ionization is given by Column 5 of Table IV while Column 6 presents the coefficient for energy loss to the vibrational levels of O_2 . The coefficient for the total energy loss is given in Column 7 of Table IV. All these coefficients which are tabulated in Table IV are shown graphically in Figures 6a and 6b.

IV. ELECTRON ENERGY LOSS RATE COEFFICIENT IN AIR

The rate coefficients for the energy loss by electrons in N_2 and O_2 , given in Tables III and IV, are utilized to obtain the coefficient for energy

loss in air by using the following relation

$$R(\text{Air}) = 0.8 R(\text{N}_2) + 0.2 R(\text{O}_2) \quad (1)$$

Here $R(\text{N}_2)$ and $R(\text{O}_2)$ are the coefficients for electron energy loss in N_2 and O_2 , respectively. The rate coefficients obtained using equation (1) are given in Table V and are shown in Figure 7 along with the total energy loss coefficients in N_2 and O_2 . It is obvious from Figure 7 that the energy loss rate in air is slightly lower than the energy loss in N_2 .

Table 1 — Rate coefficients for energy loss in N_2 (eV-cm³/sec)

T_e (eV)	A^3_Σ	B^3_π	W^3_Δ	$\hat{B}^3_\Sigma$	C^3_π
0.2	2.02 (-22)(*)	1.02 (-24)	7.43 (-25)	7.66 (-27)	7.22 (-32)
0.3	6.66 (-18)	3.25 (-19)	2.01 (-19)	7.7 (-21)	8.37 (-24)
0.4	1.28 (-15)	1.93 (-16)	1.11 (-16)	8.2 (-18)	9.40 (-20)
0.5	3.19 (-14)	9.18 (-15)	5.10 (-15)	5.5 (-16)	2.61 (-17)
0.6	2.82 (-13)	1.22 (-13)	6.71 (-14)	9.43 (-15)	1.12 (-15)
0.7	1.38 (-12)	7.86 (-13)	4.30 (-13)	7.26 (-14)	1.67 (-14)
0.8	4.64 (-12)	3.21 (-12)	1.76 (-12)	3.40 (-13)	1.26 (-13)
0.9	1.21 (-11)	9.63 (-12)	5.33 (-12)	1.14 (-12)	6.17 (-13)
1.0	2.60 (-11)	2.4 (-11)	1.3 (-11)	2.9 (-12)	2.0 (-12)
1.2	8.6 (-11)	8.8 (-11)	5.1 (-11)	1.3 (-11)	1.4 (-11)
1.5	2.283(-10)	3.3 (-10)	2.0 (-10)	6.0 (-11)	9.1 (-11)
2.0	8.02 (-10)	1.2 (-9)	8.8 (-10)	2.8 (-10)	5.8 (-10)
2.5	1.66 (-9)	2.7 (-9)	2.1 (-9)	6.9 (-10)	1.8 (-9)
3.0	2.84 (-9)	4.5 (-9)	3.8 (-9)	1.2 (-9)	3.4 (-9)
4.0	5.36 (-9)	8.4 (-9)	8.1 (-9)	2.6 (-9)	7.9 (-9)
5.0	8.02 (-9)	1.2 (-8)	1.2 (-8)	3.8 (-9)	1.2 (-8)

(*) 2.02 (-22) implies 2.02×10^{-22}

Table 1 (Cont'd) — Rate coefficients for energy loss in N_2 (eV-cm³/sec)

T_e (eV)	A^3_Σ	B^3_π	W^3_Δ	$\hat{B}^3_\Sigma$	C^3_π
6.0	9.87 (-9)	1.5 (-8)	1.5 (-8)	5.0 (-9)	1.7 (-8)
7.0	1.17 (-8)	1.7 (-8)	1.7 (-8)	5.8 (-9)	2.0 (-8)
8.0	1.29 (-8)	1.8 (-8)	2.0 (-8)	6.5 (-9)	2.2 (-8)
9.0	1.38 (-8)	1.9 (-8)	2.1 (-8)	7.0 (-9)	2.3 (-8)
10	1.48 (-8)	2.0 (-8)	2.2 (-8)	7.4 (-9)	2.5 (-8)
11	1.51 (-8)	2.0 (-8)	2.3 (-8)	7.7 (-9)	2.5 (-8)
12	1.54 (-8)	2.0 (-8)	2.4 (-8)	7.9 (-9)	2.6 (-8)
13	1.60 (-8)	2.0 (-8)	2.4 (-8)	8.0 (-9)	2.6 (-8)
14	1.60 (-8)	2.0 (-8)	2.4 (-8)	8.2 (-9)	2.6 (-8)
15	1.60 (-8)	2.0 (-8)	2.4 (-8)	8.2 (-9)	2.6 (-8)
16	1.50 (-8)	2.0 (-8)	2.4 (-8)	8.2 (-9)	2.6 (-8)
17	1.66 (-8)	2.0 (-8)	2.3 (-8)	8.2 (-9)	2.6 (-8)
18	1.66 (-8)	2.0 (-8)	2.3 (-8)	8.2 (-9)	2.6 (-8)
19	1.66 (-8)	2.0 (-8)	2.2 (-8)	8.2 (-9)	2.5 (-8)
20	1.66 (-8)	2.0 (-8)	2.2 (-8)	8.1 (-9)	2.5 (-8)

Table II — Rate coefficients for energy loss to N_2 singlets ($eV\text{-cm}^3/\text{sec}$)

$T_e(eV)$	$a^1\Sigma^-$	$a^1\pi$	$w^1\Delta$
0.2	2.15 (-27)	2.69 (-27)	2.98 (-28)
0.3	3.18 (-21)	5.10 (-21)	1.13 (-21)
0.4	4.11 (-18)	7.39 (-18)	2.38 (-18)
0.5	3.13 (-16)	6.02 (-16)	2.41 (-16)
0.6	5.76 (-15)	1.16 (-14)	5.37 (-15)
0.7	4.70 (-14)	9.73 (-14)	5.00 (-14)
0.8	2.29 (-13)	4.86 (-13)	2.69 (-13)
0.9	8.00 (-13)	1.72 (-12)	1.00 (-12)
1.0	2.2 (-12)	4.5 (-12)	2.5 (-12)
1.2	1.0 (-11)	2.2 (-11)	1.4 (-11)
1.5	4.7 (-11)	1.1 (-10)	6.2 (-11)
2.0	2.2 (-10)	5.4 (-10)	3.0 (-10)
2.5	2.6 (-10)	1.5 (-9)	7.6 (-10)
3	1.0 (-9)	2.9 (-9)	1.3 (-9)
4	2.1 (-9)	6.7 (-9)	2.8 (-9)
5	3.1 (-9)	1.1 (-8)	4.0 (-9)

Table II (Cont'd) — Rate coefficients for energy loss to N_2 singlets ($eV\text{-cm}^3/\text{sec}$)

$\tau_e(eV)$	$\hat{a} \ 1 \Sigma^-$	$a \ 1 \pi$	$W \ 1 \Delta$
6	3.9 (-9)	1.5 (-8)	5.0 (-9)
7	4.7 (-9)	1.9 (-8)	5.8 (-9)
8	5.2 (-9)	2.2 (-8)	6.3 (-9)
9	5.6 (-9)	2.6 (-8)	6.7 (-9)
10	5.9 (-9)	2.8 (-8)	6.9 (-9)
11	6.1 (-9)	3.0 (-8)	7.0 (-9)
12	6.3 (-9)	3.2 (-8)	7.1 (-9)
13	6.5 (-9)	3.3 (-8)	7.1 (-9)
14	6.6 (-9)	3.4 (-8)	7.2 (-9)
15	6.6 (-9)	3.5 (-8)	7.0 (-9)
16	6.7 (-9)	3.6 (-8)	7.0 (-9)
17	6.8 (-9)	3.7 (-8)	6.8 (-9)
18	6.8 (-9)	3.7 (-8)	6.7 (-9)
19	6.9 (-9)	3.8 (-8)	6.6 (-9)
20	6.9 (-9)	3.8 (-8)	6.4 (-9)

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Table III — Rate of energy loss in $N_2(eV\cdot cm^3/sec)$

$T_e(eV)$	TRIPLETS	SINGLETs	DISS.	ION.	VIB.	TOTAL
0.2	2.02 (-22)	4.65 (-27)	8.51 (-30)		8.0 (-12)	8.0 (-12)
0.3	7.1 (-18)	8.5 (-21)	1.01 (-22)		9.2 (-11)	9.2 (-11)
0.4	1.48 (-15)	1.25 (-17)	3.66 (-19)	6.60 (-25)	7.7 (-10)	7.7 (-10)
0.5	4.7 (-14)	1.0 (-15)	5.1 (-17)	1.82 (-21)	1.7 (-9)	1.7 (-9)
0.6	4.8 (-13)	2.06 (-15)	1.4 (-15)	3.66 (-19)	2.7 (-9)	2.7 (-9)
0.7	2.7 (-12)	1.76 (-13)	1.6 (-14)	1.65 (-17)	4.1 (-9)	4.1 (-9)
0.8	1.01 (-11)	6.54 (-13)	9.96 (-14)	2.91 (-16)	5.2 (-9)	5.2 (-9)
0.9	2.91 (-11)	3.2 (-12)	4.3 (-13)	2.7 (-15)	6.1 (-9)	6.1 (-9)
1.0	6.2 (-11)	8.39 (-12)	1.44 (-12)	1.67 (-14)	6.8 (-9)	6.85 (-9)
1.5	9.1 (-10)	2.03 (-11)	6.46 (-11)	4.11 (-12)	8.6 (-9)	9.59 (-9)
2.0	3.7 (-9)	9.99 (-10)	5.01 (-10)	7.01 (-11)	8.8 (-9)	1.41 (-8)
2.5	8.95 (-9)	2.68 (-9)	1.82 (-9)	4.05 (-10)	8.0 (-9)	1.74 (-8)
3	1.57 (-8)	5.0 (-9)	4.47 (-9)	1.34 (-9)	7.2 (-9)	3.37 (-8)
4	3.2 (-8)	1.14 (-8)	1.44 (-8)	6.42 (-9)	6.0 (-9)	7.02 (-8)
5	4.78 (-8)	1.78 (-8)	3.02 (-8)	1.71 (-8)	5.0 (-9)	1.18 (-7)

Table III (Cont'd) — Rate of energy loss in $N_2(eV\text{-cm}^3/\text{sec})$

$T_e(\text{ev})$	TRIPLETS	SINGLETs	DISS.	ION.	VIB.	TOTAL
6	6.2 (-8)	2.38 (-8)	5.04 (-8)	3.4 (-8)		1.70 (-9)
7	7.15 (-8)	2.95 (-8)	7.35 (-8)	5.7 (-8)		2.31 (-7)
8	7.94 (-8)	3.37 (-8)	9.8 (-8)	8.6 (-8)		2.97 (-7)
9	8.38 (-8)	3.83 (-8)	1.24 (-7)	1.2 (-7)		3.66 (-7)
10	8.9 (-8)	4.11 (-8)	1.51 (-7)	1.6 (-7)		4.4 (-7)
11	9.08 (-8)	4.33 (-8)	1.76 (-7)	1.9 (-7)		5.0 (-7)
12	9.33 (-8)	4.56 (-8)	2.01 (-7)	2.3 (-7)		5.69 (-7)
13	9.4 (-8)	4.68 (-8)	2.25 (-7)	2.8 (-7)		6.46 (-7)
14	9.4 (-8)	4.82 (-8)	2.49 (-7)	3.3 (-7)		7.2 (-7)
15	9.42 (-8)	4.9 (-8)	2.72 (-7)	3.8 (-7)		7.95 (-7)
16	9.42 (-8)	5.01 (-8)	2.94 (-7)	4.2 (-7)		8.58 (-7)
17	9.38 (-8)	5.09 (-8)	3.15 (-7)	4.7 (-7)		9.28 (-7)
18	9.38 (-8)	5.09 (-8)	3.36 (-7)	5.1 (-7)		9.89 (-7)
19	9.18 (-8)	5.18 (-8)	3.55 (-7)	5.6 (-7)		10.58 (-7)
20	9.17 (-8)	5.16 (-8)	3.74 (-7)	6.1 (-7)		11.27 (-7)

Table IV — Rate coefficients for energy loss in O_2 (eV-cm³/sec)

T_e (eV)	a^1_Δ	b^1_Σ	B^3_Σ	$A^3_\Sigma + \dots$	ION.	VIB.	TOTAL
0.2	2.18 (-13)	2.81 (-14)	2.56 (-23)	2.75 (-19)	8.45 (-35)	2.26 (-11)	2.28 (-11)
0.4	7.87 (-12)	2.10 (-12)	1.07 (-16)	1.97 (-14)	1.53 (-21)	3.89 (-11)	4.88 (-11)
0.6	3.3 (-11)	1.10 (-11)	6.88 (-14)	9.33 (-13)	4.47 (-17)	3.95 (-11)	8.35 (-11)
0.8	7.36 (-11)	8.71 (-11)	2.66 (-12)	6.92 (-12)	8.12 (-15)	3.58 (-11)	1.46 (-10)
1.0	1.24 (-10)	4.82 (-11)	2.54 (-11)	2.41 (-11)	1.92 (-13)	3.14 (-11)	2.53 (-10)
1.5	2.7 (-10)	1.08 (-10)	5.37 (-10)	1.41 (-10)	1.45 (-11)	2.27 (-11)	9.65 (-10)
2.0	4.13 (-10)	1.64 (-10)	2.51 (-9)	3.69 (-10)	1.42 (-10)	9.99 (-12)	3.61 (-9)
2.5	5.35 (-10)	2.11 (-10)	6.41 (-9)	6.88 (-10)	5.94 (-10)	7.14 (-12)	8.44 (-9)
3	6.35 (-10)	2.47 (-10)	1.20 (-8)	1.06 (-9)	1.63 (-9)	6.5 (-12)	1.55 (-8)
4	7.77 (-10)	3.01 (-10)	2.64 (-8)	1.90 (-9)	6.21 (-9)	5.8 (-12)	3.55 (-8)
5	8.65 (-10)	3.37 (-10)	4.25 (-8)	2.71 (-9)	1.48 (-8)	5.74 (-12)	6.12 (-8)
6	9.1 (-10)	3.63 (-10)	5.85 (-8)	3.44 (-9)	2.77 (-8)		8.96 (-8)
7	9.5 (-10)	3.83 (-10)	7.33 (-8)	4.09 (-9)	4.46 (-8)		12.3 (-8)

Table IV (Cont'd) — Rate coefficients for energy loss in $O_2(eV\text{-}cm^3/sec)$

$T_e(eV)$	$a^1\Delta$	$b^1\Sigma$	$B^3\Sigma$	$A^3\Sigma + \dots$	ION.	VIB.	TOTAL
8	9.68 (-10)	3.97 (-10)	8.67 (-8)	4.60 (-9)	6.50 (-8)		15.76 (-8)
9	9.77 (-10)	4.10 (-10)	9.94 (-8)	5.03 (-9)	8.83 (-8)		19.4 (-8)
10	9.79 (-10)	4.18 (-10)	1.09 (-7)	5.37 (-9)	1.13 (-7)		2.27 (-7)
11	9.77 (-10)	4.25 (-10)	1.19 (-7)	5.67 (-9)	1.41 (-7)		2.65 (-7)
12	9.72 (-10)	4.3 (-10)	1.28 (-7)	5.89 (-9)	1.71 (-7)		3.05 (-7)
13	9.64 (-10)	4.33 (-10)	1.36 (-7)	6.06 (-9)	2.01 (-7)		3.43 (-7)
14	9.54 (-10)	4.35 (-10)	1.43 (-7)	6.19 (-9)	2.31 (-7)		3.81 (-7)
15	9.43 (-10)	4.35 (-10)	1.49 (-7)	6.27 (-9)	2.64 (-7)		4.19 (-7)
16	9.3 (-10)	4.35 (-10)	1.54 (-7)	6.36 (-9)	2.95 (-7)		4.55 (-7)
17	9.18 (-10)	4.32 (-10)	1.59 (-7)	6.41 (-9)	3.28 (-7)		4.93 (-7)
18	9.07 (-10)	4.30 (-10)	1.64 (-7)	6.45 (-9)	3.60 (-7)		5.3 (-7)
19	8.91 (-10)	4.27 (-10)	1.69 (-7)	6.45 (-9)	3.9 (-7)		5.65 (-7)
20	8.76 (-10)	4.24 (-10)	1.72 (-7)	6.45 (-9)	4.2 (-7)		5.98 (-7)

Table V — Rate coefficients for energy loss in air(eV-cm³/sec)

T_e (eV)	0.8R(N ₂)	0.2R(O ₂)	R(AIR)
0.2	6.4 (-12)	4.55 (-12)	1.09 (-11)
0.4	6.16 (-10)	9.76 (-12)	6.26 (-10)
0.6	2.16 (-9)	1.67 (-11)	2.17 (-9)
0.8	4.16 (-9)	2.92 (-11)	4.18 (-9)
1.0	5.48 (-9)	5.06 (-11)	5.53 (-9)
1.5	7.67 (-9)	1.93 (-10)	7.86 (-9)
2.0	1.13 (-8)	7.22 (-10)	1.20 (-8)
2.5	1.39 (-8)	1.68 (-9)	1.56 (-8)
3	2.69 (-8)	3.10 (-9)	3.00 (-8)
4	5.6 (-8)	7.10 (-9)	6.31 (-8)
5	9.44 (-8)	1.22 (-8)	10.66 (-8)
6	1.36 (-7)	1.79 (-8)	1.54 (-7)
7	1.85 (-7)	2.46 (-8)	2.09 (-7)
8	2.37 (-7)	3.15 (-8)	2.68 (-7)
9	2.93 (-7)	3.88 (-8)	3.32 (-7)
10	3.52 (-7)	4.54 (-8)	3.97 (-7)

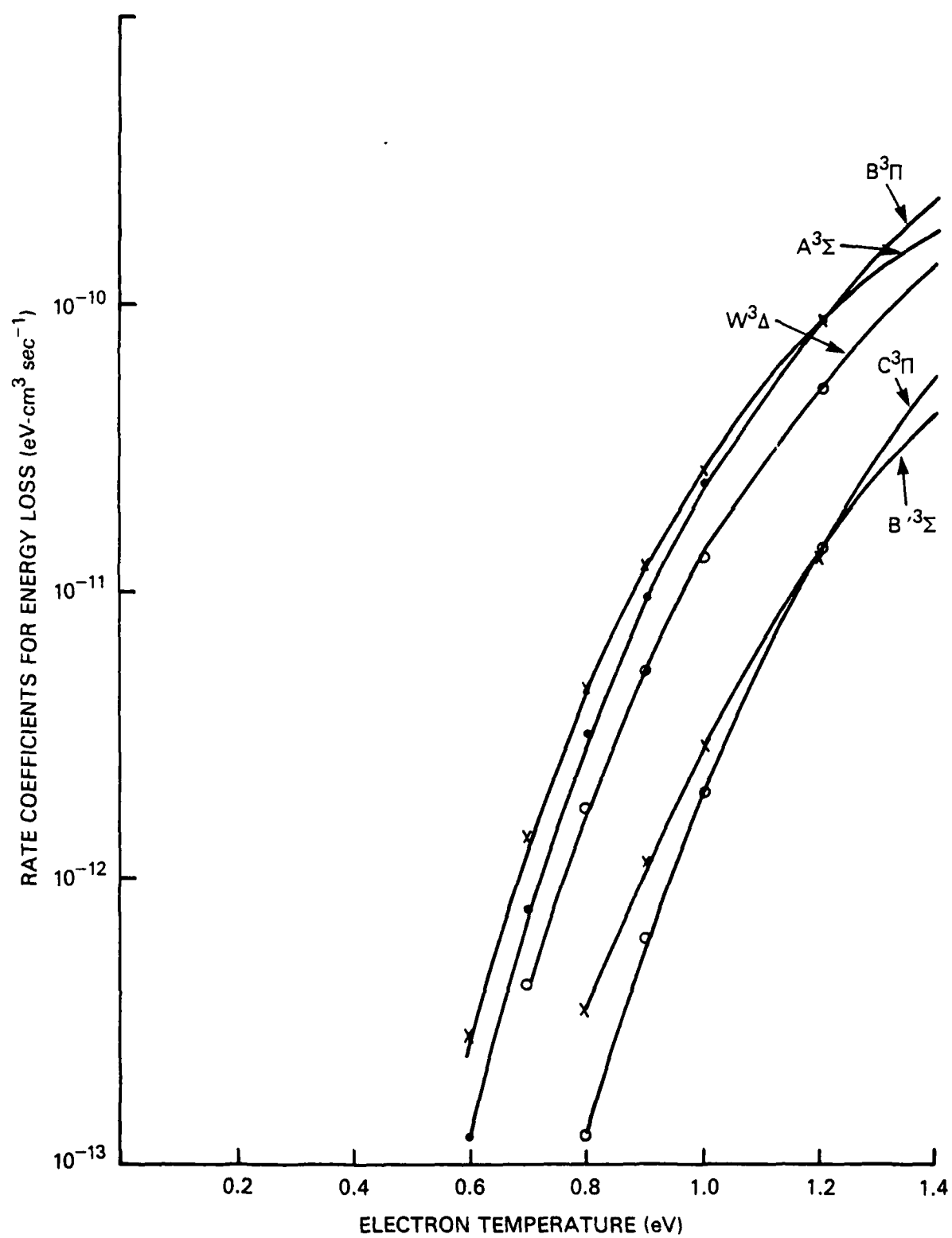


Figure 1a Electron energy loss rate coefficients to triplet states in nitrogen

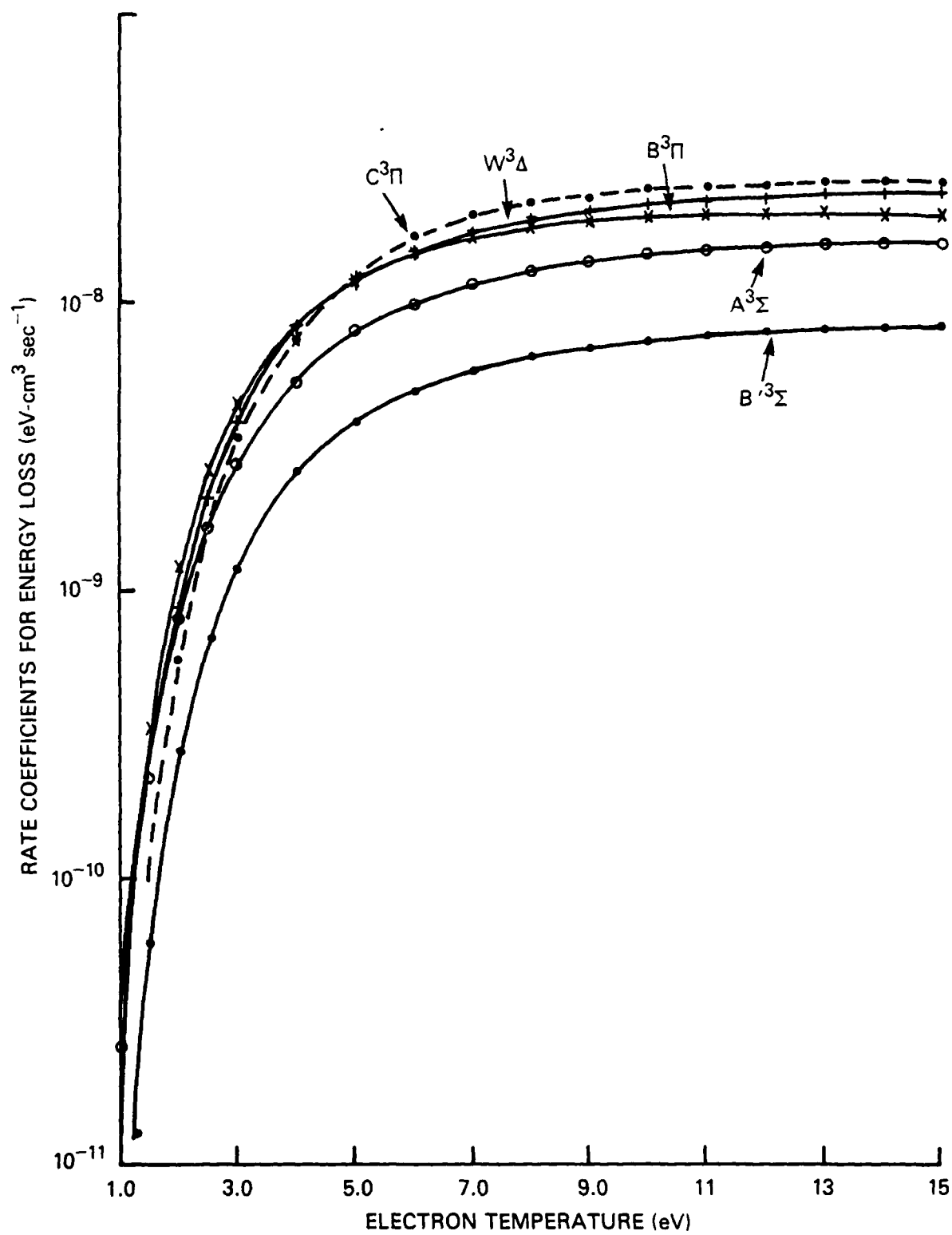


Figure 1b Electron energy loss rate coefficients to triplet states in nitrogen

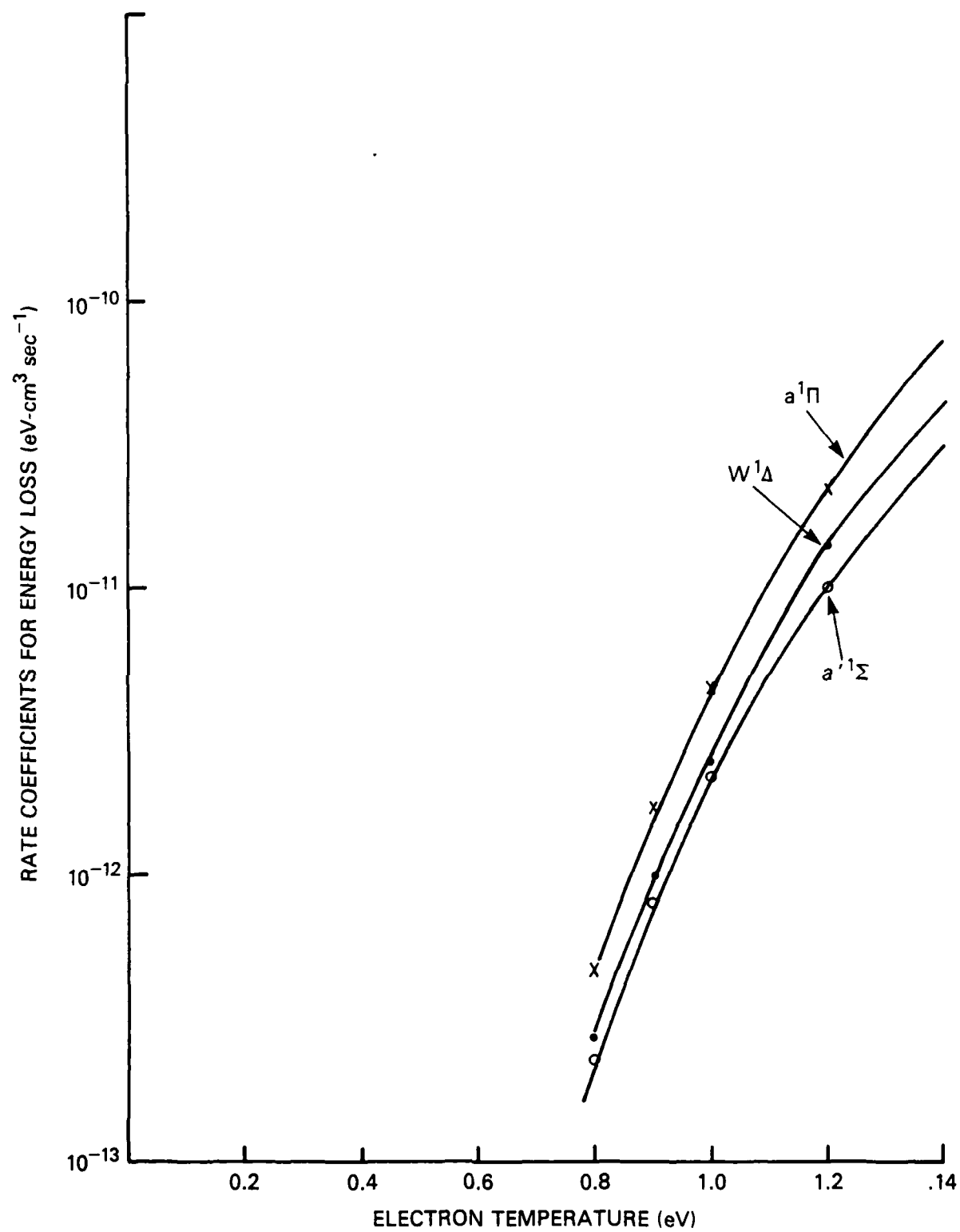


Figure 2a Electron energy loss rate coefficients to singlet states in nitrogen

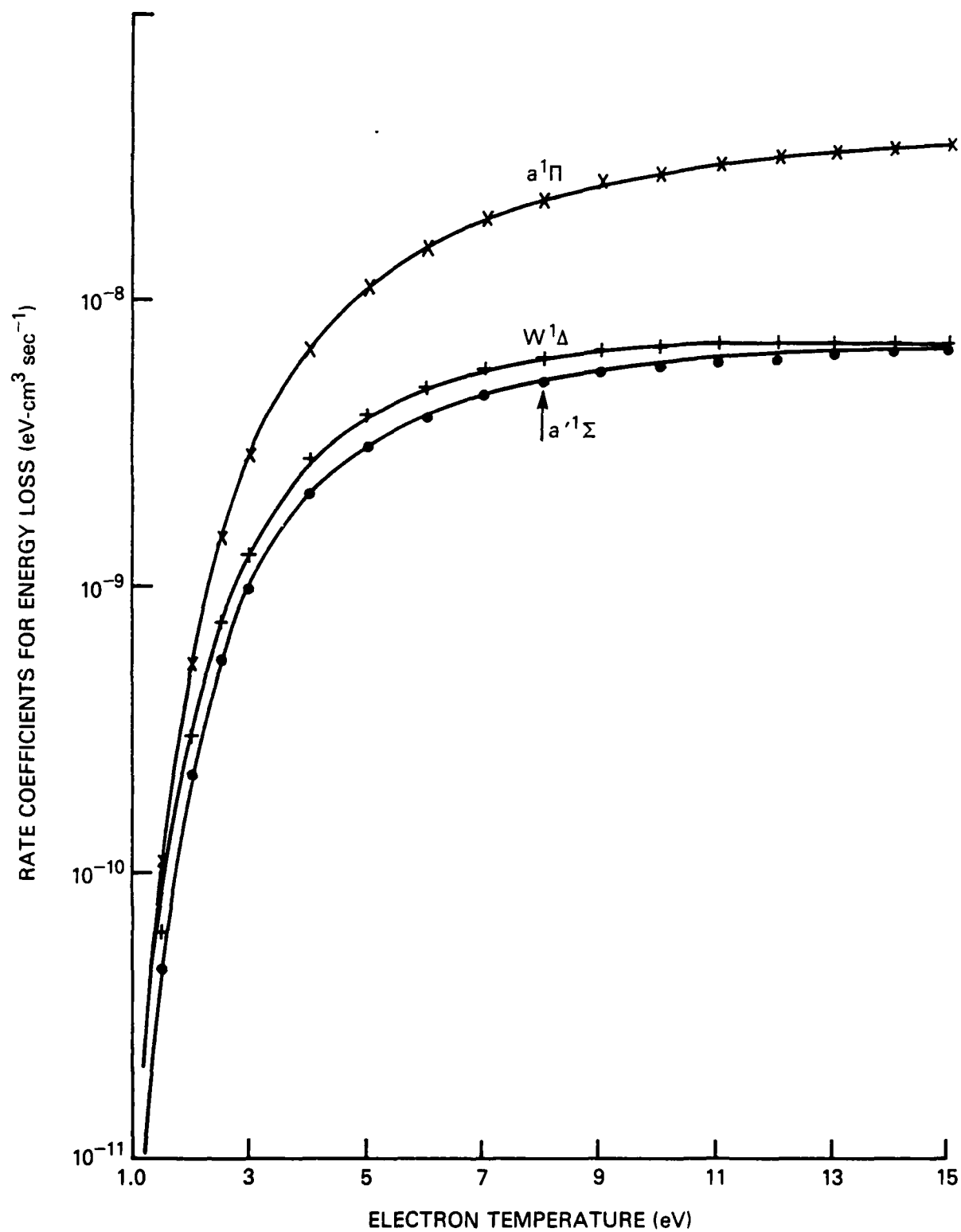


Figure 2b Electron energy loss rate coefficients to singlet states in nitrogen

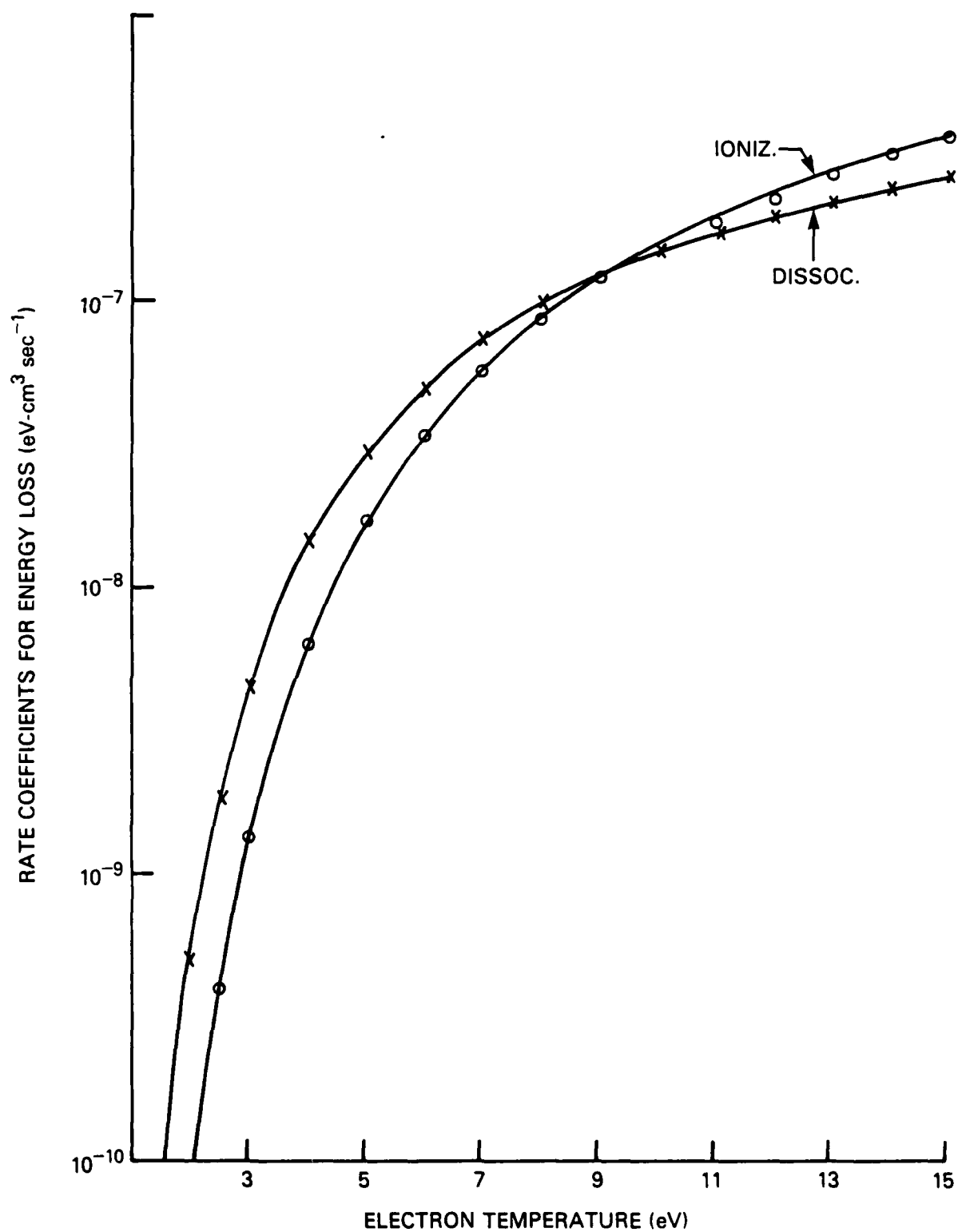


Figure 3 Electron energy loss rate coefficients to ionization and dissociation in nitrogen

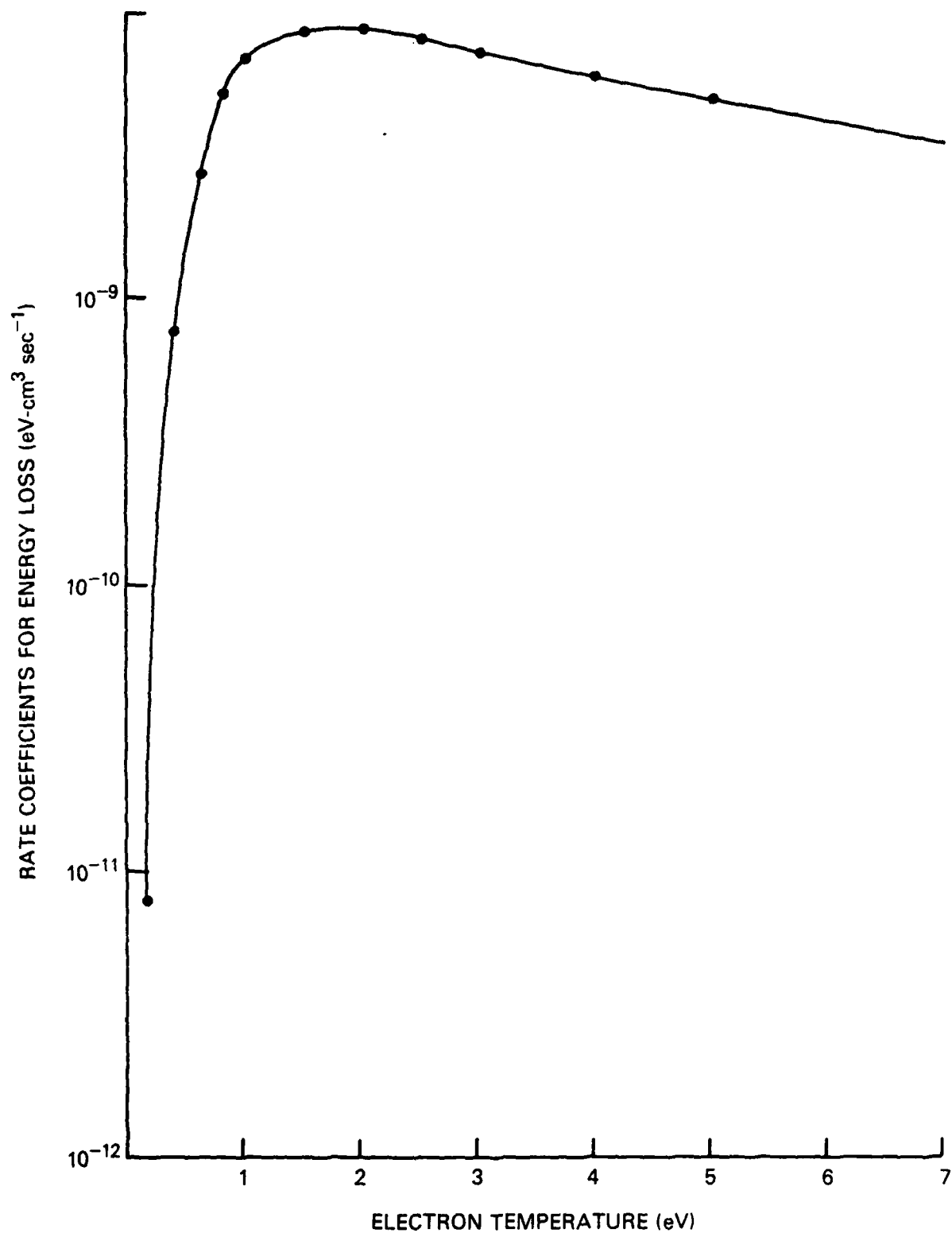


Figure 4 Electron energy loss rate coefficients for the vibrational excitation of nitrogen

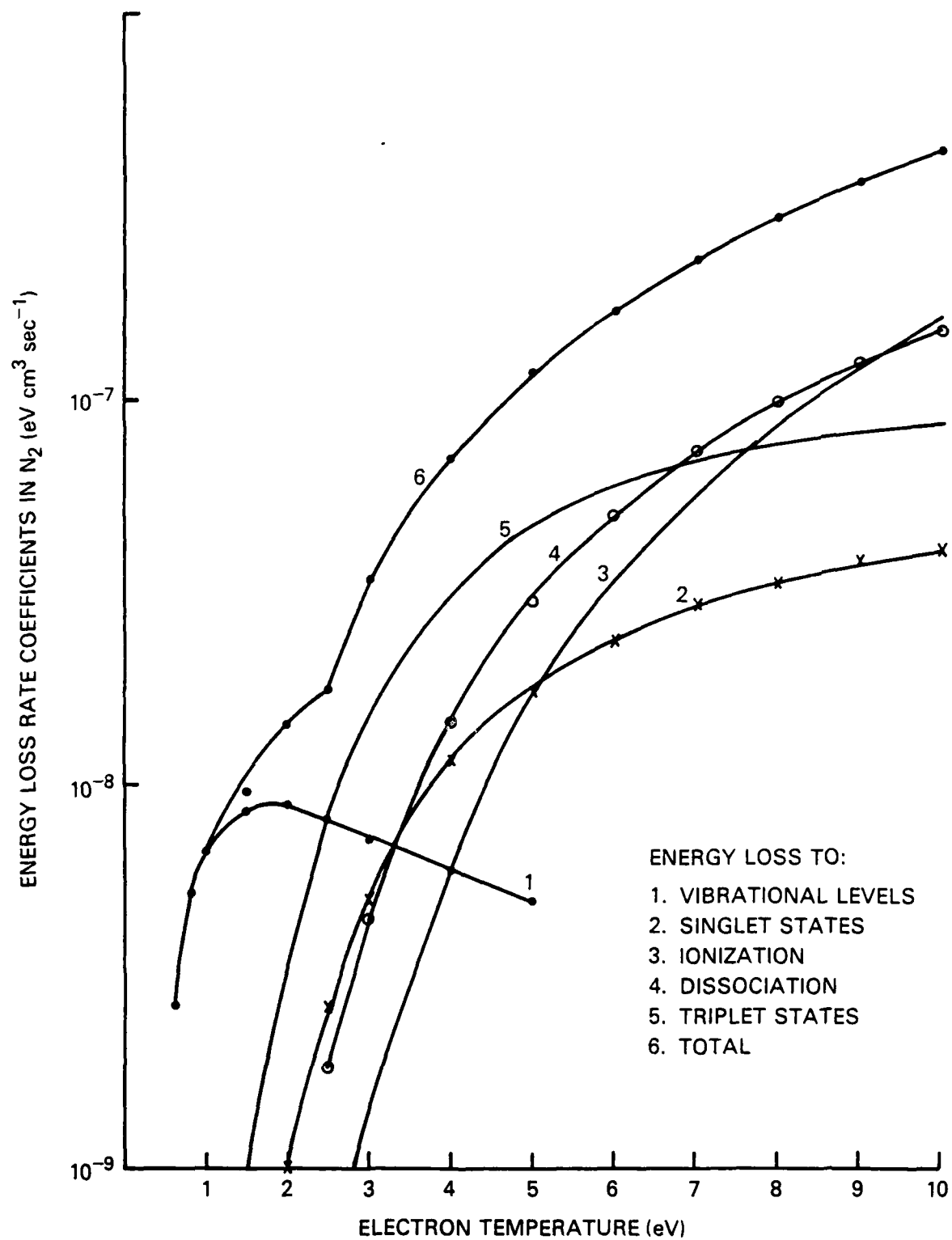


Figure 5 Total electron energy loss rate coefficient and its components in nitrogen

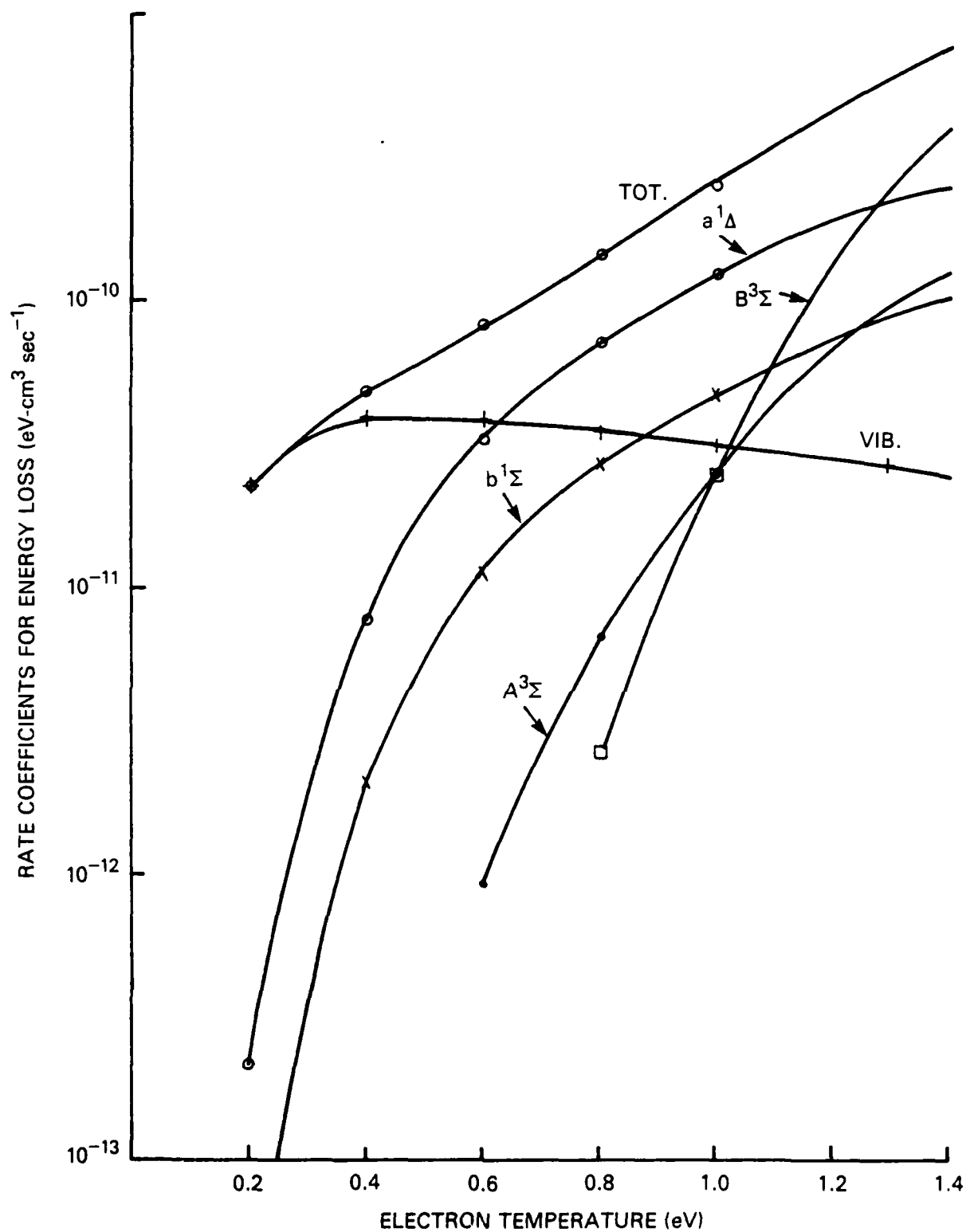


Figure 6a Total electron energy loss rate coefficient and its components in oxygen

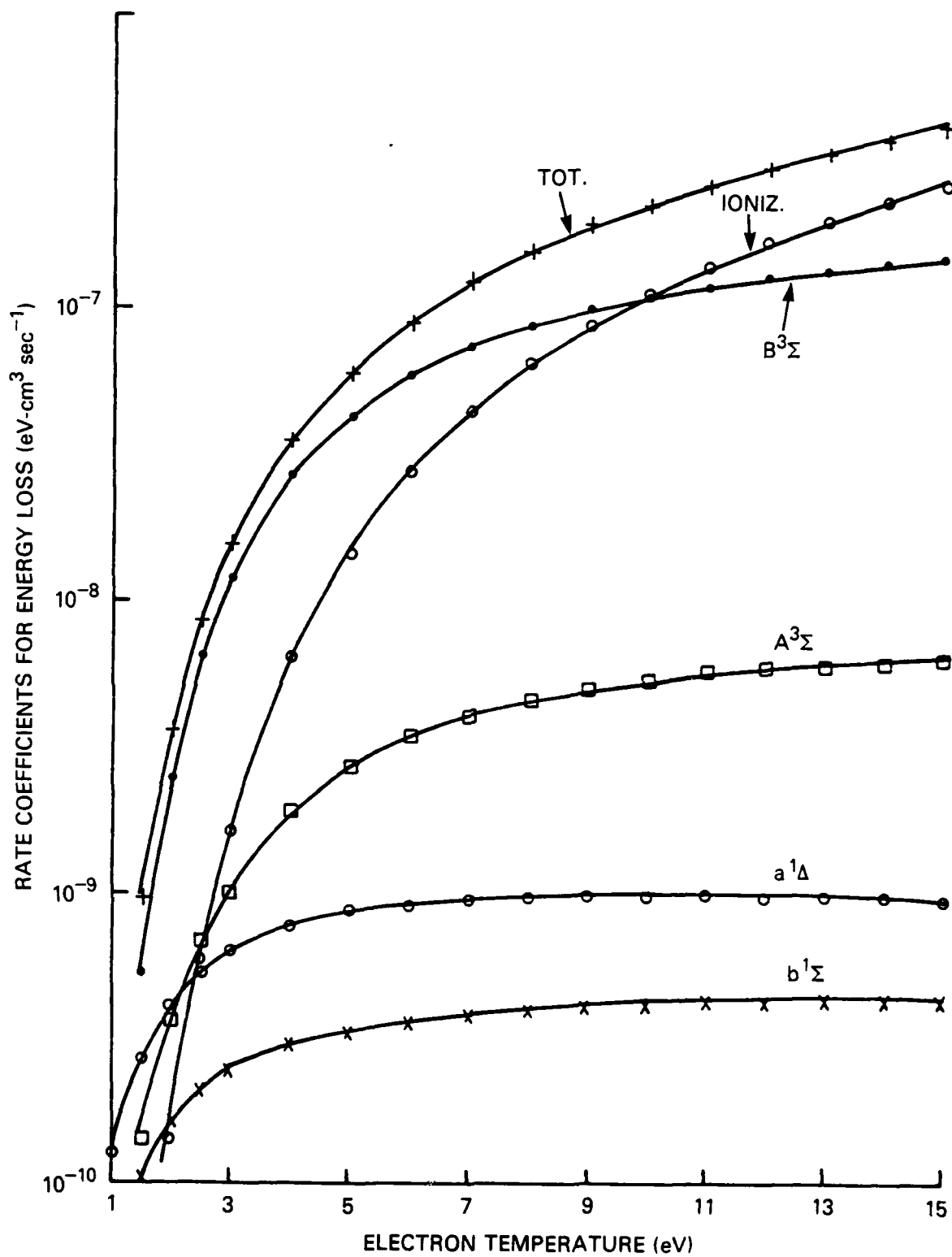


Figure 6b^c Total electron energy loss rate coefficient and its components in oxygen

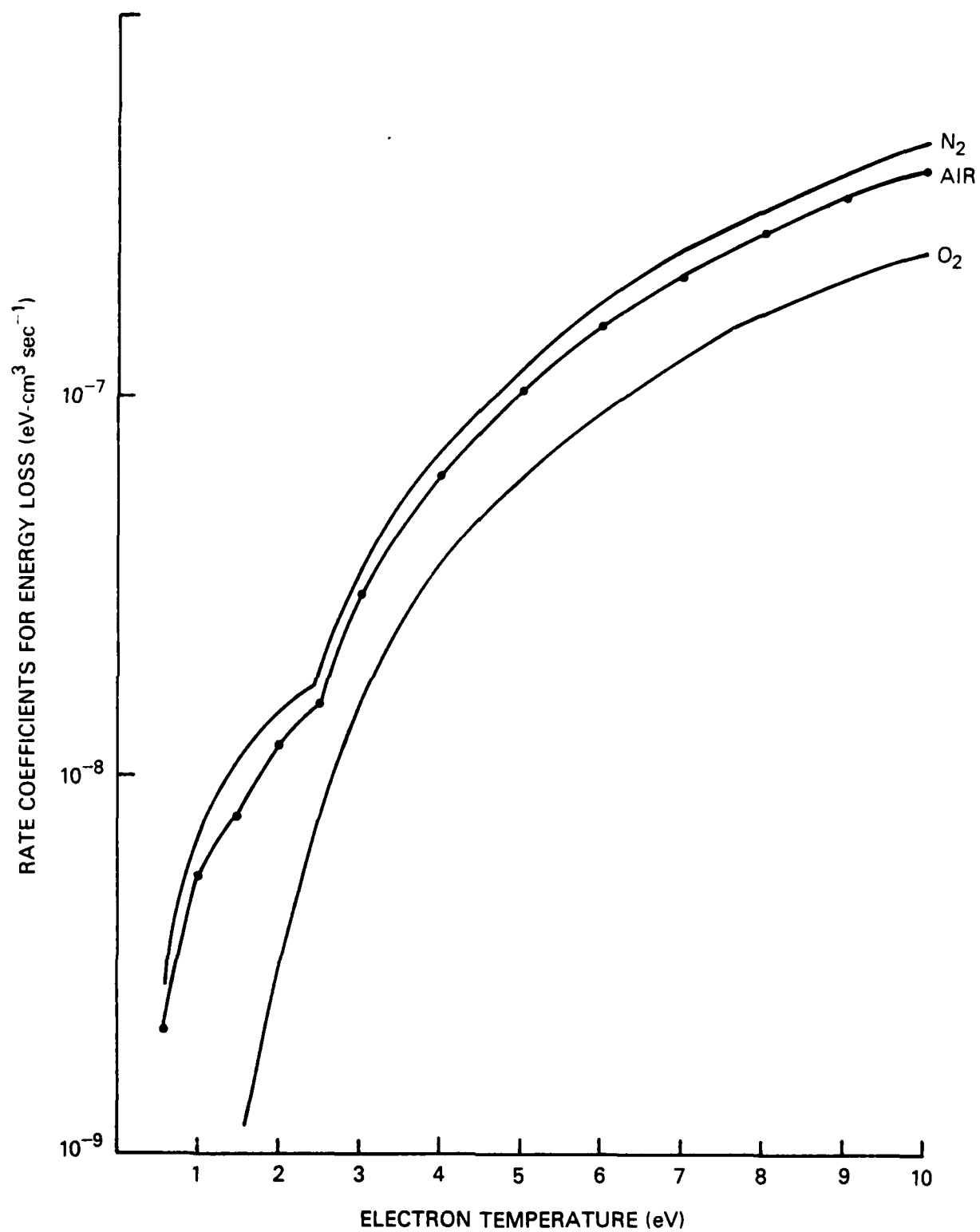


Figure 7 Total electron energy loss rate coefficients in N_2 , O_2 and air

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