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Low-Energy Electron Impact Rate Coefficients for Some Atmospheric Species

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Low-Energy Electron Impact Rate Coefficients
for Some Atmospheric Species

by

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Abstract

Low-energy electron impact excitation and ionization rate coefficients, relevant to ionospheric species, are calculated using measured or calculated cross sections.

I. Introduction

In a disturbed E and F region where ionization has occured under the influence of VUV radiation, the ejected photoelectrons possess energies of the order of several eV or higher. These electrons lose their energies through inelastic collisions with species present in the disturbed regions. The inelastic processes include ionization, electronic excitations of the atoms, atomic ions, molecules and molecular ions, and vibrational excitations of the molecules. For electrons with a few tenths of an eV energy, rotational

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excitations[1] of the molecules and the fine structure[2] excitations of the ground-state atomic oxygen may become important energy loss processes. However, in this report, the latter two processes are not considered. In addition to the usefulness of these rate coefficients to the understanding of a UV fireball, one may use them for the modeling of the every day ionosphere and other atmospheric phenomena such as day-glow, aurorae, etc.

II. Rate Coefficient

If $\sigma_{ij}(E)$ denotes the cross-section as a function of the incident electron energy E, for either the excitation or ionization of atoms, ions, or molecules, the relevant rate coefficient can be expressed as

$$X_{ij} \equiv \langle \sigma_{ij} v \rangle = K_o T^{-3/2} \int E \, \sigma_{ij}(E) \, e^{-E/T} \, dE \qquad (1)$$

where $K_o = 6.697 \times 10^7$, T is the electron temperature in units of electron volts (eV), and $\langle \sigma v \rangle$ implies the average of σ with v, the electron velocity, over an electron Maxwellian velocity distribution. In Equation (1) one may use either experimentally measured or theoretically calculated cross sections. Generally, one obtains a fit[3] for σ over the entire range if an analytic expression is not available.

The atmospheric species of interest, whose relevant excitation and ionization rate coefficients are calculated here, are N_2, N_2^+, N, O_2, and O.

A. N_2

A.1 Vibrational Excitation Rate Coefficients

The electron impact excitation rate coefficients for eight ground-state vibrational levels of N_2 are shown in Figure 1. Schultz'[4] measured cross sections, shown in Figure 2, were used. Numerical values of these rates in the electron temperature range of 0.1 - 5 eV are given in Table 1.

A.2 Electronic Excitation Rate Coefficients

The electron impact excitation cross sections of $A^3\Sigma_u^+$, $B^3\pi_g$, $C^3\pi_u$, $D^3\Sigma_+^+$, and $E^3\Sigma_g^+$ triplet states of N_2 calculated by Cartwright[5] are shown on Figures 3-7, respectively. The corresponding excitation rate coefficients are shown on Figures 8-12. Numerical values of these rates are given in Table II for the electron temperature range of 0.1-5 eV.

The excitation rate coefficient of ($a^1\pi$) of N_2 is given in Table III. This rate was obtained using the cross section given in Reference 1.

A.3 Ionization Rate Coefficient

The ionization cross section of N_2 as measured by Tate and Smith[6] is shown in Figure 13. The corresponding rate coefficient is shown in Figure 14. Numerical values of this rate are given in Table II for an electron temperature range of 0.1-5 eV.

B. N_2^+

B.1 The Electronic Excitation Rate Coefficient

The excitation of N_2^+ first negative band can occur directly as a result of the collision between energetic electrons and the nitrogen molecule. The cross section[7] for this process is shown in Figure 15 and the corresponding rate coefficient in Figure 16. Numerical values of this rate are given in Table II.

The same band can be excited by low-energy electrons in collisions with the ground state of N_2^+. The Lee and Carlton's[8] measured cross section for this process is shown in Figure 17. The excitation rate coefficient using this cross-section is given in Table IV. However, we believe that the cross section is too large and thus the corresponding rate should be modified. In an experiment[9] at NRL it was shown that this rate may be too large by as much as a factor of 60.

C. <u>O</u>

C.1 <u>Electronic Excitation Rate Coefficient</u>

The oxygen atom possesses two low-lying electronic metastable states, i.e., $O(^1D)$ and $O(^1S)$, which are of considerable aeronomic interest. The electron impact excitation cross sections for these two states and for the $O(^1D) \rightarrow O(^1S)$ transition are shown in Figure 18, as calculated by Henry et al.[10] The corresponding excitation rate coefficients are shown in Figure 19 and are tabulated in Table V.

The electron impact excitation of the resonance state of oxygen ($O(^3P) \rightarrow O(^3S)$) has recently been measured by Stone and Zipf[11] and the cross section is shown in Figure 20. The corresponding rate coefficient is shown in Figure 21 and is given in Table V.

C.2 <u>Ionization Rate Coefficient</u>

The ionization rate coefficient for atomic oxygen is tabulated in Table V and is shown in Figure 22. This rate was obtained using the Fite and Brackmann's[12] measured cross section which is shown in Figure 23.

D. <u>N</u>

D.1 <u>Electronic Excitation Rate Coefficient</u>

Two low-lying states of the nitrogen atom, i.e., $N(^2D)$ and

$N(^2P)$, which are metastable, play important roles in the disturbed E and F layers of the ionosphere. Their excitation cross sections and that of $N(^2D) \rightarrow N(^2P)$ as calculated in Reference 10, are shown in Figure 24. The corresponding rate coefficients are shown in Figure 25 and are given in Table V.

The electron impact excitation cross section of the nitrogen resonance line $N(^4S) \rightarrow N(^4P)$ has recently been measured[11] and is shown in Figure 26. The corresponding rate coefficient is shown in Figure 27 and is given in Table V.

D.2 Ionization Rate Coefficient

The ionization rate coefficient of the nitrogen atom is shown in Figure 28 and tabulated in Table V. This rate was obtained using the measured cross section of Smith et al[13], which is shown in Figure 29.

E. O_2

E.1 Electronic Excitation Rate Coefficient

The electron impact excitation cross sections of $O_2(a^1D)$ and $O_2(b^1\Sigma)$ are shown in Figures 30 and 31, respectively. These cross sections were taken from Trajmar et al.[14] The corresponding excitation rate coefficients are shown in Figures 32 and 33, respectively. Numerical values of these rates are given in Table II.

E.2 Ionization Rate Coefficient

The electron impact ionization cross section[6] of O_2 is shown in Figure 34, and the corresponding rate is shown in Figure 35. Numerical values of the ionization rate coefficient of O_2 are given in Table II.

III. Remarks

The ionization cross sections for N_2, O_2, O, and N given in this report are from the review article of Kieffer and Dunn.[15] These and other cross sections are used to obtain the corresponding rate coefficients. However, superelastic collisions are also important in a disturbed ionosphere. Therefore, one may obtain the deexcitation rate coefficients using detailed balancing.

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Table I
Electron Impact Excitation Rate Coefficients of
Eight Ground-State Vibrational Levels of N_2

T_e/X_v	X_1	X_2	X_3	X_4	X_5	X_6	X_7	X_8
0.1	1.98(-14)*	1.49(-16)	6.28(-17)	1.57(-17)	5.58(-18)	1.37(-18)	2.27(-19)	2.51(-20)
0.2	4.01(-12)	1.48(-12)	8.81(-13)	4.16(-13)	2.16(-13)	1.14(-13)	3.28(-14)	7.81(-15)
0.3	5.63(-11)	2.82(-11)	1.83(-11)	1.05(-11)	6.20(-12)	4.13(-12)	1.45(-12)	4.31(-13)
0.4	2.08(-10)	1.14(-10)	7.59(-11)	4.76(-11)	3.02(-11)	2.24(-11)	6.71(-12)	2.85(-12)
0.5	4.38(-10)	2.52	1.68(-10)	1.11(-10)	7.33(-11)	5.77(-11)	2.39(-11)	8.26(-12)
0.6	6.96(-10)	4.11	2.74	1.88	1.27(-10)	1.04(-10)	4.47	1.60(-11)
0.7	9.43(-10)	5.66	3.77	2.65	1.82	1.52	6.76	2.47
0.8	1.16(- 9)	7.04	4.67	3.35	2.32	1.98	9.00(-11)	3.33
0.9	1.34	8.20	5.41	3.96	2.75	2.38	1.10(-10)	4.12
1.0	1.48	9.12	5.99	4.45	3.11	2.72	1.27	4.80
1.1	1.58	9.84(-10)	6.43	4.85	3.38	2.99	1.42	5.37
1.2	1.66	1.04(- 9)	6.75	5.15	3.60	3.20	1.53	5.83
1.3	1.71	1.08	6.96	5.39	3.75	3.37	1.62	6.19
1.4	1.74	1.10	7.09	5.56	3.86	3.48	1.69	6.46
1.5	1.76	1.12	7.16	5.67	3.93	3.57	1.74	6.65
1.6	1.77	1.12	7.17	5.75	3.96	3.62	1.77	6.78
1.7	1.76	1.12	7.15	5.79	3.97	3.65	1.79	6.86
1.8	1.75	1.12	7.09	5.81	3.96	3.66	1.80	6.89
1.9	1.73	1.11	7.00	5.80	3.94	3.65	1.80	6.89
2.5	1.56	1.02(- 9)	6.26	5.51	3.61	3.45	1.71	6.46
3.0	1.39	9.21(-10)	5.57	5.15	3.36	3.20	1.58	5.88
3.5	1.24	8.29	4.93	4.77	2.93	2.95	1.44	5.29
4.0	1.11(- 9)	7.47	4.38	4.43	2.64	2.73	1.32	4.74
4.5	9.95(-10)	6.74	3.90	4.12	2.38	2.55	1.21	4.24
5.0	8.96(-10)	6.11(-10)	3.49(-10)	3.84(-10)	2.16(-10)	2.39(-10)	1.12(-10)	3.80(-11)

*Numbers in parenthesis indicate powers of 10 by which the entries are to be multiplied. Where no parenthesis are given the entries are multiplied by the power of 10 for the preceding entries.

(TE) are Electron Impact Excitation Rate
tively. The Remaining Columns are the
ed Directly from the Ground State of N_2,
Ionization, Respectively.

	Z	N2+(X-B)	O2 A DEL	O2 B SIG	O2 IONIZ
	78	0.0	3.42E-14	1.27E-17	1.37E-15
	43	6.84E-50	1.81E-12	2.76E-14	1.99E-12
	32	2.16E-36	8.20E-12	4.15E-13	2.62E-11
	26	1.18E-29	1.94E-11	1.74E-12	1.04E-10
	-22	1.29E-25	3.45E-11	4.31E-12	2.51E-10
	-20	6.30E-23	5.31E-11	8.10E-12	4.69E-10
	-18	5.23E-21	7.46E-11	1.30E-11	7.56E-10
	-17	1.44E-19	9.85E-11	1.86E-11	1.10E-09
	-16	1.89E-18	1.24E-10	2.50E-11	1.51E-09
	E-15	1.49E-17	1.52E-10	3.17E-11	1.96E-09
	E-15	8.04E-17	1.80E-10	3.88E-11	2.46E-09
	E-14	3.28E-16	2.09E-10	4.60E-11	2.99E-09
	7E-14	1.08E-15	2.39E-10	5.32E-11	3.56E-09
	9E-13	3.01E-15	2.68E-10	6.05E-11	4.15E-09
	6E-13	7.30E-15	2.98E-10	6.76E-11	4.77E-09
	5E-13	1.59E-14	3.27E-10	7.46E-11	5.40E-09
	07E-12	3.16E-14	3.55E-10	8.15E-11	6.06E-09
	86E-12	5.82E-14	3.83E-10	8.82E-11	6.72E-09
	.07E-12	1.01E-13	4.10E-10	9.46E-11	7.40E-09
	.81E-12	1.65E-13	4.35E-10	1.01E-10	8.09E-09
	.25E-12	2.59E-13	4.62E-10	1.07E-10	8.78E-09
	.05E-11	3.90E-13	4.86E-10	1.13E-10	9.48E-09
	.49E-11	5.67E-13	5.09E-10	1.18E-10	1.02E-08
	2.04E-11	7.99E-13	5.32E-10	1.24E-10	1.09E-08
	2.74E-11	1.10E-12	5.53E-10	1.29E-10	1.16E-08
	3.59E-11	1.47E-12	5.73E-10	1.34E-10	1.23E-08
	4.62E-11	1.93E-12	5.93E-10	1.38E-10	1.30E-08
	5.86E-11	2.49E-12	6.11E-10	1.43E-10	1.37E-08
	7.30E-11	3.16E-12	6.29E-10	1.47E-10	1.44E-08
	8.99E-11	3.95E-12	6.45E-10	1.51E-10	1.51E-08
	1.09E-10	4.87E-12	6.62E-10	1.55E-10	1.58E-08
	1.31E-10	5.92E-12	6.77E-10	1.59E-10	1.65E-08
	1.56E-10	7.12E-12	6.92E-10	1.62E-10	1.72E-08
	1.84E-10	8.48E-12	7.06E-10	1.65E-10	1.79E-08
)	2.15E-10	1.00E-11	7.19E-10	1.69E-10	1.85E-08
0	2.49E-10	1.17E-11	7.31E-10	1.72E-10	1.92E-08
0	2.87E-10	1.36E-11	7.43E-10	1.75E-10	1.99E-08
.0	3.28E-10	1.57E-11	7.54E-10	1.77E-10	2.06E-08
.0	3.73E-10	1.79E-11	7.64E-10	1.80E-10	2.12E-08
10	4.21E-10	2.04E-11	7.74E-10	1.82E-10	2.19E-08
10	4.73E-10	2.30E-11	7.84E-10	1.85E-10	2.25E-08
-10	5.29E-10	2.59E-11	7.92E-10	1.87E-10	2.32E-08
-10	5.89E-10	2.90E-11	8.01E-10	1.89E-10	2.38E-08
-10	6.53E-10	3.23E-11	8.09E-10	1.91E-10	2.44E-08
-10	7.21E-10	3.58E-11	8.16E-10	1.93E-10	2.51E-08
-10	7.93E-10	3.95E-11	8.23E-10	1.95E-10	2.57E-08
E-10	8.69E-10	4.34E-11	8.30E-10	1.97E-10	2.63E-08
E-10	9.49E-10	4.76E-11	8.36E-10	1.98E-10	2.69E-08
E-09	1.03E-09	5.20E-11	8.42E-10	2.00E-10	2.75E-08
7E-09	1.12E-09	5.66E-11	8.48E-10	2.01E-10	2.81E-08

Table III

Electron Impact Excitation Rate Coefficient of $N_2(a^1\pi)$.

T	$X(a^1\pi)$
1.0	4.12 (-12)
1.5	6.18 (-11)
2.0	2.25 (-10)
2.5	4.67 (-10)
3.0	7.35 (-10)
3.5	9.9 (-10)
4.0	1.21 (-9)
4.5	1.40 (-9)
5.0	1.54 (-9)
5.5	1.65 (-9)
6.0	1.73 (-9)
7.0	1.83 (-9)
8.0	1.86 (-9)
9.0	1.84 (-9)
10.0	1.80 (-9)
12.0	1.68 (-9)
14.0	1.54 (-9)
16.0	1.41 (-9)
18.0	1.28 (-9)
20.0	[illegible]

Table IV
Electron Impact Excitation Rate Coefficient of O-O Band of the First Negative System of N_2^+ by Direct Excitation from the Ground State of N_2^+

T	$X(N_2^+(B))$
0.5	2.28 (-9)
1.0	7.32 (-8)
1.5	2.08 (-7)
2.0	3.24 (-7)
2.5	3.75 (-7)
3.0	4.59 (-7)
3.5	4.65 (-7)
4.0	5.05 (-7)
4.5	5.07 (-7)
5.0	5.10 (-7)

Table V

Electron Impact Excitation Rate Coefficients for the Lower Lying O and N Metastable and Resonance States. O(3p ~ 1D) Implies Excitation $O(^3p) \rightarrow O(^1D)$, etc. Atomic Oxygen and Nitrogen Ionization Rate Coefficients are Indicated under the O IONIZ and N IONIZ Columns, Respectively.

TE	O(3P-1D)	O(3P-1S)	O(1D-1S)	O(3P-3S)	O IONIZ	N(4S-2D)	N(4S-2P)	N(2D-2P)	N(4S-4P)	N IONIZ
0.1	1.73E-18	1.78E-28	1.53E-19	6.19E-49	1.10E-67	3.44E-19	3.80E-25	2.57E-14	2.37E-50	0.0
0.2	5.58E-14	1.96E-19	1.44E-14	8.17E-29	3.14E-38	6.28E-14	3.37E-17	1.18E-11	2.63E-29	0.0
0.3	2.01E-12	2.10E-16	6.99E-13	4.60E-22	2.08E-28	3.92E-12	1.67E-14	9.39E-11	3.01E-22	0.0
0.4	1.28E-11	7.13E-15	4.95E-12	1.15E-18	1.71E-23	3.19E-11	3.90E-13	2.67E-10	1.07E-18	0.0
0.5	4.00E-11	6.04E-14	1.61E-11	1.30E-16	1.55E-20	1.13E-10	2.63E-12	5.04E-10	1.50E-16	7.24E-23
0.6	8.66E-11	2.55E-13	3.53E-11	3.11E-15	1.46E-18	2.64E-10	9.46E-12	7.73E-10	4.12E-15	3.14E-20
0.7	1.52E-10	7.25E-13	6.17E-11	3.05E-14	3.81E-17	4.84E-10	2.37E-11	1.05E-09	4.48E-14	1.61E-18
0.8	2.32E-10	1.60E-12	9.40E-11	1.71E-13	4.43E-16	7.61E-10	4.73E-11	1.33E-09	2.71E-13	2.88E-17
0.9	3.24E-10	2.99E-12	1.30E-10	6.59E-13	3.01E-15	1.08E-09	8.10E-11	1.60E-09	1.11E-12	2.66E-16
1.0	4.24E-10	4.93E-12	1.69E-10	1.95E-12	1.40E-14	1.43E-09	1.25E-10	1.85E-09	3.48E-12	1.57E-15
1.1	5.30E-10	7.48E-12	2.09E-10	4.77E-12	4.95E-14	1.74E-09	1.77E-10	2.09E-09	8.89E-12	6.69E-15
1.2	6.38E-10	1.05E-11	2.49E-10	1.01E-11	1.42E-13	2.16E-09	2.37E-10	2.32E-09	1.95E-11	2.24E-14
1.3	7.47E-10	1.43E-11	2.90E-10	1.90E-11	3.50E-13	2.53E-09	3.04E-10	2.53E-09	3.83E-11	6.26E-14
1.4	8.56E-10	1.85E-11	3.29E-10	3.28E-11	7.58E-13	2.89E-09	3.75E-10	2.73E-09	6.85E-11	1.51E-13
1.5	9.63E-10	2.32E-11	3.68E-10	5.26E-11	1.49E-12	3.24E-09	4.50E-10	2.91E-09	1.14E-10	3.25E-13
1.6	1.07E-09	2.82E-11	4.05E-10	7.96E-11	2.69E-12	3.58E-09	5.28E-10	3.09E-09	1.78E-10	6.36E-13
1.7	1.17E-09	3.37E-11	4.41E-10	1.15E-10	4.54E-12	3.91E-09	6.07E-10	3.25E-09	2.64E-10	1.15E-12
1.8	1.27E-09	3.94E-11	4.76E-10	1.59E-10	7.26E-12	4.23E-09	6.87E-10	3.40E-09	3.77E-10	1.96E-12
1.9	1.36E-09	4.53E-11	5.09E-10	2.13E-10	1.11E-11	4.53E-09	7.68E-10	3.54E-09	5.18E-10	3.16E-12
2.0	1.46E-09	5.15E-11	5.41E-10	2.76E-10	1.62E-11	4.82E-09	8.48E-10	3.67E-09	6.92E-10	4.86E-12
2.1	1.54E-09	5.78E-11	5.72E-10	3.50E-10	2.29E-11	5.09E-09	9.27E-10	3.79E-09	9.01E-10	7.20E-12
2.2	1.63E-09	6.42E-11	6.01E-10	4.34E-10	3.14E-11	5.35E-09	1.01E-09	3.91E-09	1.15E-09	1.03E-11
2.3	1.71E-09	7.07E-11	6.30E-10	5.28E-10	4.20E-11	5.59E-09	1.08E-09	4.01E-09	1.43E-09	1.43E-11
2.4	1.79E-09	7.72E-11	6.57E-10	6.31E-10	5.49E-11	5.83E-09	1.16E-09	4.11E-09	1.75E-09	1.93E-11
2.5	1.87E-09	8.37E-11	6.82E-10	7.44E-10	7.03E-11	6.05E-09	1.23E-09	4.21E-09	2.12E-09	2.55E-11
2.6	1.94E-09	9.02E-11	7.07E-10	8.65E-10	8.84E-11	6.25E-09	1.30E-09	4.29E-09	2.52E-09	3.30E-11
2.7	2.01E-09	9.67E-11	7.31E-10	9.94E-10	1.09E-10	6.46E-09	1.37E-09	4.38E-09	2.96E-09	4.20E-11
2.8	2.07E-09	1.03E-10	7.53E-10	1.13E-09	1.34E-10	6.65E-09	1.44E-09	4.45E-09	3.45E-09	5.26E-11
2.9	2.13E-09	1.10E-10	7.75E-10	1.27E-09	1.61E-10	6.83E-09	1.50E-09	4.53E-09	3.97E-09	6.48E-11
3.0	2.20E-09	1.16E-10	7.96E-10	1.42E-09	1.92E-10	7.00E-09	1.57E-09	4.60E-09	4.53E-09	7.89E-11
3.1	2.25E-09	1.22E-10	8.16E-10	1.58E-09	2.26E-10	7.16E-09	1.63E-09	4.66E-09	5.13E-09	9.49E-11
3.2	2.31E-09	1.28E-10	8.35E-10	1.74E-09	2.64E-10	7.31E-09	1.69E-09	4.72E-09	5.77E-09	1.13E-10
3.3	2.36E-09	1.34E-10	8.53E-10	1.90E-09	3.05E-10	7.45E-09	1.75E-09	4.78E-09	6.44E-09	1.33E-10
3.4	2.41E-09	1.40E-10	8.71E-10	2.07E-09	3.51E-10	7.59E-09	1.80E-09	4.83E-09	7.15E-09	1.55E-10
3.5	2.46E-09	1.46E-10	8.88E-10	2.24E-09	4.00E-10	7.72E-09	1.86E-09	4.88E-09	7.89E-09	1.80E-10
3.6	2.51E-09	1.52E-10	9.04E-10	2.42E-09	4.53E-10	7.84E-09	1.91E-09	4.93E-09	8.66E-09	2.07E-10
3.7	2.55E-09	1.58E-10	9.20E-10	2.59E-09	5.09E-10	7.96E-09	1.96E-09	4.97E-09	9.46E-09	2.36E-10
3.8	2.60E-09	1.63E-10	9.35E-10	2.77E-09	5.70E-10	8.07E-09	2.01E-09	5.01E-09	1.03E-08	2.68E-10
3.9	2.64E-09	1.69E-10	9.49E-10	2.95E-09	6.34E-10	8.18E-09	2.05E-09	5.05E-09	1.11E-08	3.02E-10
4.0	2.68E-09	1.74E-10	9.63E-10	3.12E-09	7.03E-10	8.28E-09	2.10E-09	5.09E-09	1.20E-08	3.39E-10
4.1	2.71E-09	1.79E-10	9.76E-10	3.30E-09	7.75E-10	8.37E-09	2.14E-09	5.12E-09	1.29E-08	3.78E-10
4.2	2.75E-09	1.84E-10	9.89E-10	3.48E-09	8.51E-10	8.46E-09	2.18E-09	5.15E-09	1.38E-08	4.20E-10
4.3	2.78E-09	1.89E-10	1.00E-09	3.66E-09	9.30E-10	8.55E-09	2.22E-09	5.18E-09	1.48E-08	4.64E-10
4.4	2.82E-09	1.94E-10	1.01E-09	3.84E-09	1.01E-09	8.63E-09	2.26E-09	5.21E-09	1.58E-08	5.11E-10
4.5	2.85E-09	1.99E-10	1.03E-09	4.01E-09	1.10E-09	8.71E-09	2.30E-09	5.24E-09	1.67E-08	5.60E-10
4.6	2.88E-09	2.04E-10	1.04E-09	4.19E-09	1.19E-09	8.78E-09	2.33E-09	5.26E-09	1.77E-08	6.12E-10
4.7	2.91E-09	2.08E-10	1.05E-09	4.36E-09	1.29E-09	8.85E-09	2.37E-09	5.29E-09	1.87E-08	6.67E-10
4.8	2.94E-09	2.13E-10	1.06E-09	4.53E-09	1.38E-09	8.92E-09	2.40E-09	5.31E-09	1.98E-08	7.24E-10
4.9	2.96E-09	2.17E-10	1.07E-09	4.70E-09	1.49E-09	8.98E-09	2.43E-09	5.33E-09	2.08E-08	7.83E-10
5.0	2.99E-09	2.21E-10	1.08E-09	4.87E-09	1.59E-09	9.04E-09	2.46E-09	5.34E-09	2.18E-08	8.45E-10

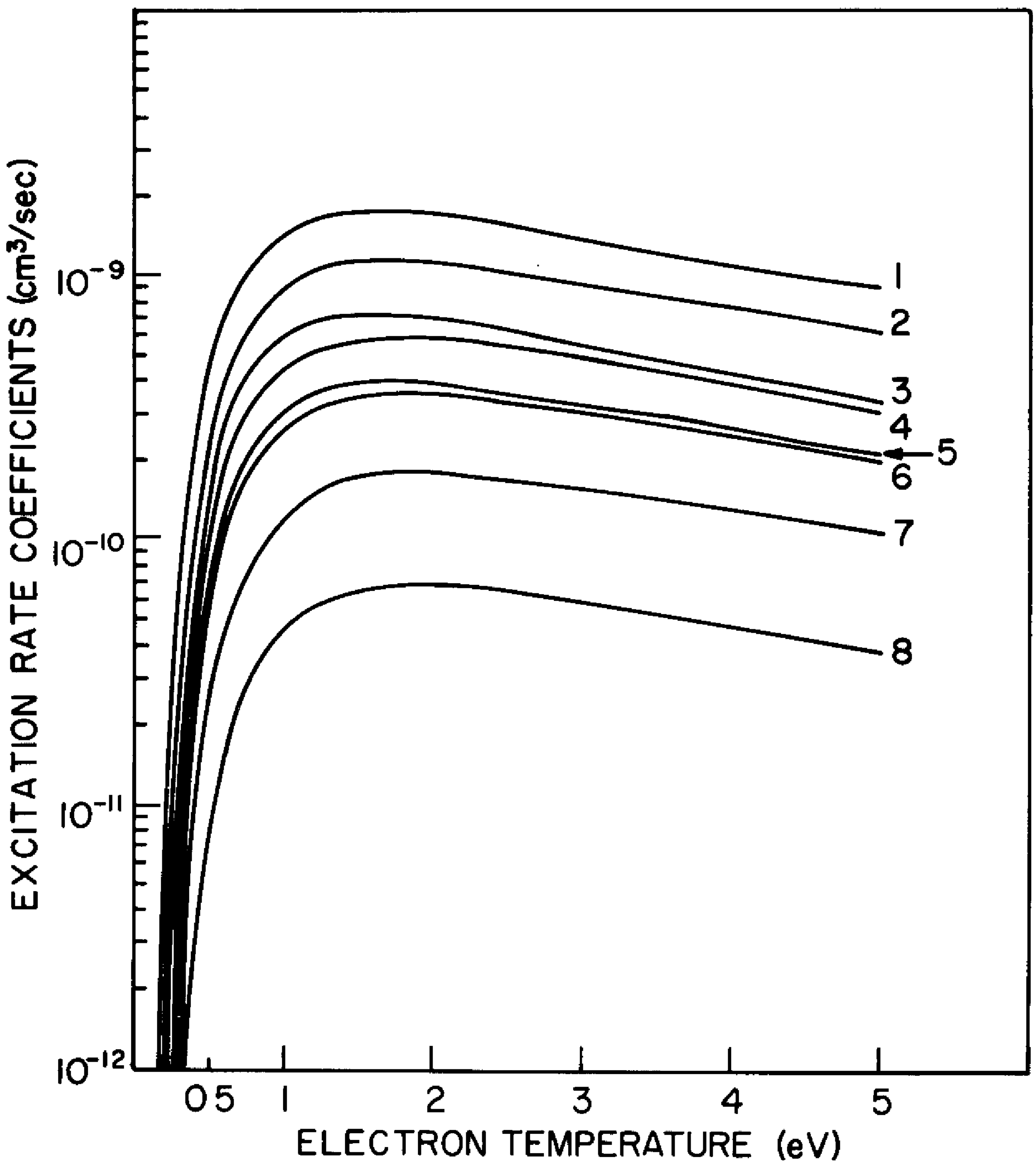

Fig. 1 – Electron impact excitation rate coefficients of N_2 vibrational levels.

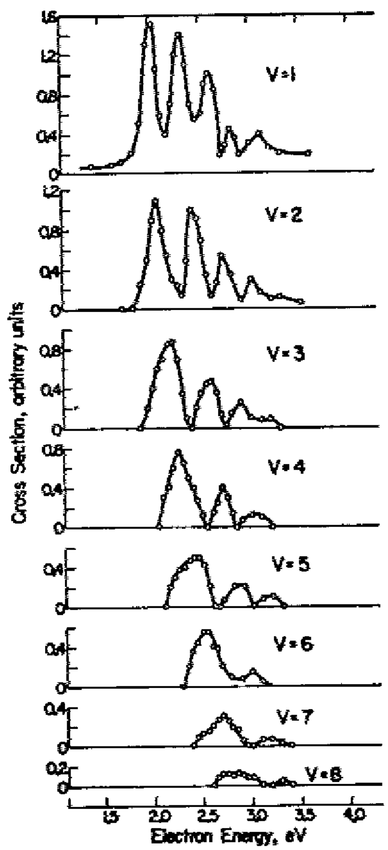

Fig. 2 – Electron impact excitation cross section of N_2 vibrational levels.

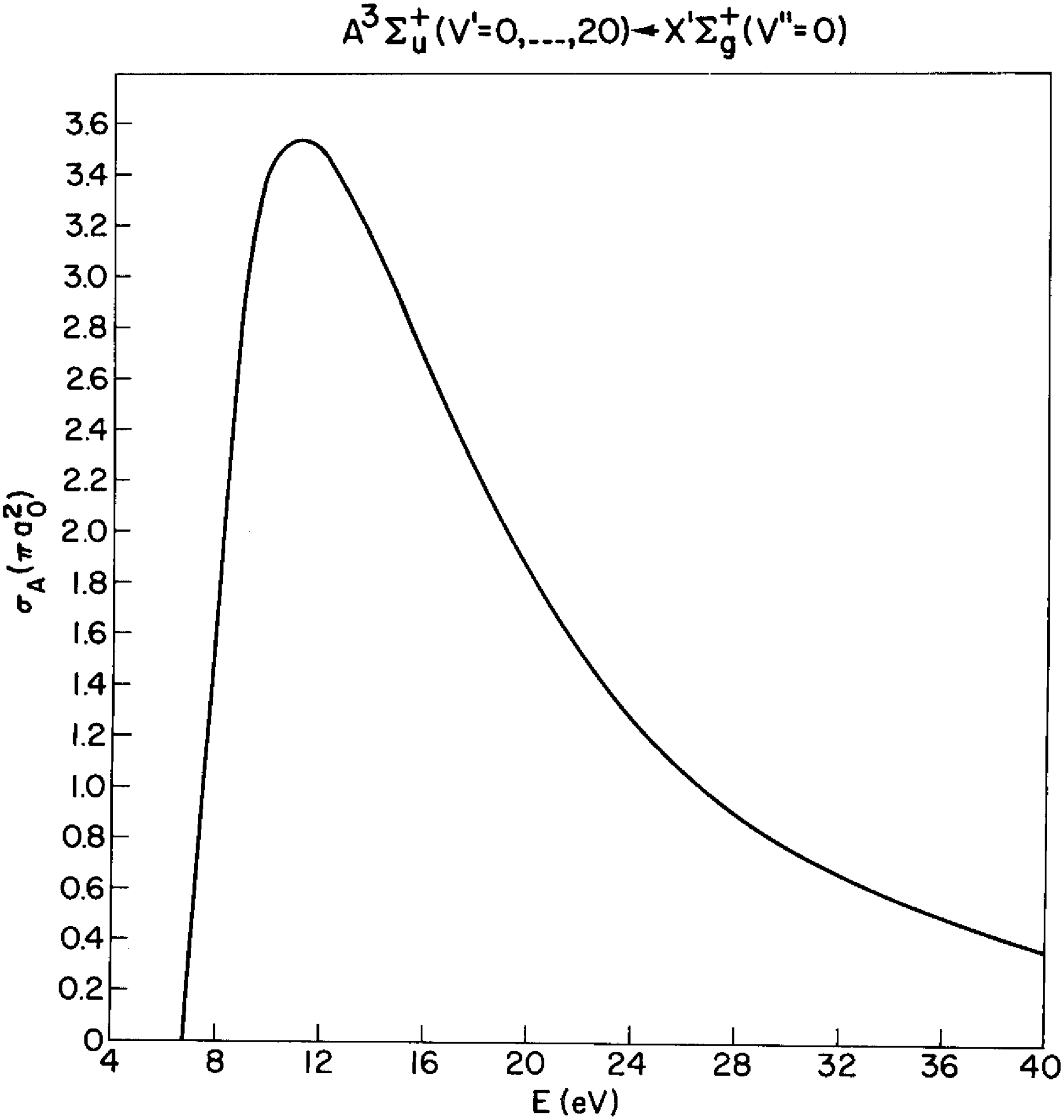

Fig. 3 – Electron impact excitation cross section of $N_2(A^3\Sigma_u^+)$.

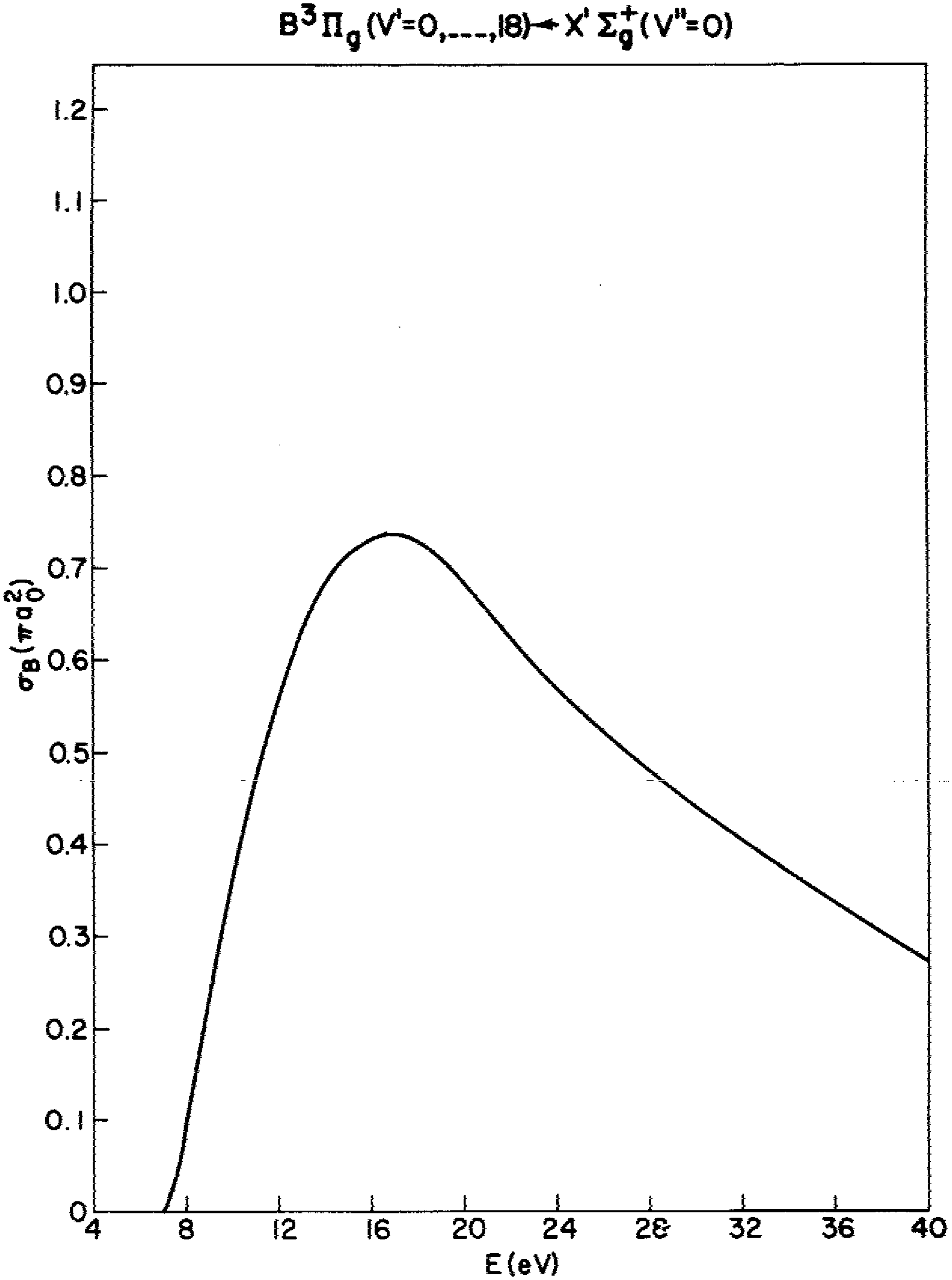

Fig. 4—Electron impact excitation cross section of $N_2(B^3\pi_g)$.

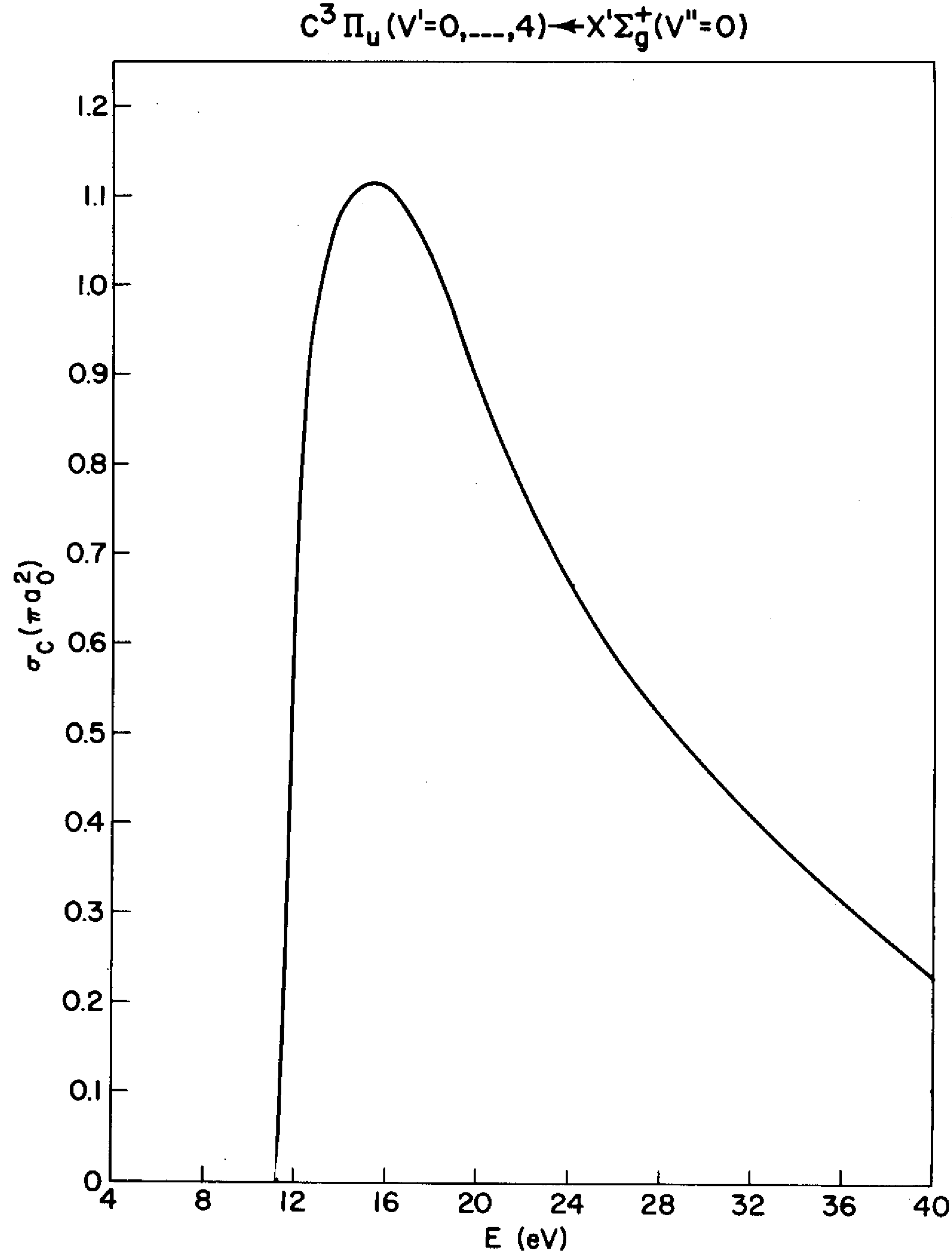

Fig. 5 – Electron impact excitation cross section of $N_2(C^3\pi_u)$.

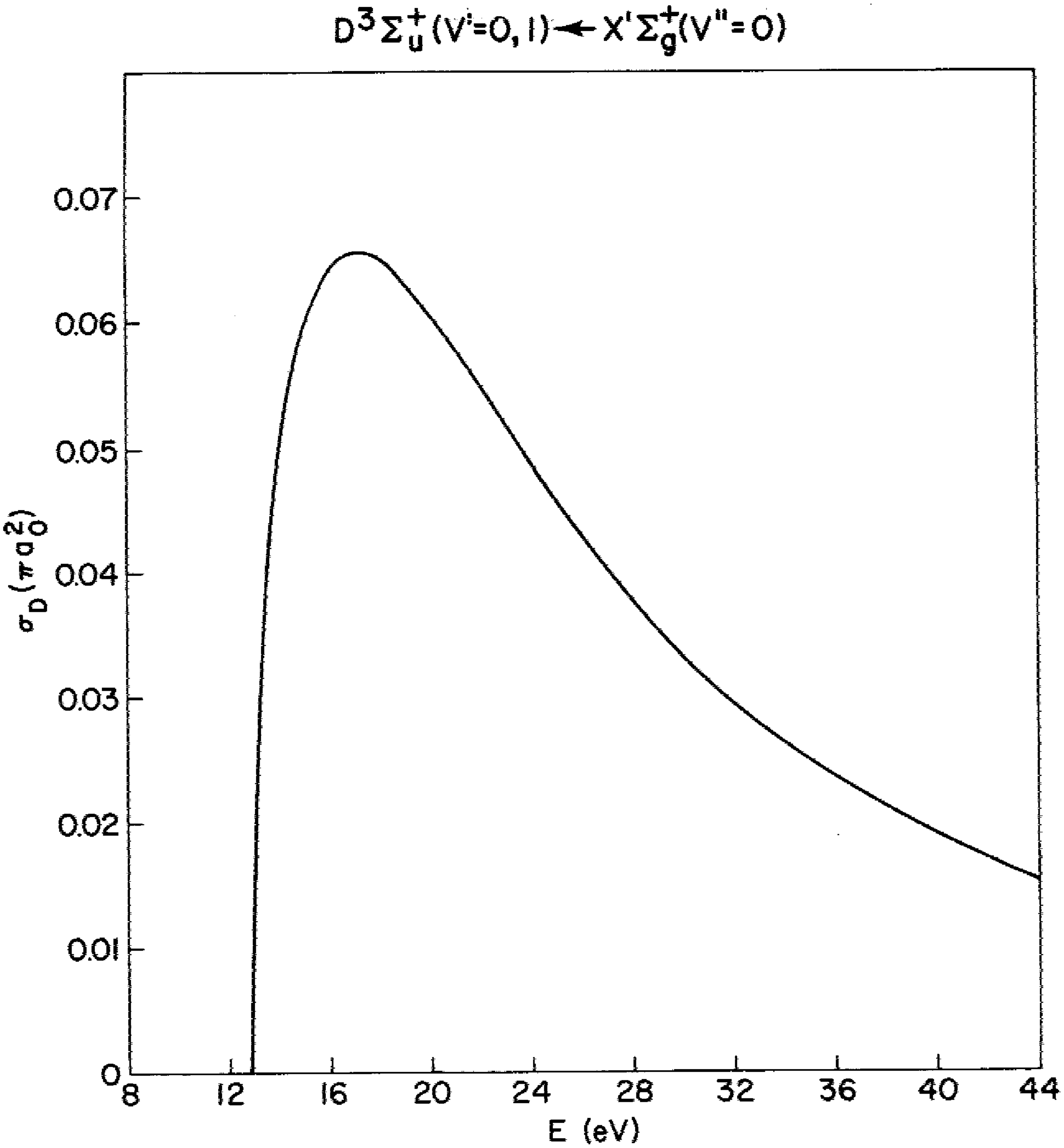

Fig. 6—Electron impact excitation cross section of $N_2(D^3\Sigma_u^+)$.

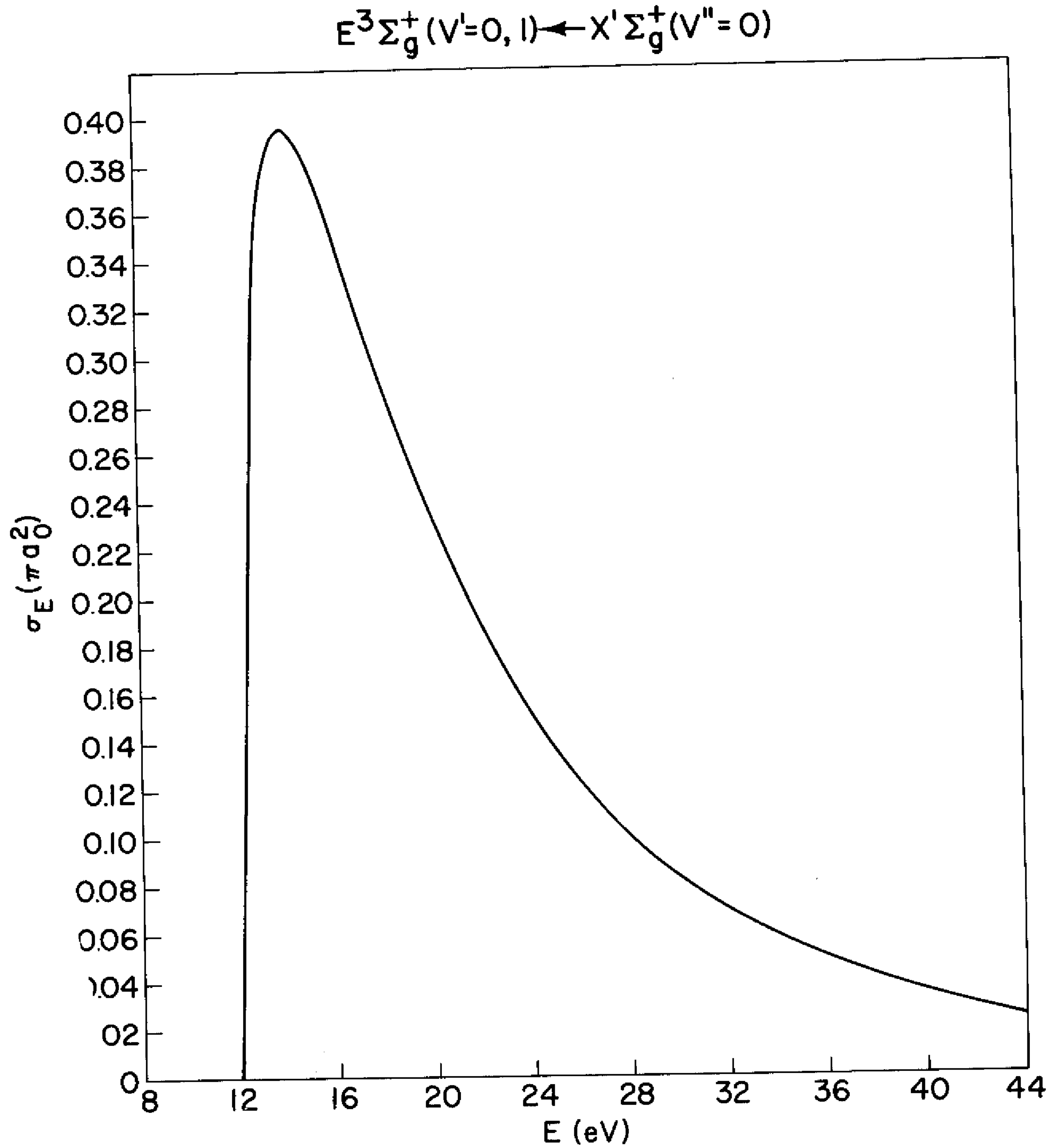

Fig. 7—Electron impact excitation cross section of $N_2(E^3\Sigma_g^+)$.

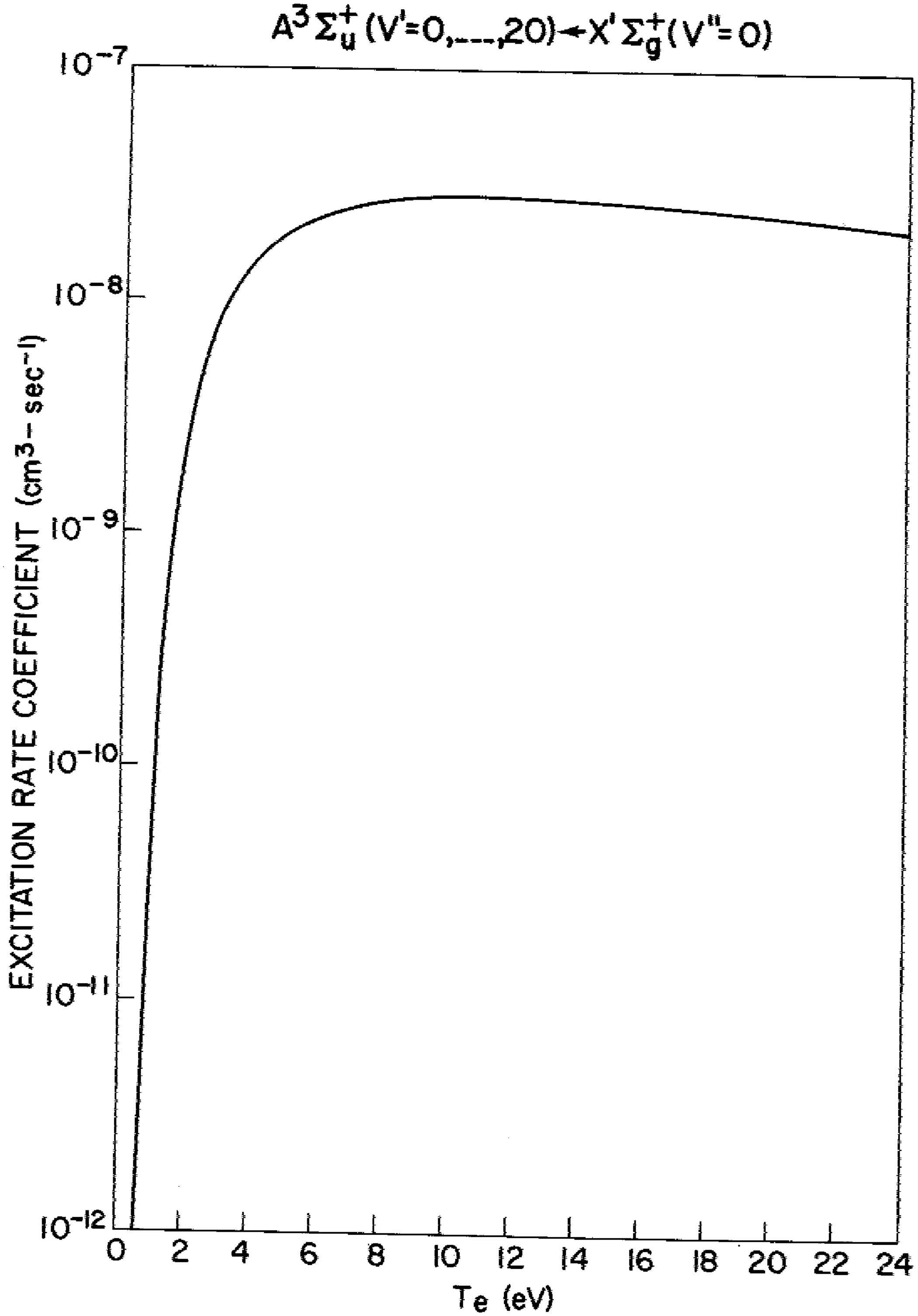

Fig. 8 — $N_2(A^3\Sigma_u^+)$ excitation rate coefficient as a function of the electron temperature T_e.

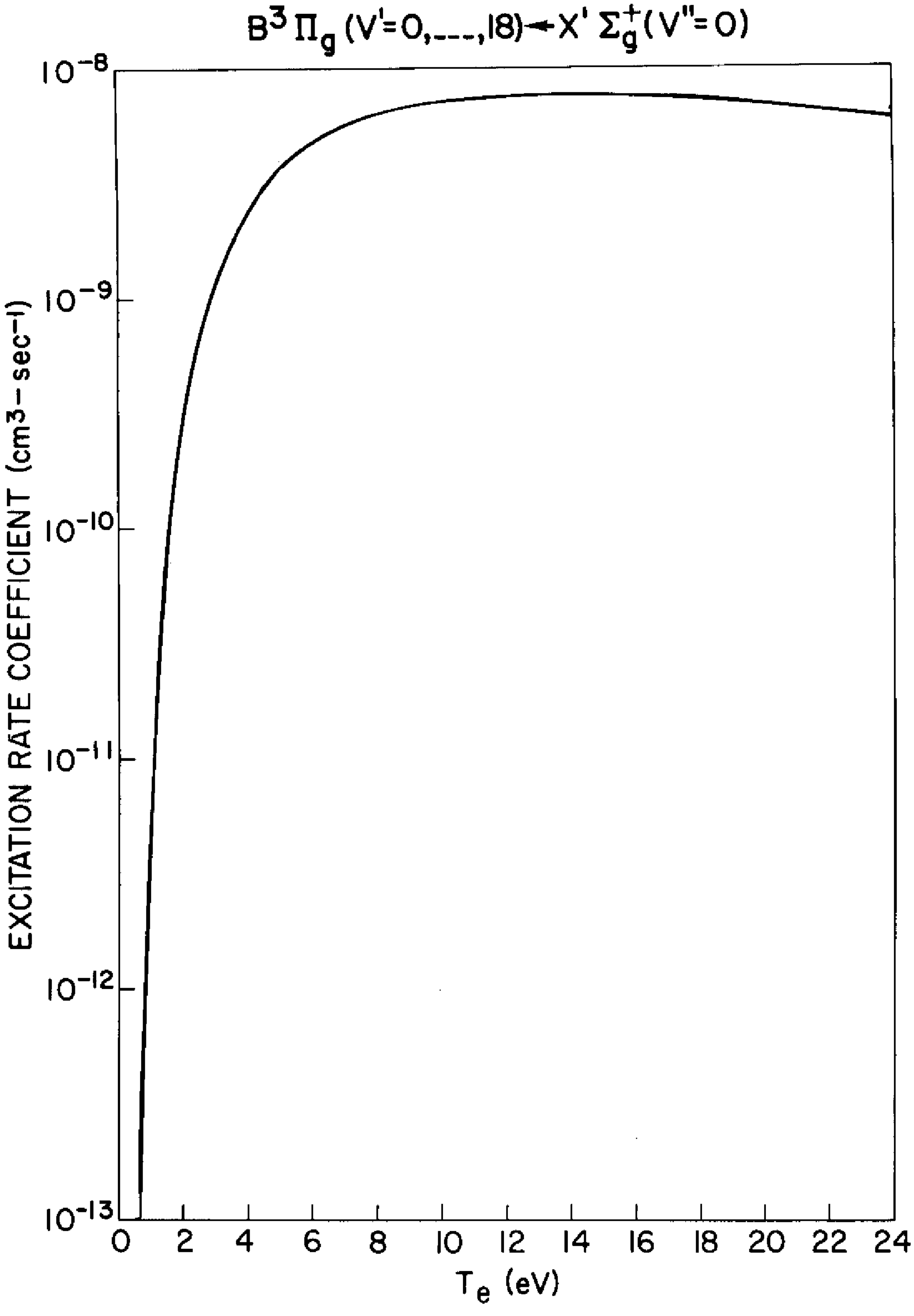

Fig. 9—$N_2(B^3\pi_g)$ excitation rate coefficient as a function of electron temperature.

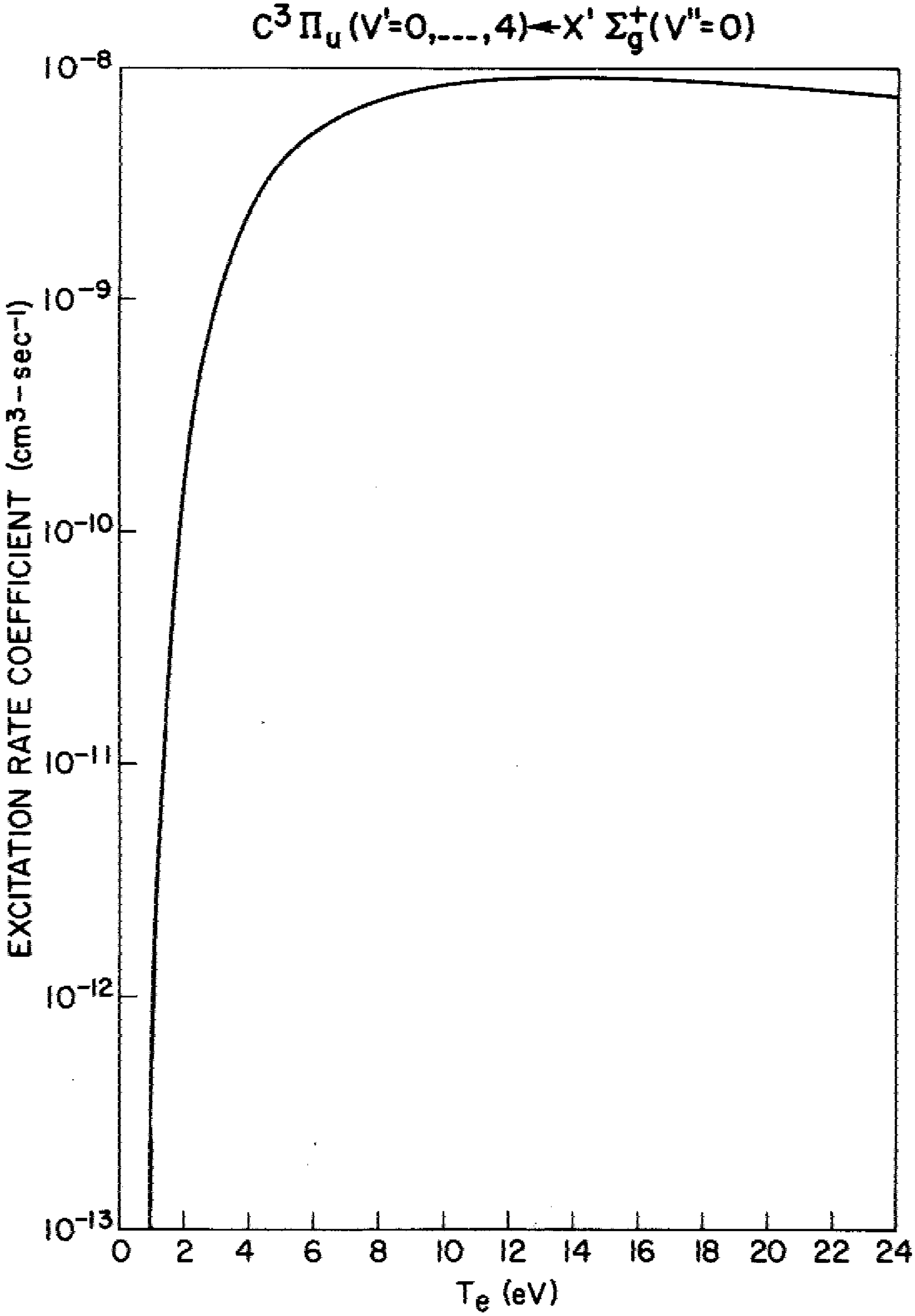

Fig. 10—$N_2(C^3\pi_u)$ excitation rate coefficient as a function of the electron temperature T_e.

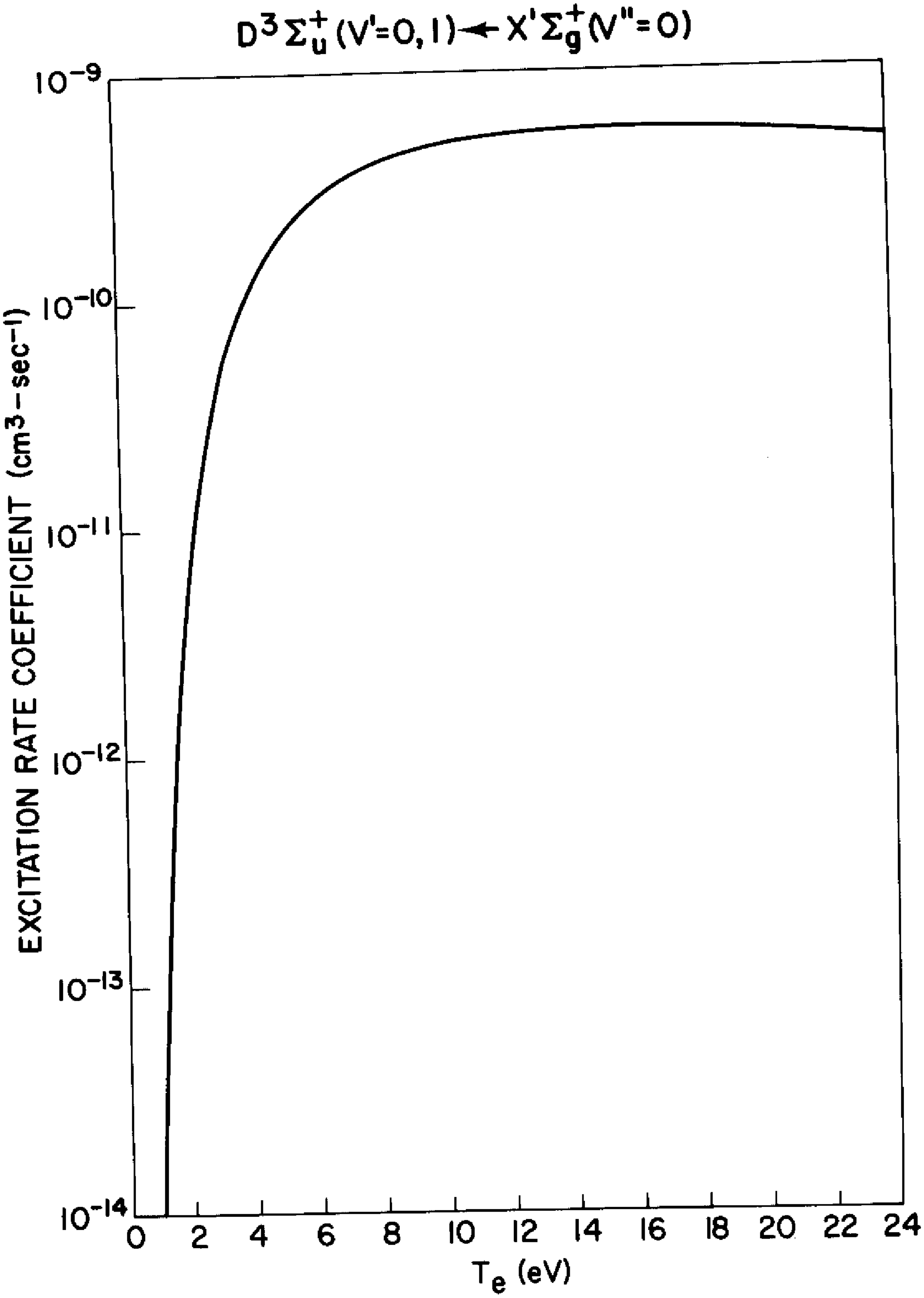

Fig. 11 – $N_2(D^3\Sigma_u^+)$ excitation rate coefficient as a function of the electron temperature T_e.

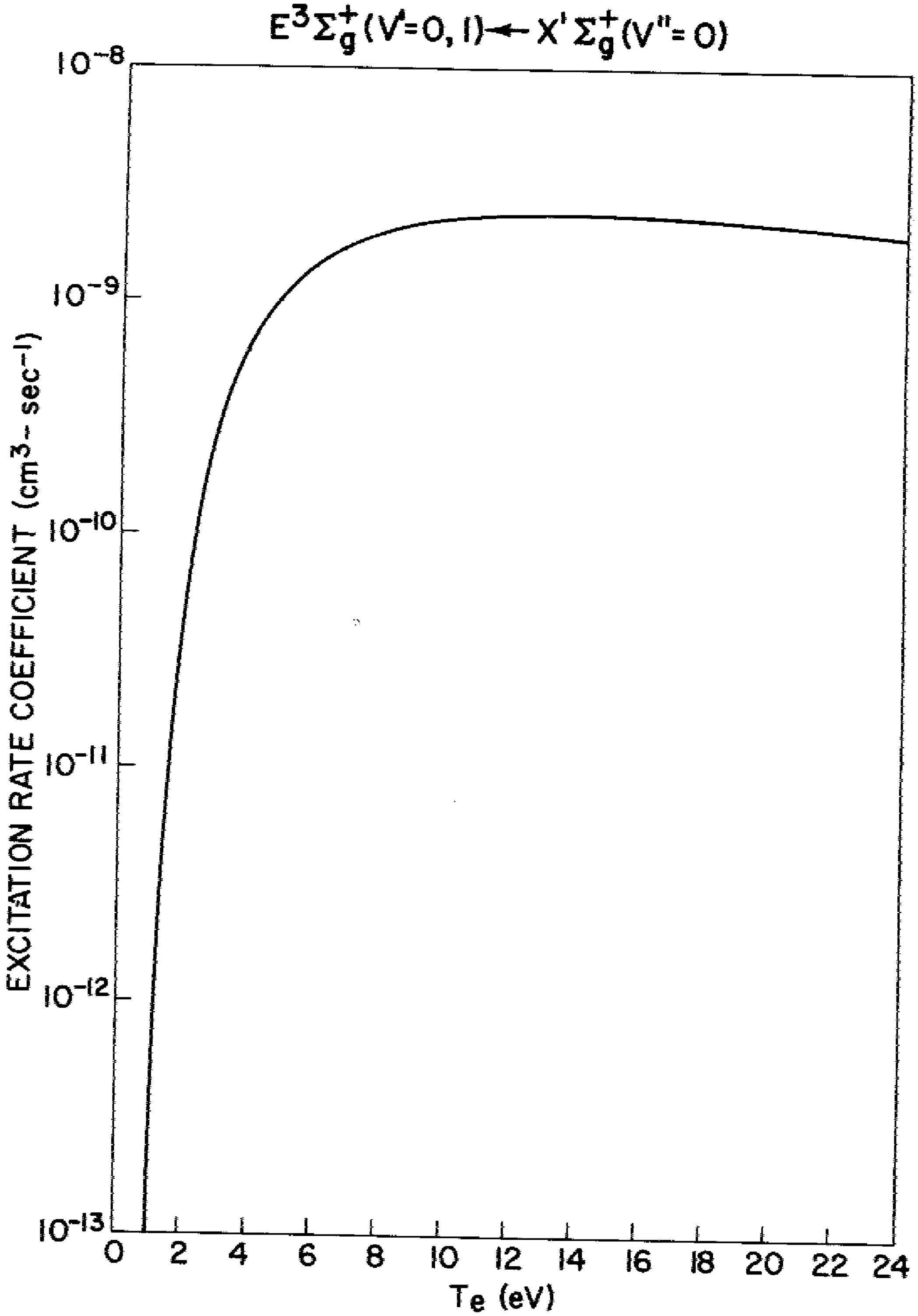

Fig. 12 – $N_2(E^3\Sigma_g^+)$ excitation rate coefficient as a function of the electron temperature T_e.

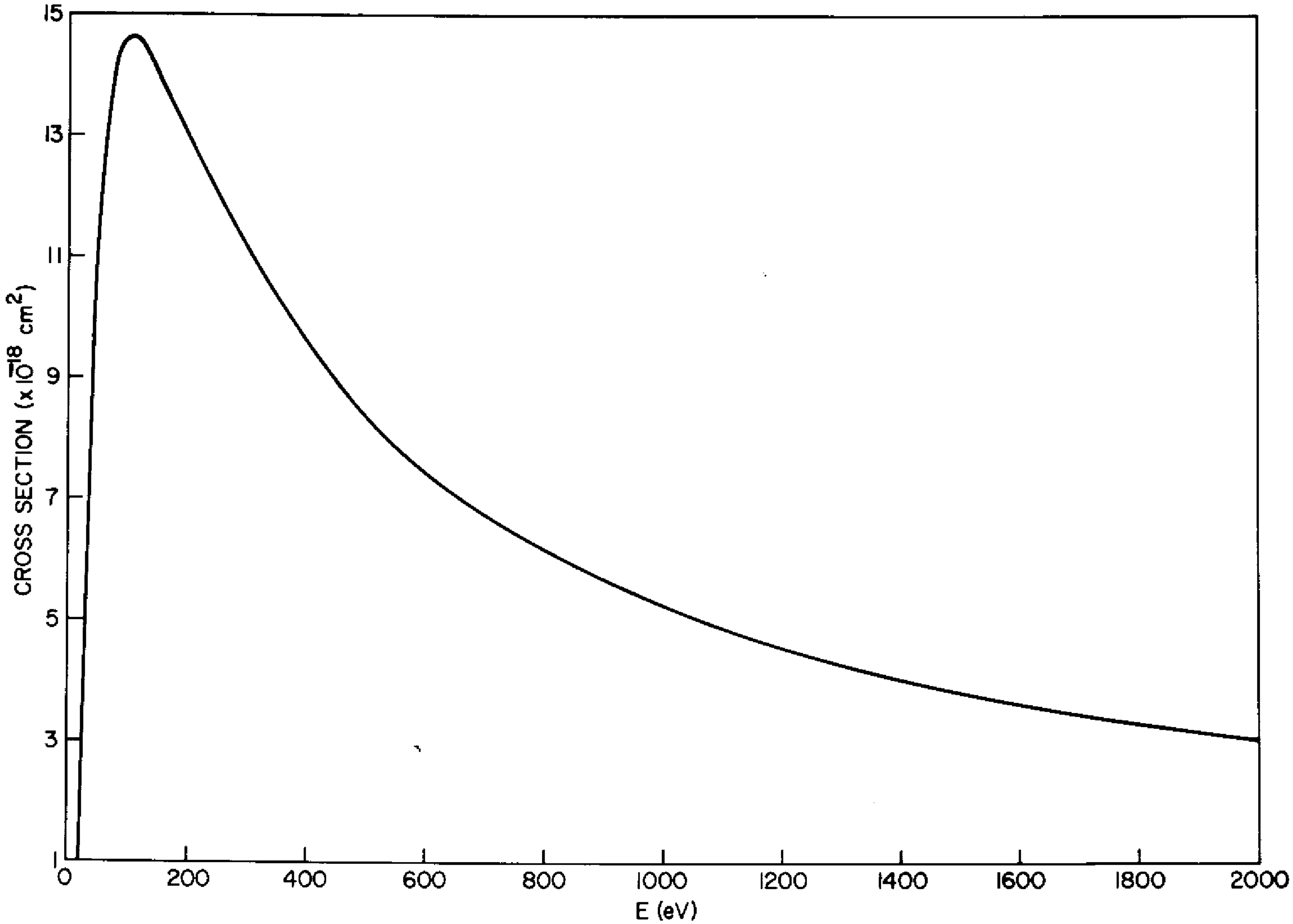

Fig. 15 – Electron impact excitation cross section of the (O, O) band of the first negative system of N_2^+. This cross section is due to direct excitation from the N_2 ground state.

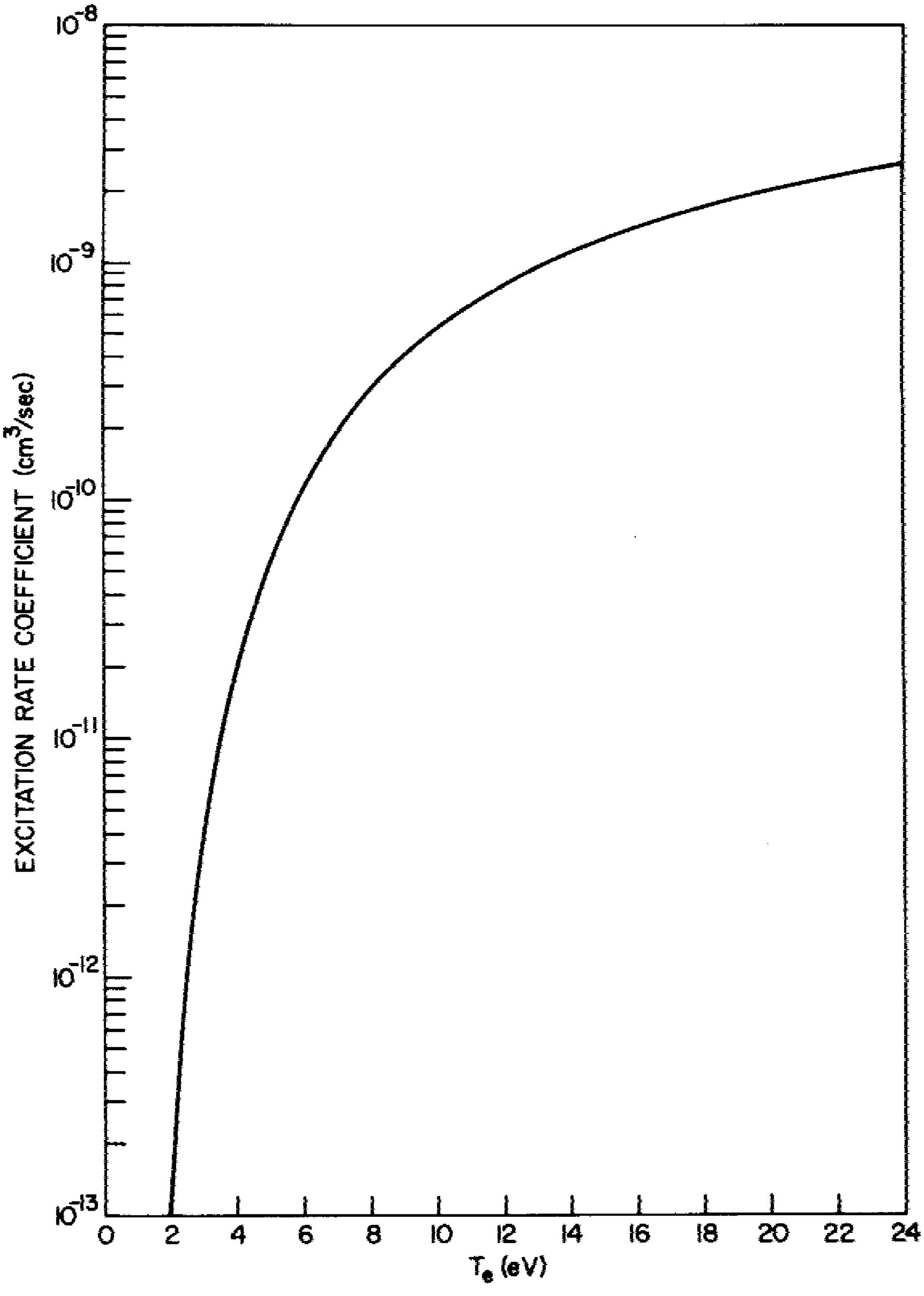

Fig. 16—Electron impact excitation rate coefficient for the (O, O) band of the first negative system of N_2^+. This rate is for direct excitation from the ground state of N_2.

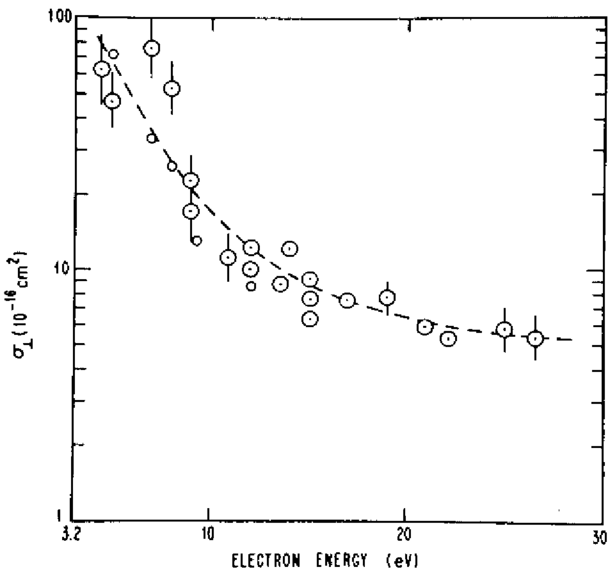

Fig. 17—Lee and Carlton[8] measured cross sections of the first negative (O, O) band system of N_2^+ direct from the N_2^+ ground state.

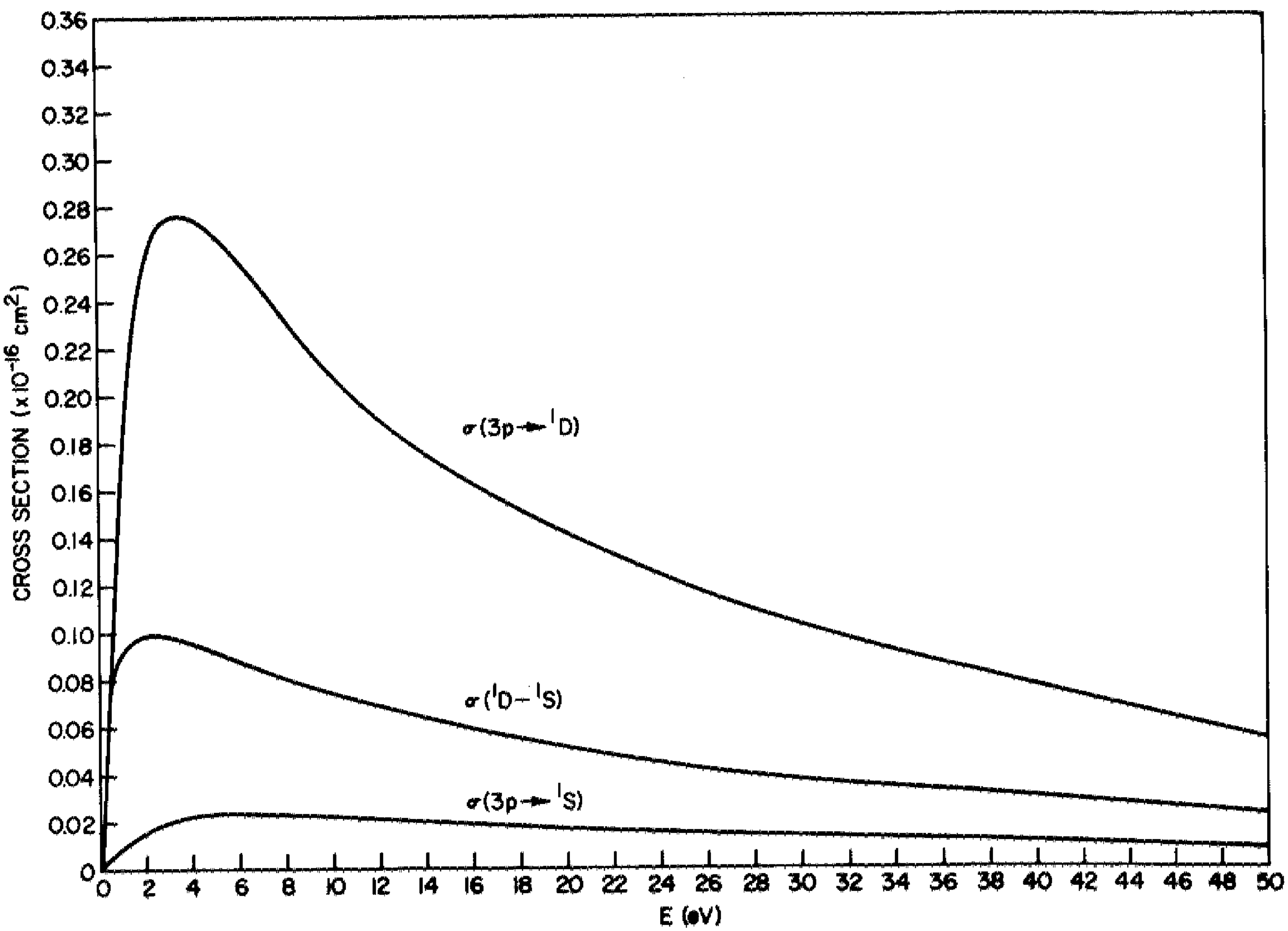

Fig. 18 – Henry et al's[10] calculated electron impact excitation cross-sections of the low-lying metastable states of oxygen.

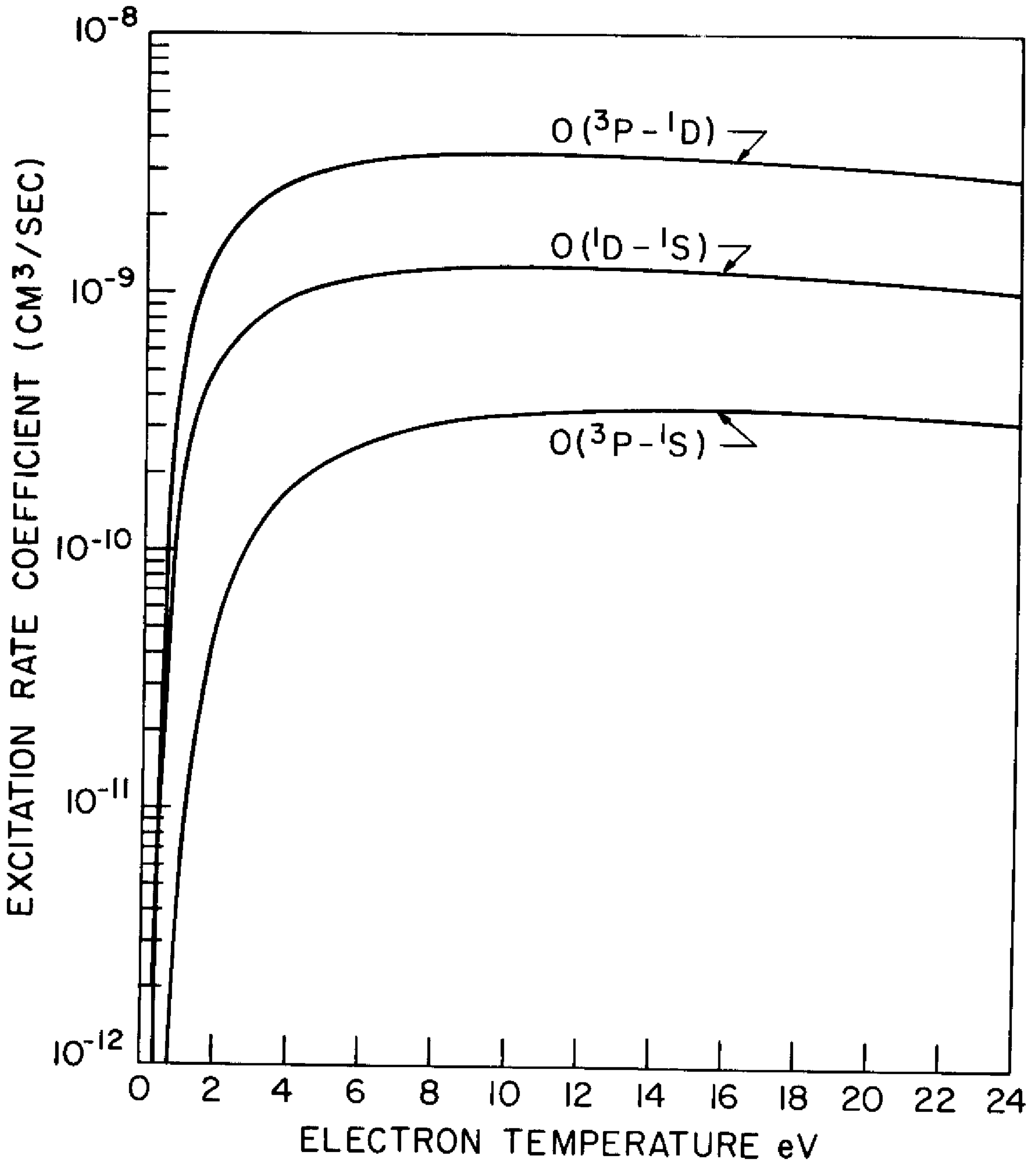

Fig. 19—Electron impact excitation rate coefficient for the $O(^3p) \rightarrow O(^1D)$, $O(^1D) \rightarrow O(^1S)$, and $O(^3p) \rightarrow O(^1S)$ transitions.

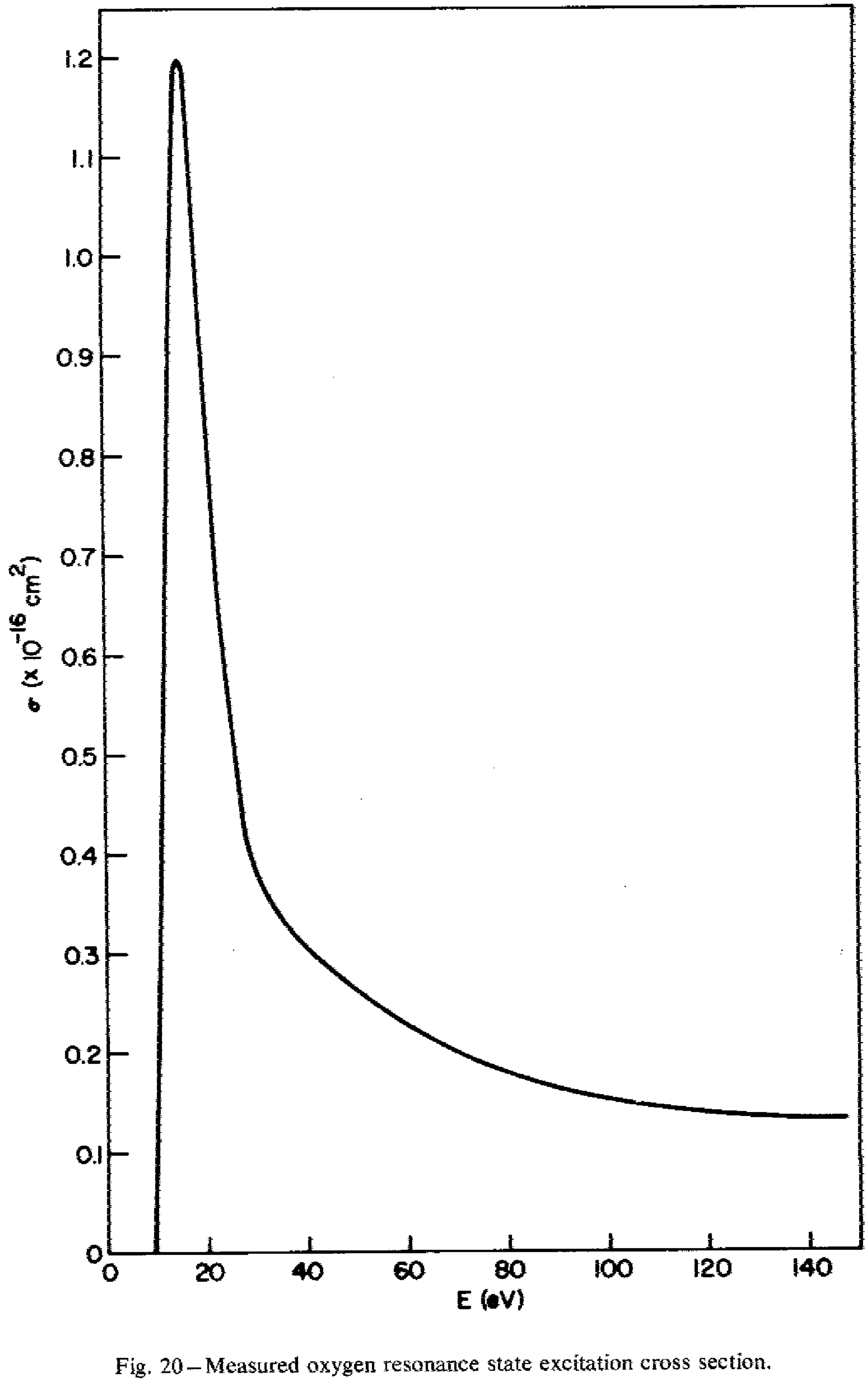

Fig. 20 – Measured oxygen resonance state excitation cross section.

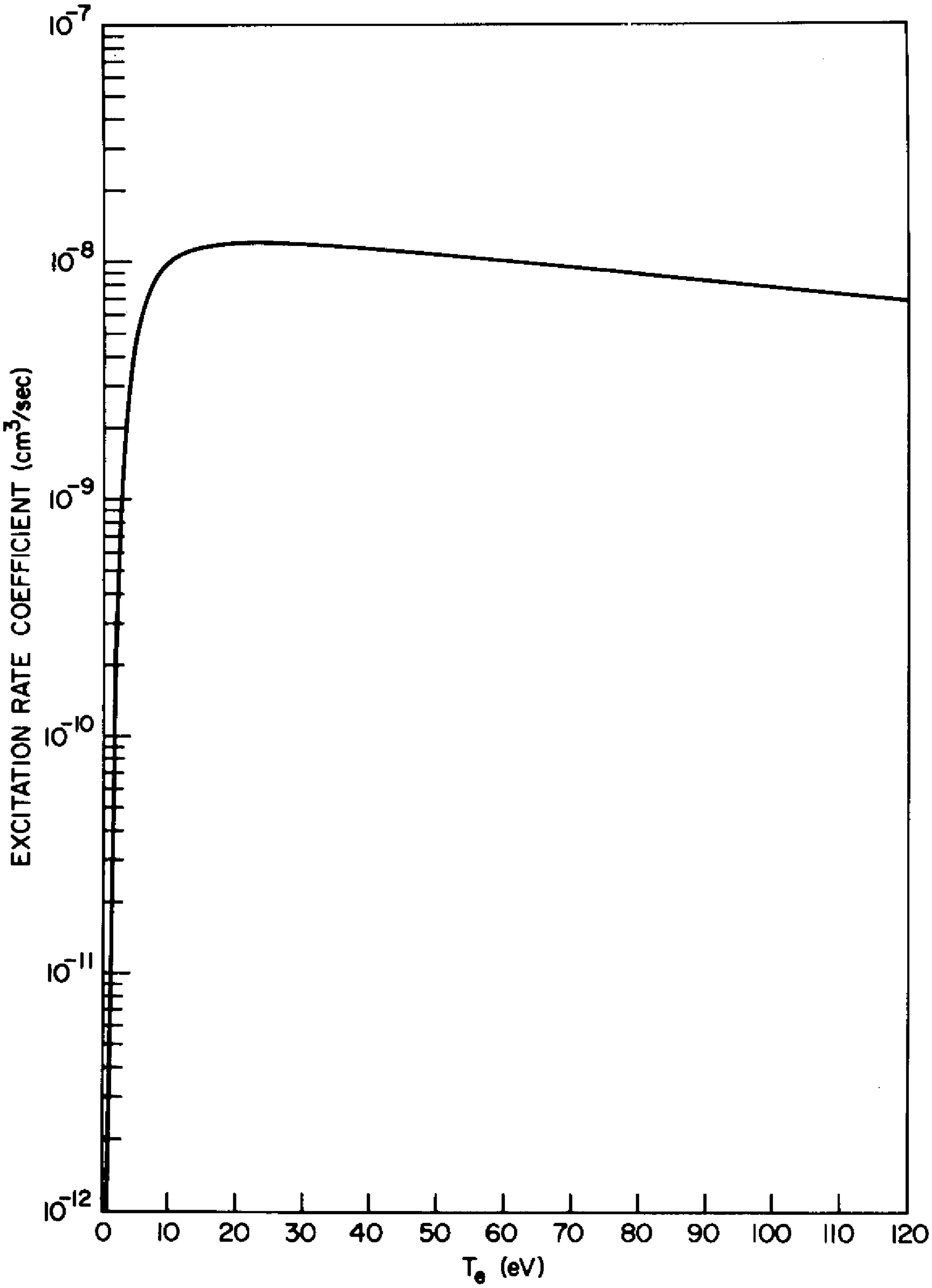

Fig. 21 — Electron impact excitation rate coefficient of the oxygen resonance line.

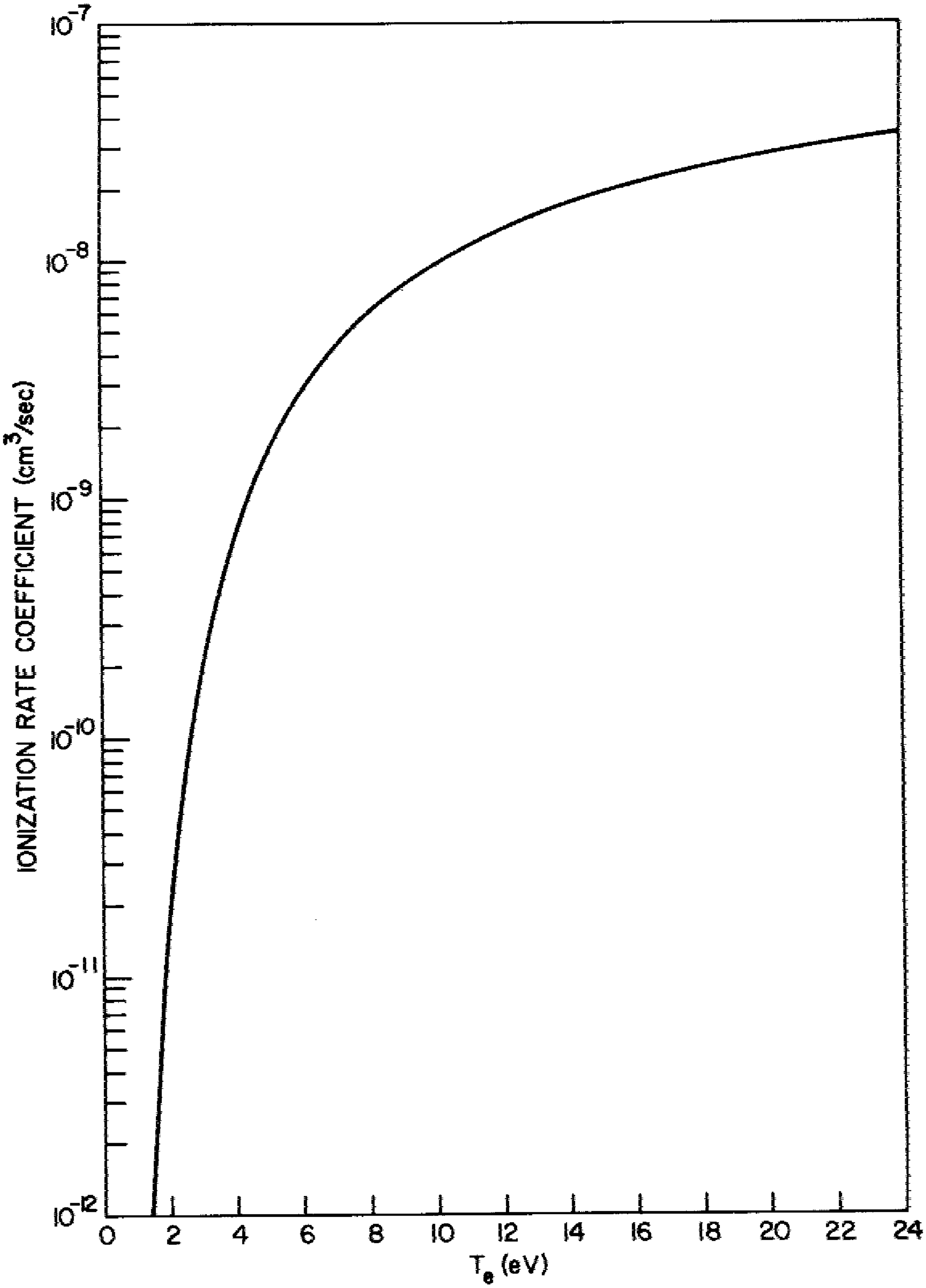

Fig. 22 – Ionization rate coefficient of the oxygen atom.

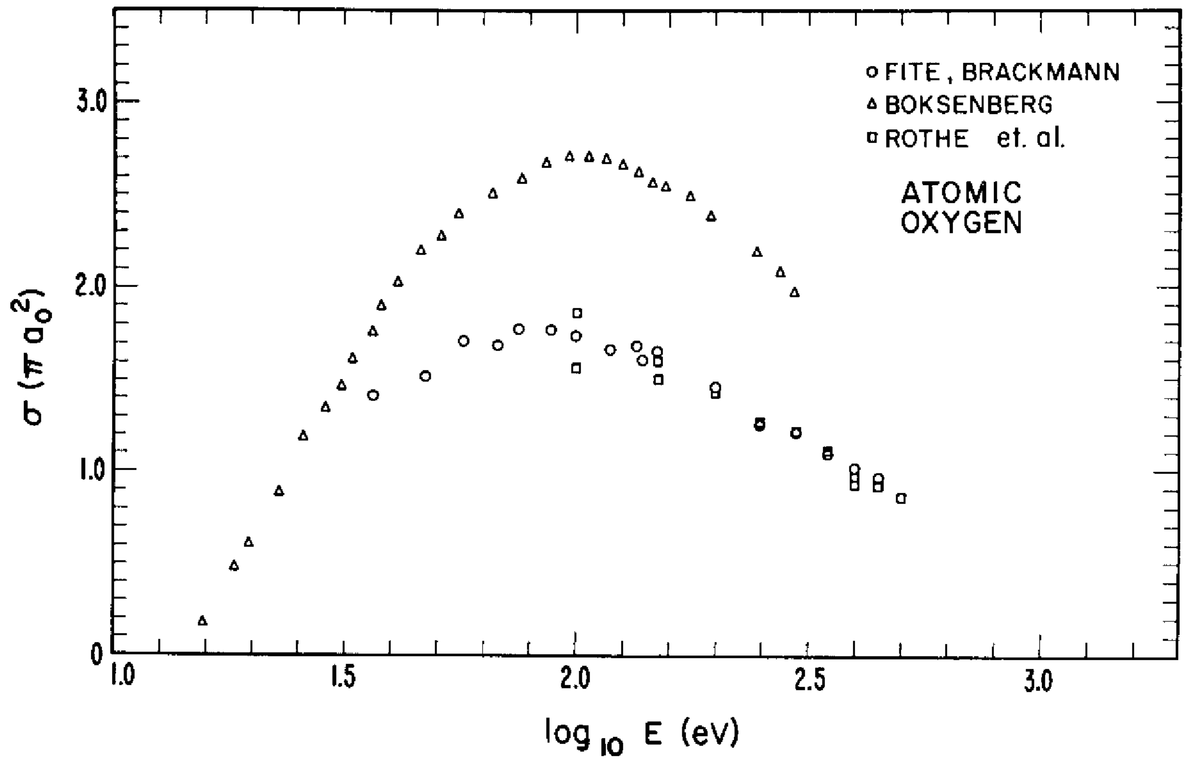

Fig. 23 — Oxygen ionization cross section (see Ref. 15).

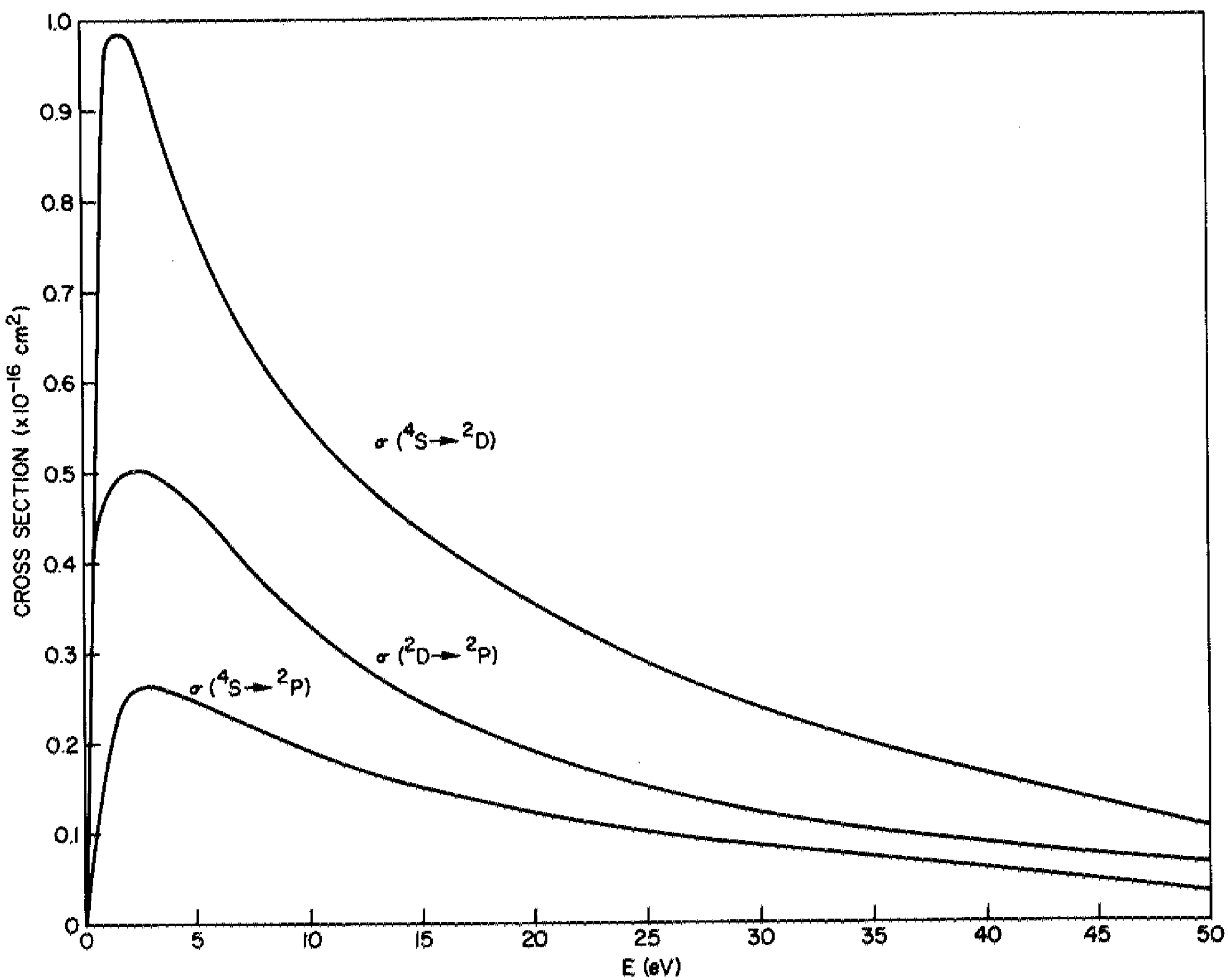

Fig. 24 – Henry et al's[10] electron impact excitation cross section of the low-lying metastable states of nitrogen.

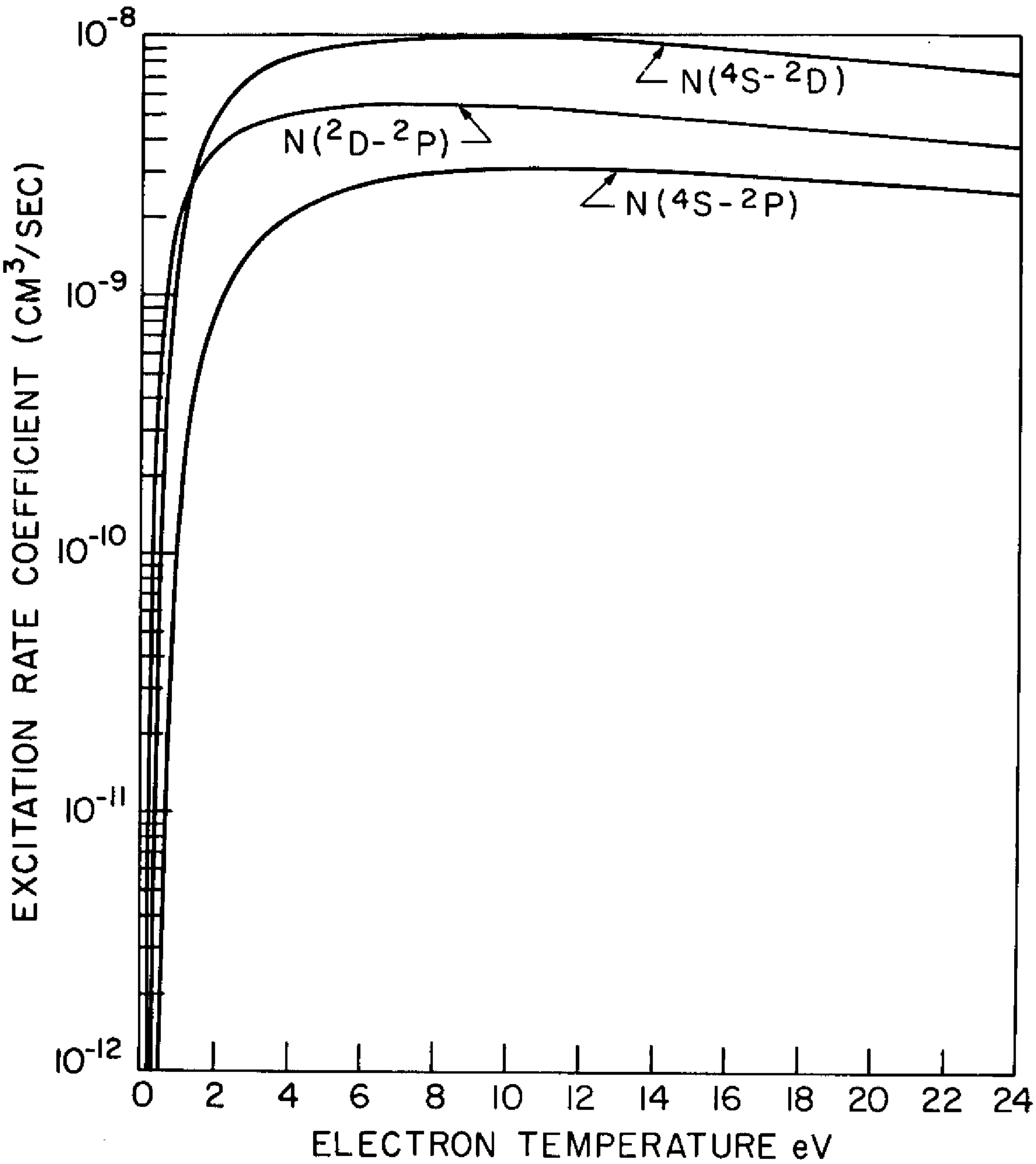

Fig. 25 – Electron impact excitation rate coefficients for $N(^4S) \rightarrow N(^2D)$, $N(^4S) \rightarrow N(^2P)$, and $N(^2D) \rightarrow N(^2P)$.

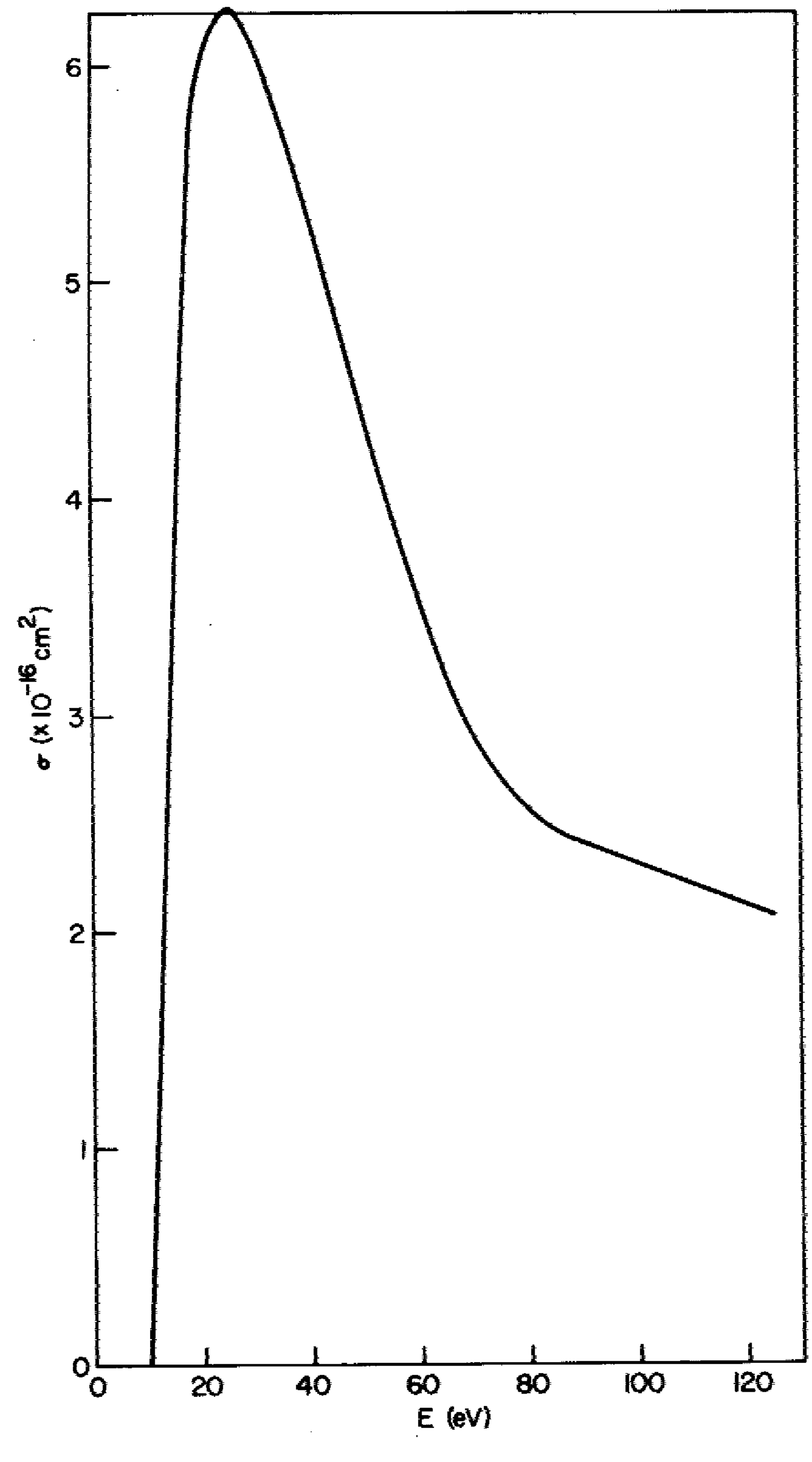

Fig. 26 – Nitrogen resonance state excitation cross section.

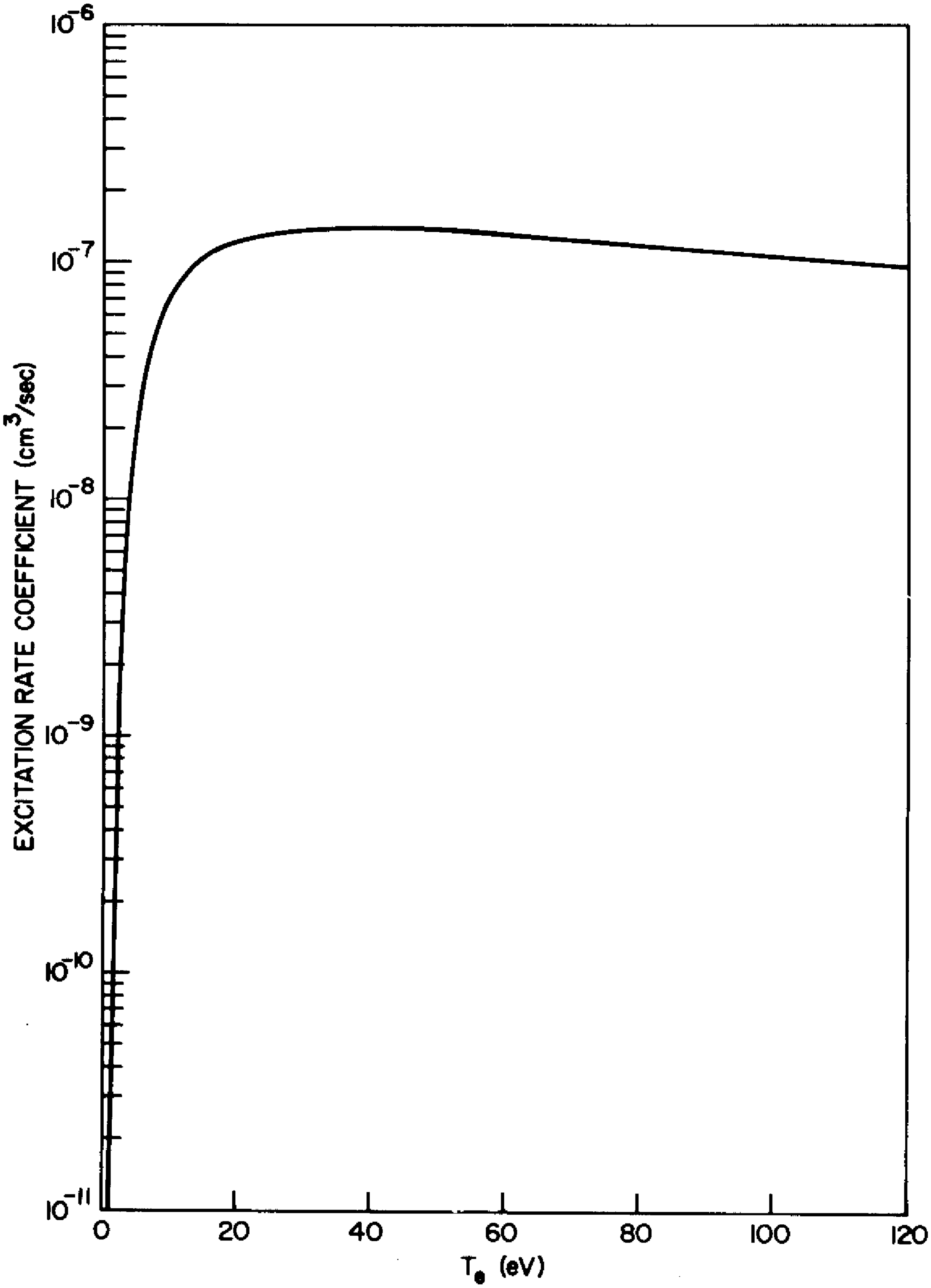

Fig. 27 – Electron impact excitation rate coefficient of the nitrogen resonance state.

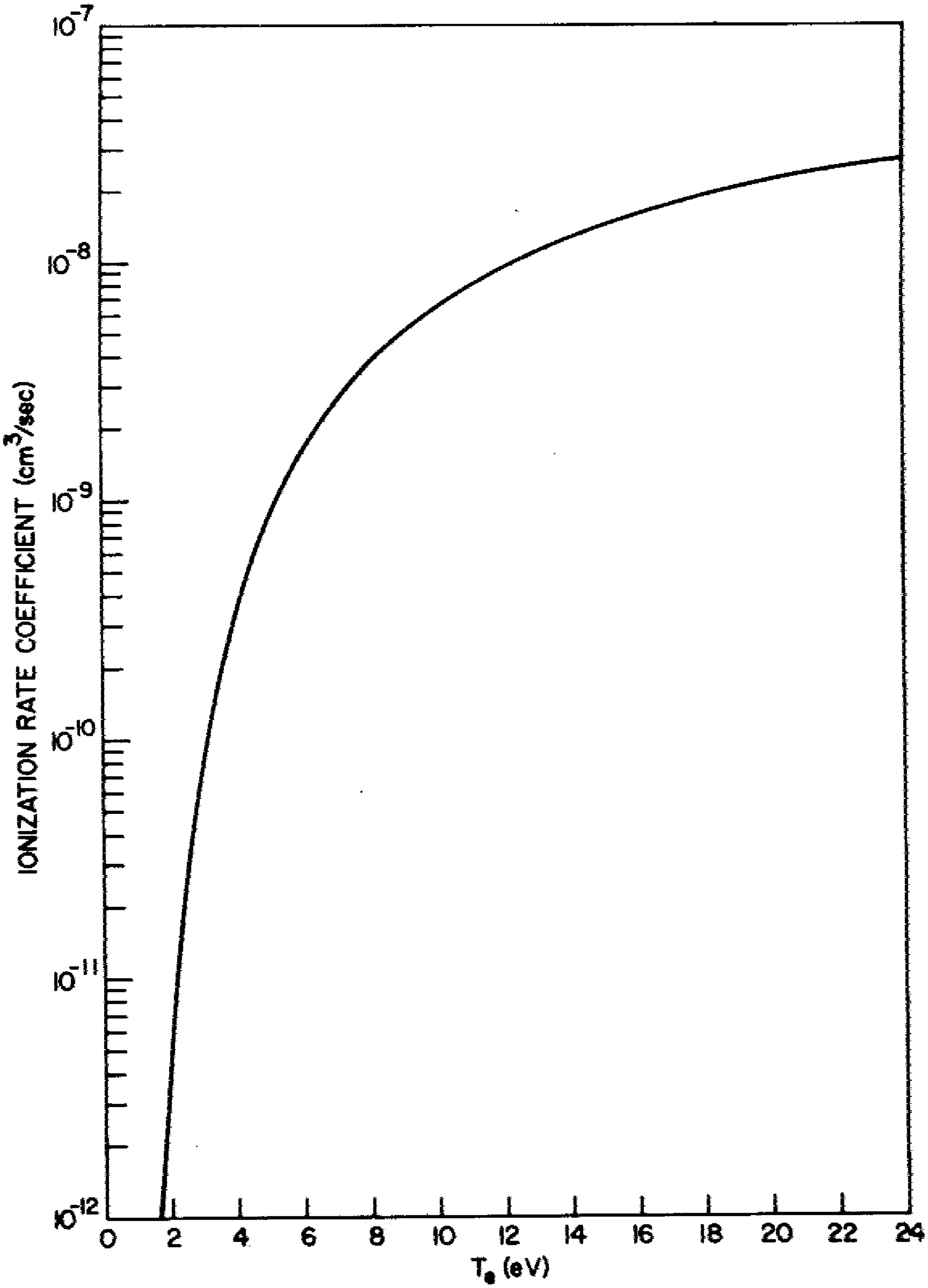

Fig. 28 — Nitrogen ionization rate coefficient.

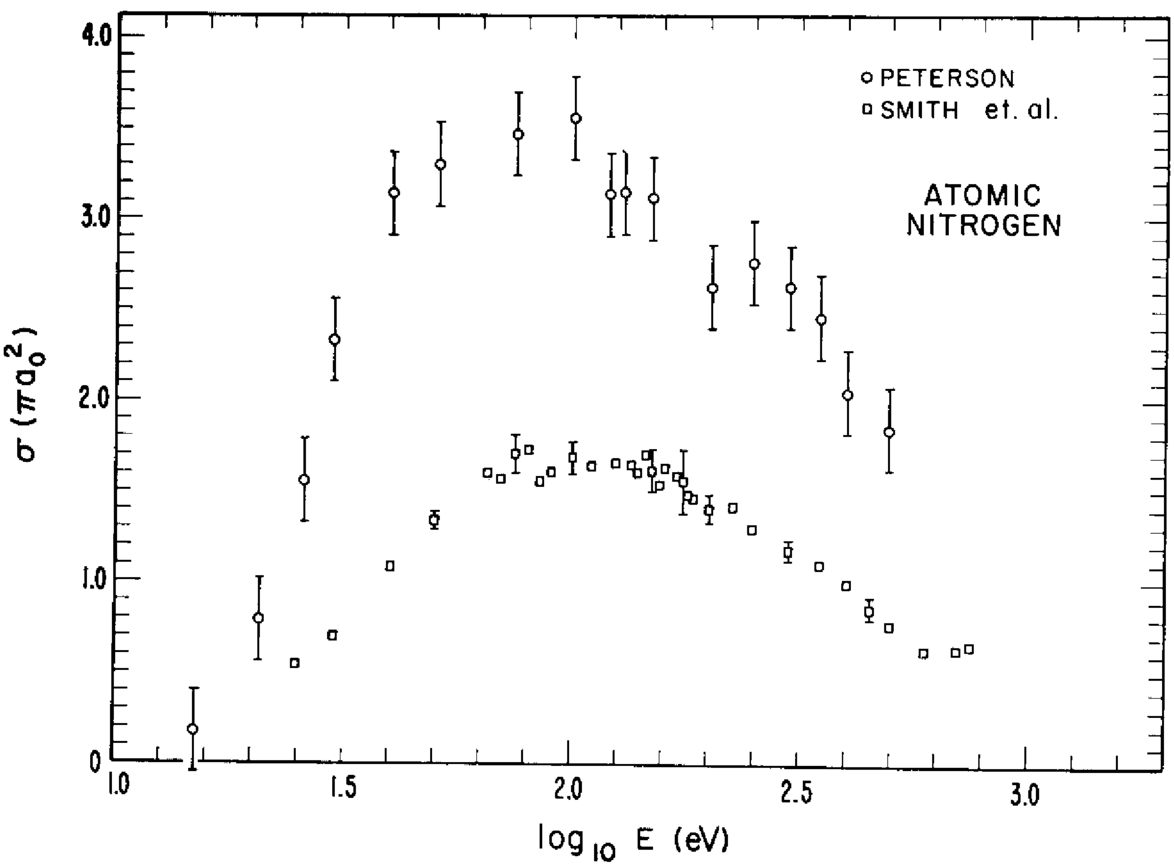

Fig. 29 – Nitrogen ionization cross section (see Ref. 15).

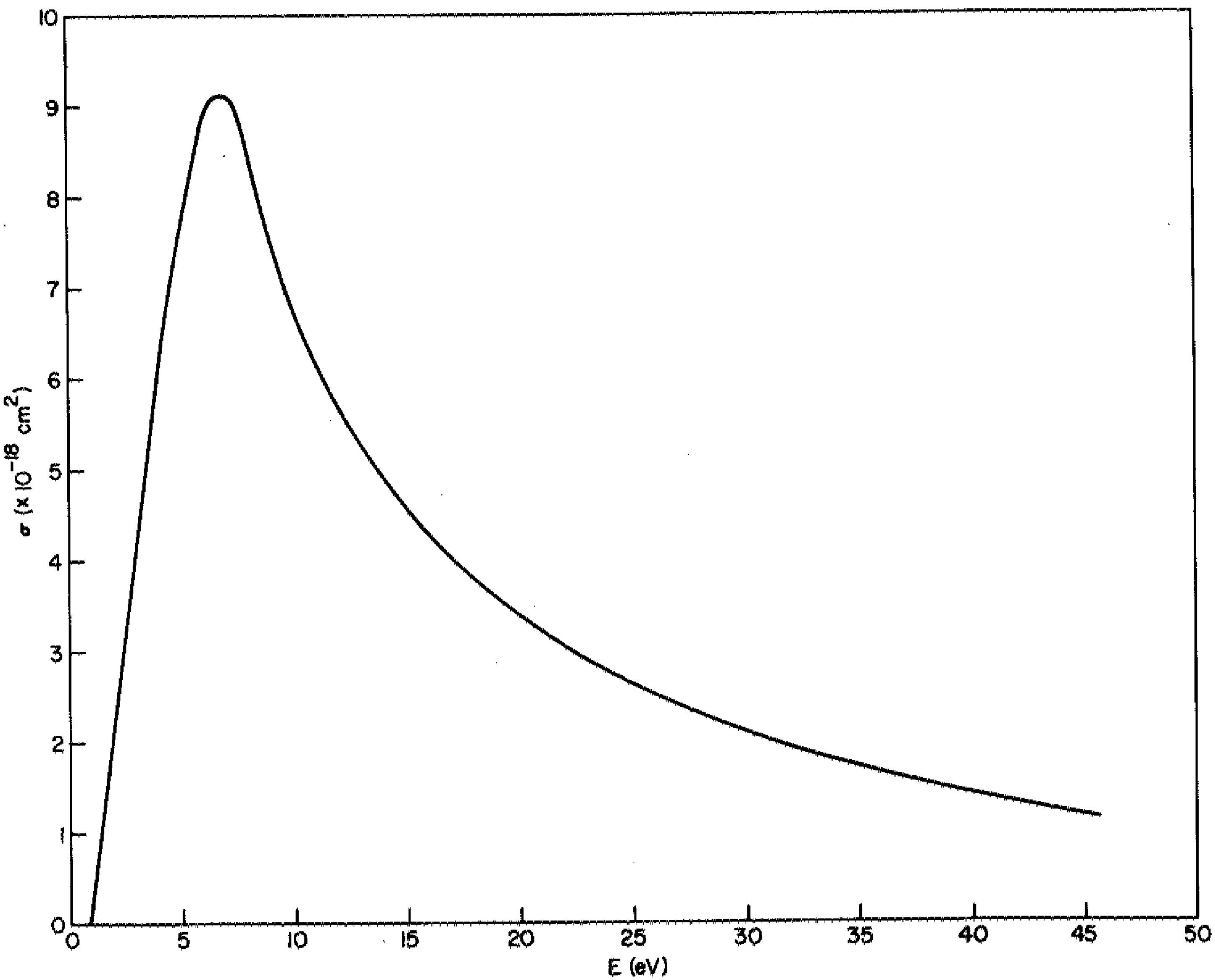

Fig. 30 – $O_2(a^1\Delta)$ excitation cross section.

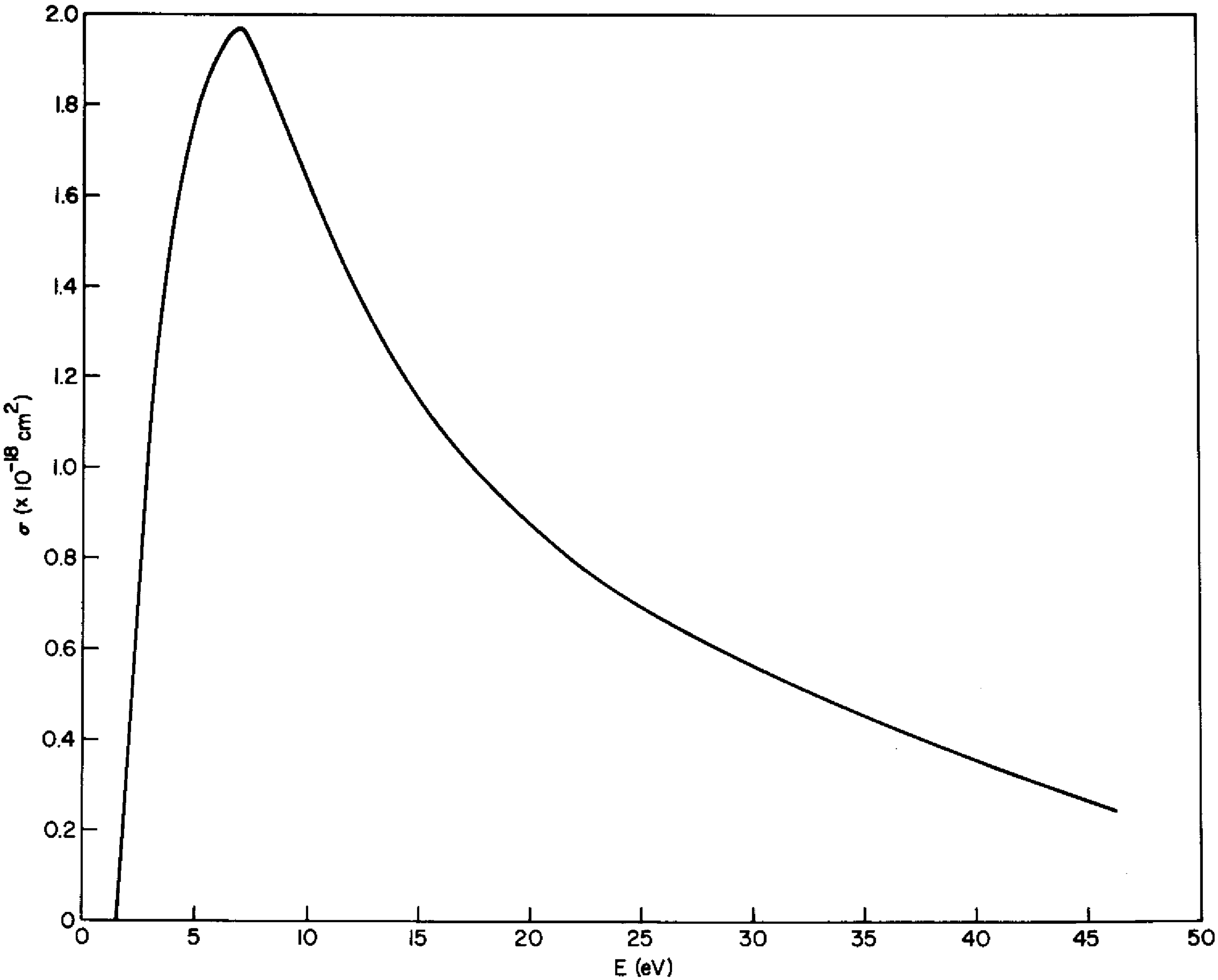

Fig. 31 — $O_2(b^1\Sigma)$ excitation cross section.

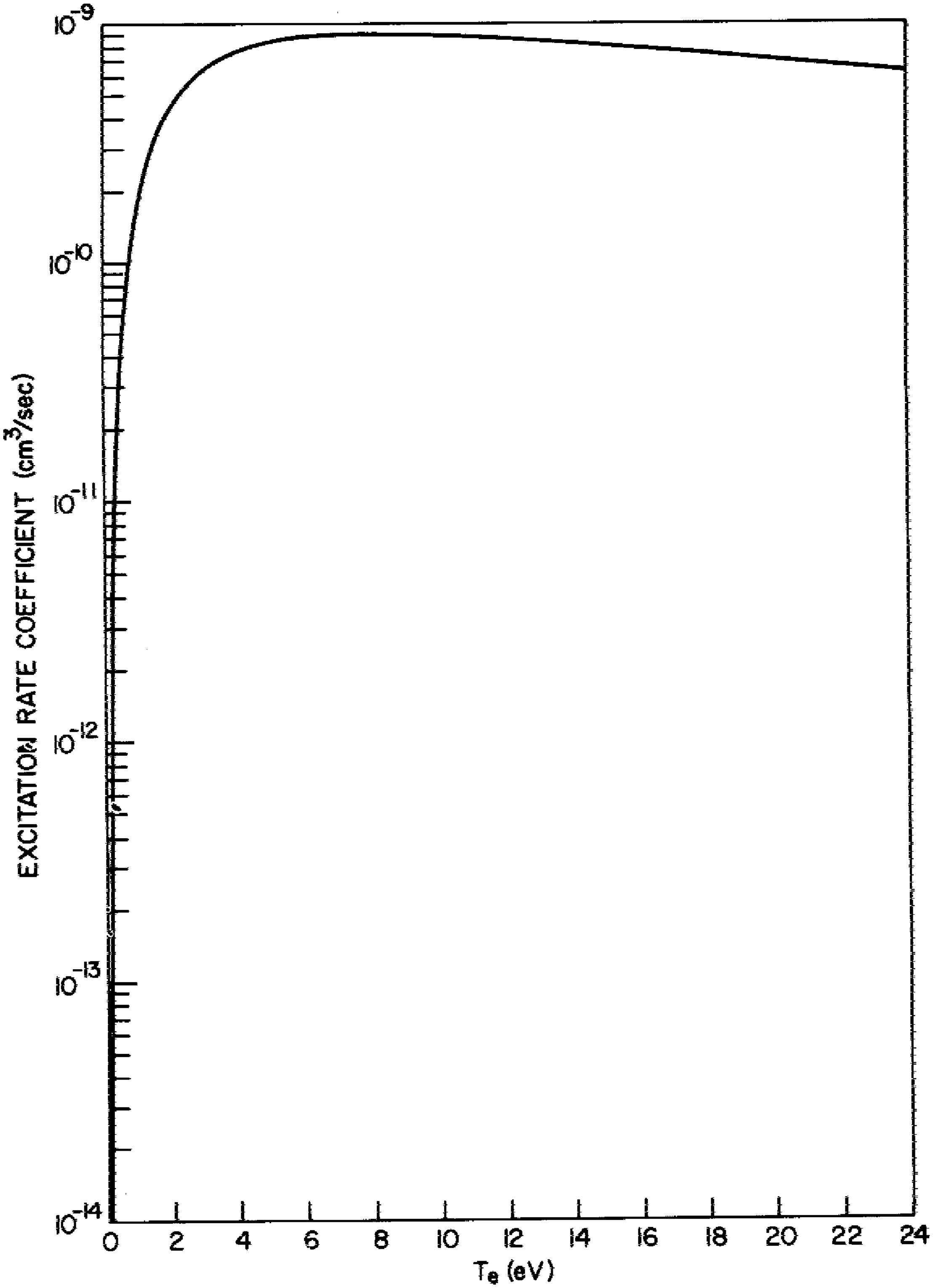

Fig. 32 – Electron impact excitation rate coefficient of $O_2(a^1\Delta)$.

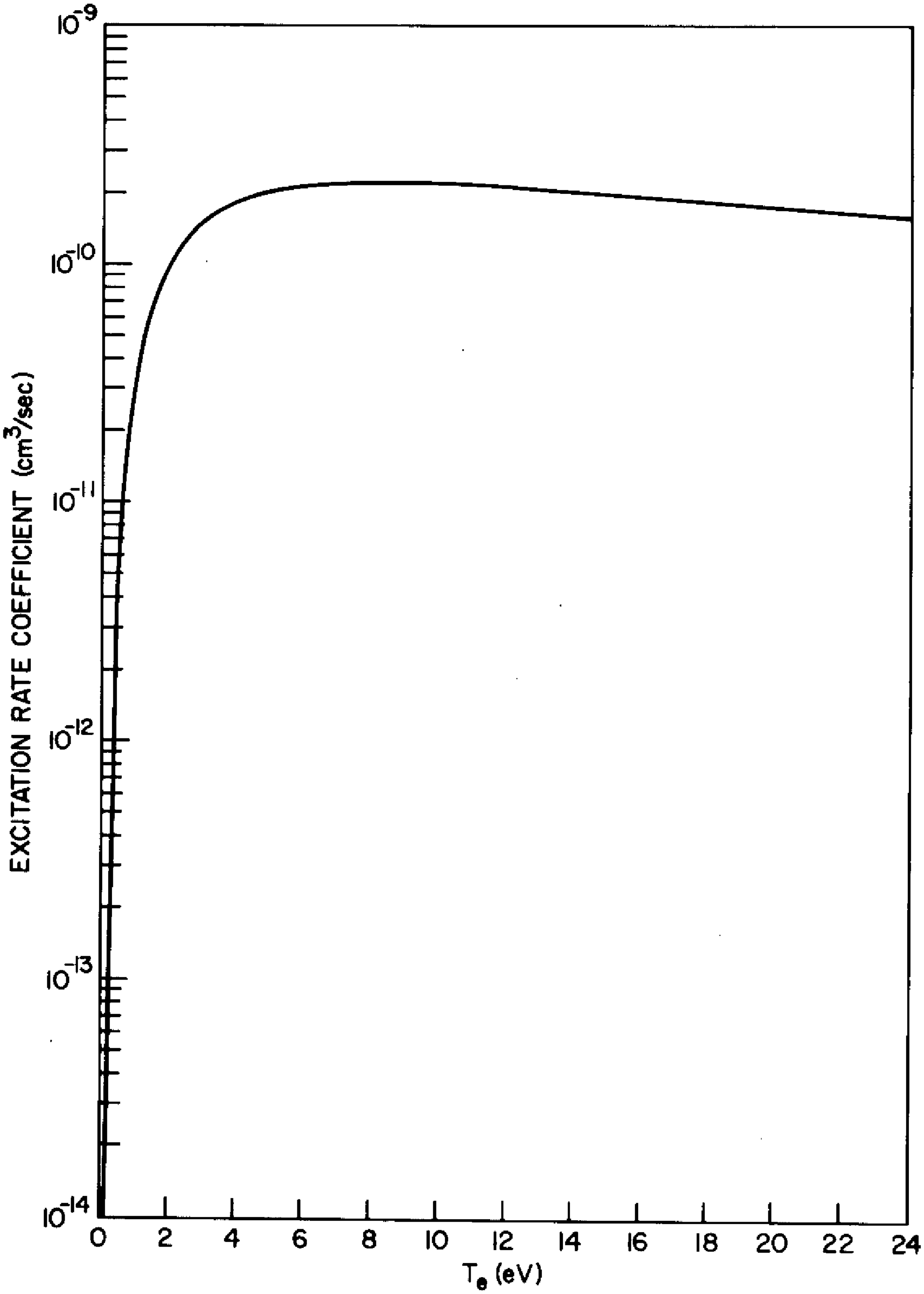

Fig. 33—Electron impact excitation rate coefficient of $O_2(b^1\Sigma)$.

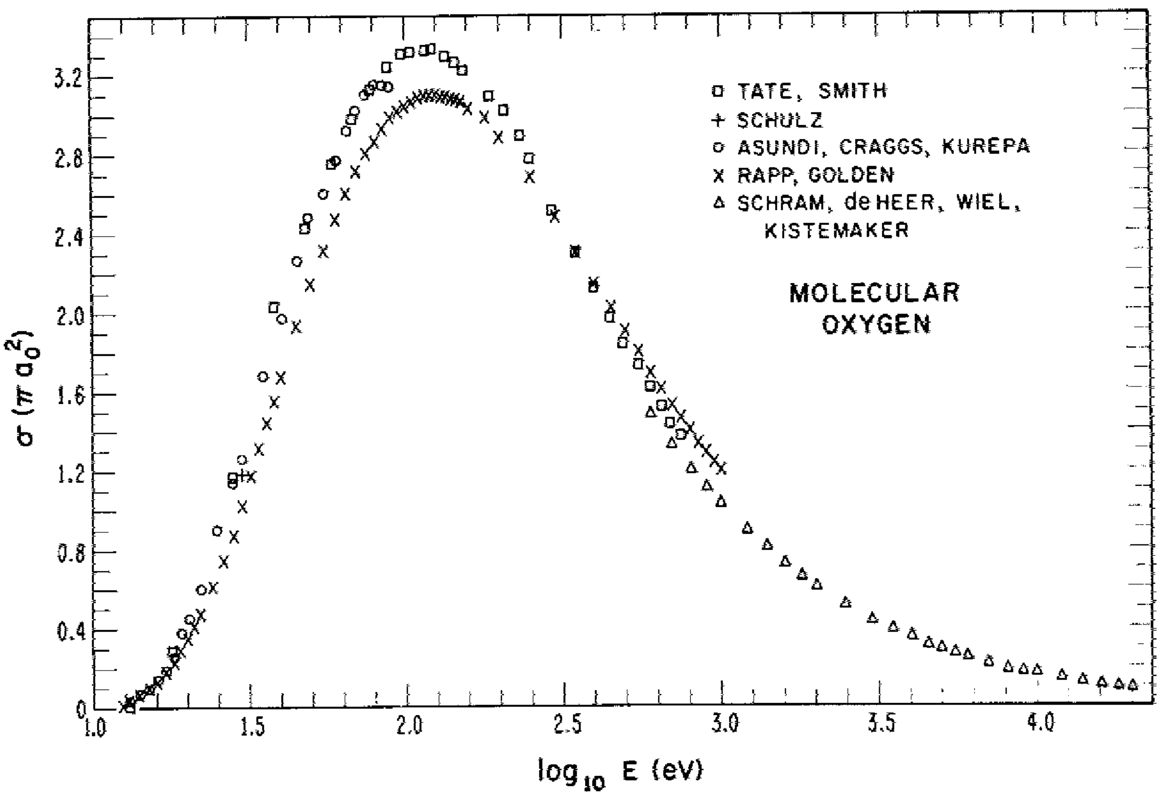

Fig. 34—Oxygen molecular ionization cross section.

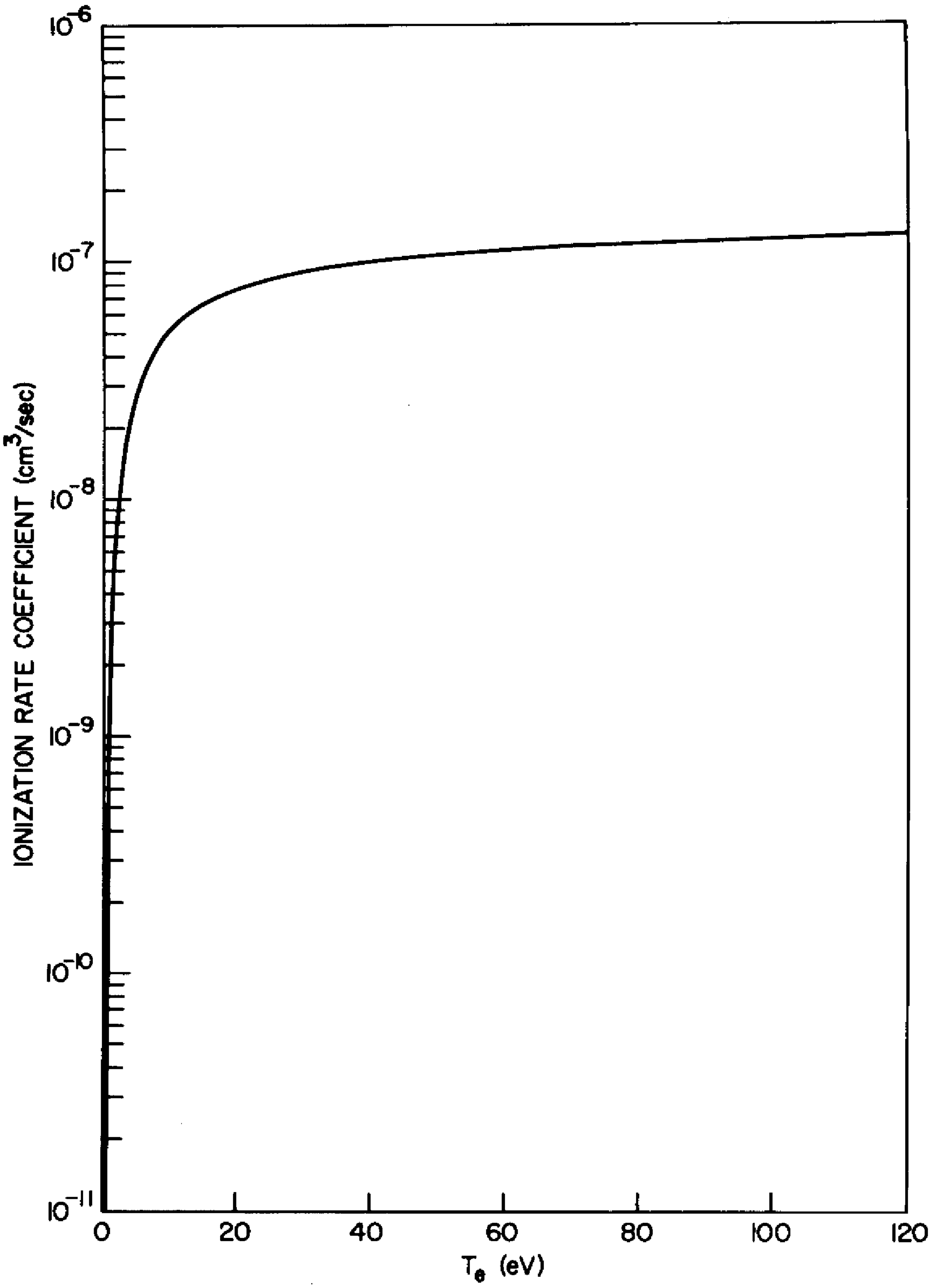

Fig. 35—Electron impact ionization rate coefficient of O_2.