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RECOMMENDED DATA FOR EXCITATION RATE COEFFICIENTS OF HELIUM ATOMS AND HELIUM-LIKE IONS BY ELECTRON IMPACT

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Abstract

Cross sections or effective collision strengths are compiled for electron-impact excitation of helium atoms and He-like ions. An evaluation is made to recommend the "best" values for use for the transitions $1^1S-2^{1,3}S$ and $1^1S-2^{1,3}P$ of target ions of Z=2,3,6,8,12,20,22,26,28,34 and 42.
The resulting recommended values are fitted to an analytical formula and the fitting coefficients are given in a table. The rate coefficients calculated therefrom are shown graphically. The reliability of the recommended data is roughly estimated.

1. Introduction

Data for excitation rate coefficients of helium atoms and He-like ions by electron impact, which are of principal importance for plasma diagnostics and energy losses in fusion plasmas, are evaluated. Transitions $1s^2\ ^1S \rightarrow 1s2s\ ^{1,3}S$ and $1s2p\ ^{1,3}P$ are considered. For users' convenience, the rate coefficients are fitted to an analytical formula as given by Itikawa et al.[1], who evaluated electon-impact excitation data for all ions of carbon and oxygen.

Literature sources are taken from the bibliographies on excitation of positive ions by electron impact which were published by Itikawa et al.[2]. In addition, the more recent literature sources are taken from the International Bulletin on Atomic and Molecular Data for Fusion which has been published by the International Atomic Energy Agency, and a recent list which is maintained in the Research Information Center of Institute of Plasma Physics, Nagoya University.

2. Data Source and Evaluation

A review of the theoretical methods used and results on the excitations of positive ions by electron impact up to 1981 was made by Henry[3] following Seaton's work in 1975[4].
Henry concluded that for He-like ions the cross sections can be very sensitive to the choice of target wavefunctions, particularly those for the transition $1s^2\ ^1S \rightarrow 1s2s\ ^1S$ in low Z (atomic number) ions, and at energies near threshold resonance effects must be included in order to obtain cross sections accurately.

After Henry's review was published, the importance of resonance effects has been demonstrated in distoreted-wave(DW), close-coupling (CC) and R-matrix(R-mat) calculations. Resonance effects result in a very significant enhancement of the cross sections for most of the forbidden transitions and are less important for optically allowed transitions. In addition to the autoionization effect (AI), it has been pointed out by Pradhan[5] that intermediate coupling (IC) and dielectronic recombination effects(DER) are important for highly ionized ions of high Z elements ($Z \geq 20$).

Data which were obtained using accurate target wavefunctions, and taking into account resonance effects for all Z, and intermediate coupling and dielectronic recombination effects for $Z \geq 20$, are thus selected from the literature as the recommended data for electron impact excitation of He-like ions.

Data for the transitions $1s^2\ ^1S \rightarrow 1s2s\ ^{1,3}S$, and $1s^2\ ^1S \rightarrow 1s2p\ ^{1,3}P$ of targets of Z=2, 3, 6, 8, 12, 20, 22, 26, 28, 34 and 42 in helium atoms and He-like ions from the above selection are evaluated in this paper.

2.1 Comparison of Data Sources

Some collision strengths and remarks on the selected sources are given below.

2.1.1. He

Many experimental and theoretical data are available for helium atoms. Aggarwal et al.[6] assessed these data and gave the excitation rate coefficients over a wide range of the

electron temperature. Recently, Berrington et al.[7] calculated cross section by an 19-state R-matrix method. Their calculations gave smaller cross sections than previous ones calculated by 11-state[8] as well as 5-state[9], and showed the importance of coupling to higher channels in close-coupling and R-matrix calculations. The differences between the two calculations in refs. 7 and 8 are generally 2 ~ 5 % and within 10%. A comparison of data between ref. 6, 7 and 8 is given in Fig. 1. A solid line shows the recommended value for the $1^1S \rightarrow 2^1S$ transition.

2.1.2. Li^+

Five-state close coupling calculations have been reported by Van Wyngaarden et al.[10] for Li^+, C^{4+}, O^{6+} and Si^{12+}. Itikawa and Sakimoto[11] and Nakazaki[12] carried out by the distorted wave method and by the first order Coulomb-exchange approximation, respectively, using the same target wave functions employed by Van Wyngaarden et al., and Badnell[13] calculated collision strenghs using the distorted wave approximation for He-like ions between Li^+ and Fe^{24+}. These calculations did not take resonance effects into account. Christensen and Norcross[14] have examined the sensitivity of the cross sections to the scattering approximation, target wave functions and resonance effects by using five-state close-coupling and distorted wave calculations for Li^+ at energies near threshold. Only one experiment, by Rogers et al.[15], has been reported so far on the cross section for the transition $1^1S \rightarrow 2^3P$ in He-like ions. Collision strengths for the transitions $1^1S \rightarrow 2^3S$, 2^3P, 2^1S and 2^1P are shown in

figures 2 - 3 as function of $X = E/\Delta E$, i.e the incident electron energy in threshold units. Solid lines indicate the values taken for the fits which will be discussed in Sec. 3.

2.1.3. C^{4+}, O^{6+}, and Mg^{10+}

R-matrix calculations, which explicitly include resonance and channel coupling effects and are therefore likely to give the most reliable data for electron impact excitation of ions at low energies, have been carried out for He-like ions with Z = 6,8,12 by Kingston and Tayal[16-20]. The results were expressed in effective collision strengths because of the complex resonance structures: they explicitly included the $1s3\ell n'\ell'$ resonance series. Eleven target states, $1s^2\ ^1S$, $1s2s\ ^{1,3}S$, $1s2p\ ^{1,3}P$, $1s3s\ ^{1,3}S$, $1s3p\ ^{1,3}P$ and $1s3d\ ^{1,3}D$ were included in their calculations and their wave functions are constructed from 1s, 2s, 2p, 3s, 3p, 3d, 4s and 4p orbitals (4 means pseudo orbitals). They have confirmed that the excitation energies and the length and velocity values of oscillator strengths obtained in their calculation were in good agreement with the observed values, and with those of Schiff et al.[21]. Other calculations which can be compared with the R-matrix approximation are examined. Pradhan et al.[22,23] performed a distorted-wave calculation including autoionizing resonances and presented effective collision strengths. Steenman-Clark and Faucher[24] also calculated excitation rate coefficients for the forbidden transitions $1s^2\ ^1S \rightarrow 1s2s\ ^3S$ for ions with Z = 8,12,20 and 26 taking account of the effect of resonances and their radiative decay by using the distorted-wave method.

In Table I, we give sources of data for electron impact excitaion of He-like ions of Z = 6, 8, 12 which are given as effective collision strengths and which include resonance effects.

Figures 4 - 7 show a comparison of the temperature dependence in effective collision strengths for C^{4+}, O^{6+} and Mg^{10+} ions for the transitions $1^1S \rightarrow 2^{1,3}S$ and $1^1S \rightarrow 2^{1,3}P$. These data are taken from the R-matrix calculations with resonance effects. These figures show that the temperature dependences for C^{4+} and O^{6+} are quite different at low temperatures except for $1^1S \rightarrow 2^1P$.

Recently, Zhang and Sampson[25] gave excitation rate coefficients for 18 ions in the range $8 \leq Z \leq 74$. Their calculations were done in intermediate coupling, and the resonance contribution from $1s3\ell"n'\ell'''$ were included. They compared their results with those in ref.19 and found no significant difference for the transitions $1^1S \rightarrow 2^3S$, 2^3P of Mg^{10+}.

2.1.4. Ca^{18+}, Ti^{21+}, Fe^{24+}, Ni^{26+}, Se^{32+} and Mo^{40+}

For high Z ions, configuration interaction effects may be small and the target wave functions may be represented simply. However, the LS coupling approximation breaks down and IC effects must be included. Jones[26] investigated the IC effects on ions with Z = 14, 20, 26 using the distoreted wave approximation. He found that collision strengths for the transitions $1^1S_0 \rightarrow 2^3P_1$ increase relative to LS coupling values for ions $Z \geq 20$. So far, calculations with IC have been made and it has been seen that for the ions with $Z \geq 20$

the results by the Coulomb-Born method with exchange agree closely with those by the distoreted wave method.

Pradhan[27-30] investigated the role of resonances for ions with Z = 20, 26, 34 and 42 using nine-state close-coupling and distorted-wave approximations. He concluded that all three effects considered in his study, departure from LS coupling, resonance enhancement due to autoionization, and reduction in autoionization enhancement due to dielectronic recombination, can be of considerable importance in the collision strengths of highly ionized ions with $Z \geq 20$. The resonance contributions in ref.22 and 30 are mostly in disagreement with those in ref.25 by a factor of 2, but the total effective excitation rate coefficients are in agreement to within 20%. The rate coefficients for Fe^{24+} $1^1S - 2^3S$ by Pradhan[30], Steenman - Clark and Faucher[24] and Fancher and Dubau[31] are compared in Fig.8. The results in ref.30 are always larger than those in ref.24 by 20-40% and by 10-20% in ref.31 as shown in Fig.10.

2.2 Evaluated data source

Since the electron energy range for the data referred to in Sec. 2.1 is limited to low temperatures, they are not sufficient to give recommended rate coefficients for the wide temperature range needed especially in fusion plasmas. Generally in an ionizing plasma, such as a tokamak plasma, the temperature where the ions exist is relatively high compared with that in ionization equilibrium. We therefore combine the rate coefficients obtained by CC or R-mat methods at low temperatures with the cross sections obtained at

relatively high energies by DW methods to get the recommended data. It is requested to present the data not only in low temperature ranges where resonance effects are important but also in high temperature ranges.

The references from which the recommended data are selected are listed in Table II for each ion with their temperature ranges.

3. Data Evaluation and Fits

Once the recommended cross sections have been determined, a fit was made to analytical formulas, which facilitates their application. The original data are mainly presented as the effective collision strength γ, which is given by

$$\gamma = \int_0^\infty \Omega e^{-E/KT_e} d(E/kT_e)$$

$$= y \int_1^\infty \Omega e^{-yX} dX \qquad (1)$$

where $X = E/\Delta E$, $y = \Delta E/kT_e$, T_e is the electron temperature and ΔE is the excitation energy. The excitation rate coefficient can be calculated in the form

$$R = 8.010 \times 10^{-8}\ e^{-y}\gamma / \left(w_i \sqrt{T_e(eV)}\right)\ cm^3 s^{-1}, \qquad (2)$$

where w_i is the statistical weight of the lower state.
In the fitting procedure the collision strength Ω is assumed to be expressed by the following formula

$$\Omega = A + B/X + C/X^2 + D/X^3 + E\ \ln X. \qquad (3)$$

Then, the effective collision strength γ is obtained as follows :

$$\gamma = y\ \{(A/y+C) + D/2(1-y) + e^{y}E_1(y)\ (B-Cy+Dy^2/2+E/y)\}, \quad (4)$$

where $$E_1(y) = \int_y^{\infty} e^{-t}/t\ dt.$$

In principle four parameters A, B, C and E (D=0) for allowed transitions and A, B, C and D (E=0) for forbidden transitions are used in fitting procedure. The fitting error is usually less than 10% and always less than the estimated uncertainties of the recommended effective collision strengths.

When γ can not be fitted well by eq. (4), the effective collision strength in the resornance region Ω_R^{eff} is introduced as follows,

$$\Omega \equiv \Omega_R(X) + \Omega_{NR}(X). \quad 5(a)$$

$\Omega_{NR}(X)$, the non-resonant collision strength, is defined for $X > X_1$ by eq. (3),

and $\Omega_R(X) = PX + Q$ for $1 \leq X \leq X_1$ 5(b)

Here γ is written as

$$\gamma = \gamma_{NR} + \gamma_R, \quad (6)$$

where

$$\gamma_{NR} = y\, e^{(1-X_1)y}\{(A/y + C/X_1 + D/2(1/X_1^2 - y/X_1) + E\ \ln X_1/y) + e^{yX_1}\, E_1(X_1y)\,(B - Cy + Dy^2/2 + E/y)\}, \quad (7)$$

and

$$\gamma_R = P(1+1/y)\{1-e^{(1-X_1)y}(X_1+1/y)/(1+1/y)\} + Q(1-e^{(1-X_1)y}). \qquad (8)$$

The quantities P, Q and X_1 are determined by equating the effective collision strength γ calculated with 5(a) and 5(b) to γ given in the original literature source. Since the parameters are derived to fit the effective collision strength γ, the collision strength Ω, calculated from the fit parameters has no real meaning.

For Li^+ ions, the data by Model II (CC and target 1) in ref.14 are used. Since the contribution of resonances for 1^1S - 2^3S is estimated to be about 10%, we neglect the resonance contribution near threshold. The data used for evaluation are shown by solid lines in Figs. 2-5.

The values of the collision strength Ω approach $4w_i f_{ij}/\Delta E \ln X$ at high energies where f_{ij} is the oscillator strength for the dipole transition 1^1S - 2^1P and ΔE the excitation energy in unit of Ryd. We fit Ω or γ with a given value of $4w_i f_{ij}/\Delta E$ for parameter E in eq.(3) for 1^1S - 2^1P, and derived the values for A, B and C (D=0). Fitting with four parameters A, B, C and E gives better results than three parameter fits with A,B, and C, but we used three parameter fits since the difference between the two methods is less than 8% and the fitting error is less than 10%. At higher temperatures this method is expected to be much more reliable, as the asymptotic value in the Bethe limit is obtained.

In Table III, the fitting coefficients as defined above are given together with the excitation energy and accuracy. When eq.(5) is used, the parameters P, Q and X_1 are also tabulated

for Ω_R. In such cases, the coefficients A, B, C, D, E are for Ω_{NR} only. The recommended values of the rate coefficients which are reproduced with the use of the fit parameters, are shown in the Graphs. When using the present recommended data, one should note their validity range and accuracy, both of which are shown in Table II and III, respectively. We have derived the analytical formulas of the effective collision strength by a fitting procedure over a finite range of temperature for which the original data exist. It is risky to simply extend the formulas outside of their validity range. Extrapolation is permissible to some extent, but its accuracy depends on the transition. Finally, the accuracy in Table III should not be considered very rigorous, since it represents only an "educated guess" in most cases.

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Table I

Data sources for effective collision strengths including resonance effects for n=1 - n=2 of C^{4+}, O^{6+} and Mg^{10+}.

Authors	Ref. No.	Ions	Transitions	Data Reported	Temperature Range	Method
Pradhan (1981)	23	C^{4+} O^{6+}	$1^1S - 2^3S$ $- 2^3P$ $- 2^1S$ $- 2^1P$	γ	2(4)-1(7)$^+$K	DW*
Steenman-Clark (1984)	24	O^{6+} Mg^{10+}	$1^1S - 2^3S$ $- 2^3S$	R	3(5)-5(6)K 7(5)-7(6)K	DW
Kingston&Tayal (1983)	17	O^{6+}	$1^1S - 2^3S$ $- 2^3P$	γ	1(4)-1(7)K	5R-mat**, 11R-mat
Tayal&Kingston (1984)	18	O^{6+}	$1^1S - 2^1S$ $- 2^1P$ $- 2^3S$ $- 2^3P$	γ	1(4)-5(6)K	5R-mat, 11R-mat
Tayal&Kingston (1984)	19	C^{4+} Mg^{10+}	$1^1S - 2^3S$ $- 2^3P$ $1^1S - 2^3S$ $- 2^3P$	γ	1(4)-1(7)K	5R-mat, 11R-mat
Tayal (1986)	20	C^{4+}	$1^1S - 2^1S$ $- 2^1P$	γ	4(4)-4(6)K	5R-mat, 11R-mat

note: *DW = Distorted wave, **5R-mat = 5 states R-matrix
$^+2(4) - 1(7)K = 2\times10^4 \sim 1\times10^7 K$

Table II

Evaluated data source and temperature (energy) range

Ion		Ref. No.	Temperature(Energy)range	Data Reported	Method
He					
	1^1S-2^3S	7	T_e = 5(3) - 5(4)K	γ	R-mat
	-2^3P	6	T_e = 1(6) - 3(6)K	γ	E
	-2^1S				
	-2^1P				
Li^+					
	1^1S-2^3S	14	X = 1.0 - 1.2	Ω	CC
	-2^3P	10	X = 2.0 - 5.0	Ω	CC
	-2^1S				
	-2^1P				
C^{4+}					
	1^1S-2^3S	1	X = 1.05 - 42.0	Ω, R	E
	-2^3P				E
	1^1S-2^1S	20	T_e = 4(4) - 4(6)K	γ	R-mat
	-2^1P	1	T_e = 6(6) - 8(8)K		E
O^{6+}					
	1^1S-2^2S	1	X = 1.0 - 30.0	Ω, R	E
	-2^3P				
	-2^2S				
	-2^1P				

Mg^{10+}

1^1S-2^3S	19	T_e = 1(4) - 1(7)K	γ	R-mat
-2^3P	13	X = 1.0 - 5.0	Ω	DW
1^1S-2^1S	25	T_e = 6.9(5) - 1.7(7)K	γ	CB+DW
$-2'P$				

Ca^{18+}

1^1S-2^3S	30	T_e = 2(6) - 1.6(8)K	γ	DW
-2^3P	29	X = 1.2 - 7.0	Ω	DW
-2^1S				
-2^1P				

Ti^{20+}

1^1S-2^3S	25	Te = 4.3(6) - 1.1(8)K	γ	CB+DW
-2^3P				
-2^1S				
-2^1P				

Fe^{24+}

1^1S-2^3S	30	T_e = 6.3(6) - 5(8)K	γ	DW
-2^3P	27	X = 1.2 - 10.	Ω	DW
-2^1S				
-2^1P				

Ni^{26+}

1^1S-2^3S	25	Te = 8.8(6) - 2.2(8)K	γ	CB+DW
-2^3P				
-2^1S				
-2^1P				

Se^{32+}

1^1S-2^3S	27	X = 1.2 - 11.7	Ω	DW
-2^3P				
-2^1S				
-2^1P				

Mo^{40+}

1^1S-2^3S	27	X = 1.2 - 11.4	Ω	DW
	28	T_e = 5(7) - 3(8)K	R	DW
1^1S-2^3P	27	X = 1.2 - 11.4	Ω	DW
-2^1S				
-2^1P				

Note:

DW = Distorted Wave, CC = Close Coupling, R-mat = R-matrix, E = Evaluated

CB = Coulomb Born

γ = Effective collision strength, Ω = Collision strength,

R = Rate coefficient

Figure Captions

Fig. 1 The effective collision strength γ as a function of electron temperature $T_e(K)$ by Aggarwal et al.[6] and Berrington et al[7]. A solid line shows the recommended data.

Fig. 2 Comparison of the collision strength for Li^+ $1^1S \rightarrow 2^3P$.
A solid line indicates the recommended value.

Fig. 3 Comparison of the collision strength for Li^+ $1^1S \rightarrow 2^1P$.
A solid line indicates the recommended value.

Fig. 4 The effective collision strength γ by 11 states R - matrix as a function of the electron temperature $T_e(K)$ for $1^1S \rightarrow 2^3S$ of C^{4+}, O^{6+} and Mg^{10+}.

Fig. 5 The effective collision strength γ by 11 states R - matrix as a function of the electron temperature $T_e(K)$ for $1^1S \rightarrow 2^3P$ of C^{4+}, O^{6+} and Mg^{10+}.

Fig. 6 The effective collision strength γ by 11 states R - matrix as a function of the electron temperature $T_e(K)$ for $1^1S \rightarrow 2^1S$ of C^{4+} and O^{6+}.

Fig. 7 The effective collision strength γ by 11 states R - matrix as a function of the electron temperature $T_e(K)$ for $1^1S \rightarrow 2^1P$ of C^{4+} and O^{6+}.

Fig. 8 Comparison of the excitation rate coefficients of Fe^{+24} by Pradhan[30] with those by Steenman-Clark and Faucher[24] and Faucher and Dubau[31].

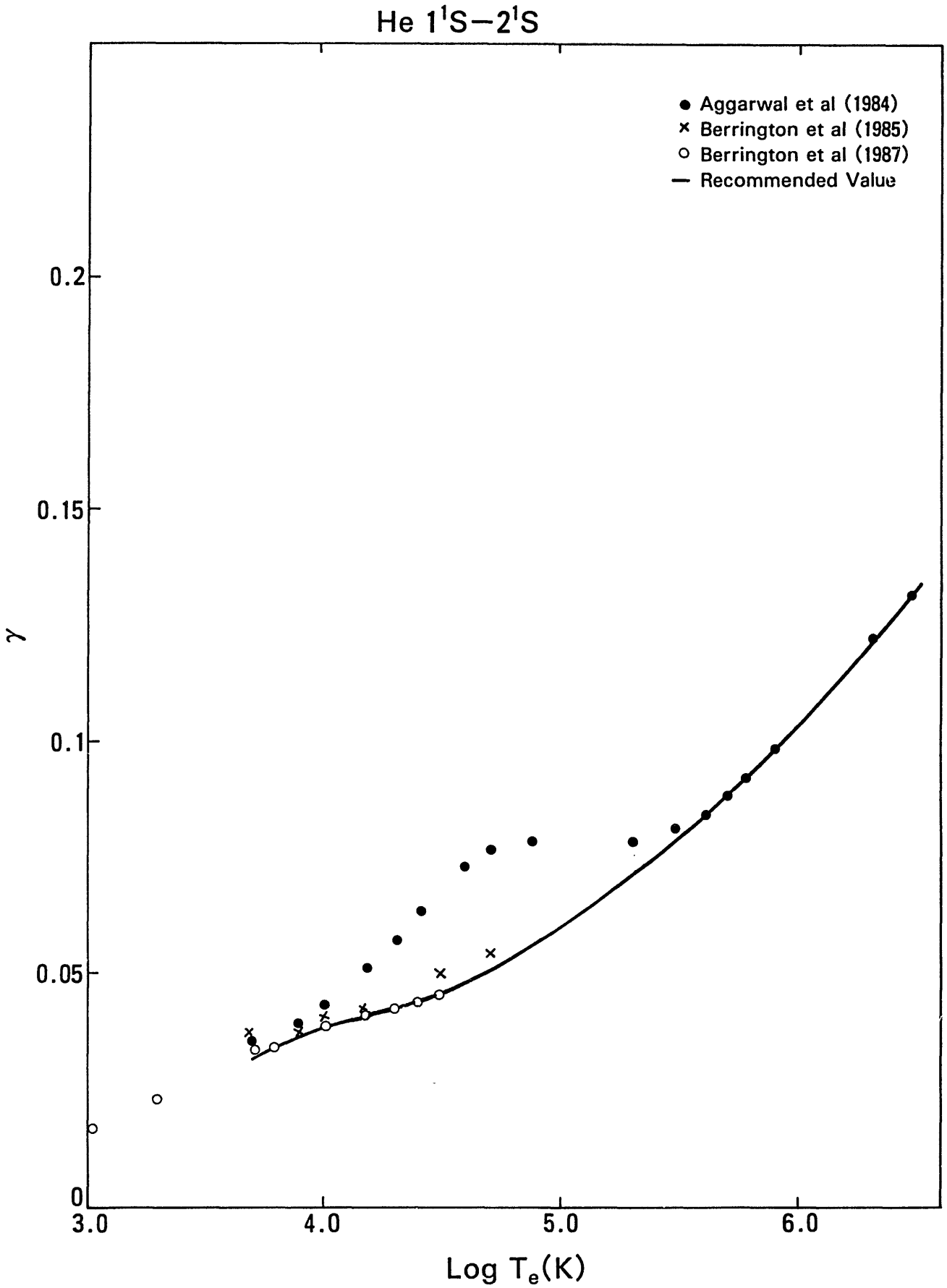

He 1¹S−2¹S
● Aggarwal et al (1984)
× Berrington et al (1985)
○ Berrington et al (1987)
— Recommended Value
0.2
0.15
0.1
0.05
0
γ
3.0
4.0
5.0
6.0
Log Te(K)

Fig.1

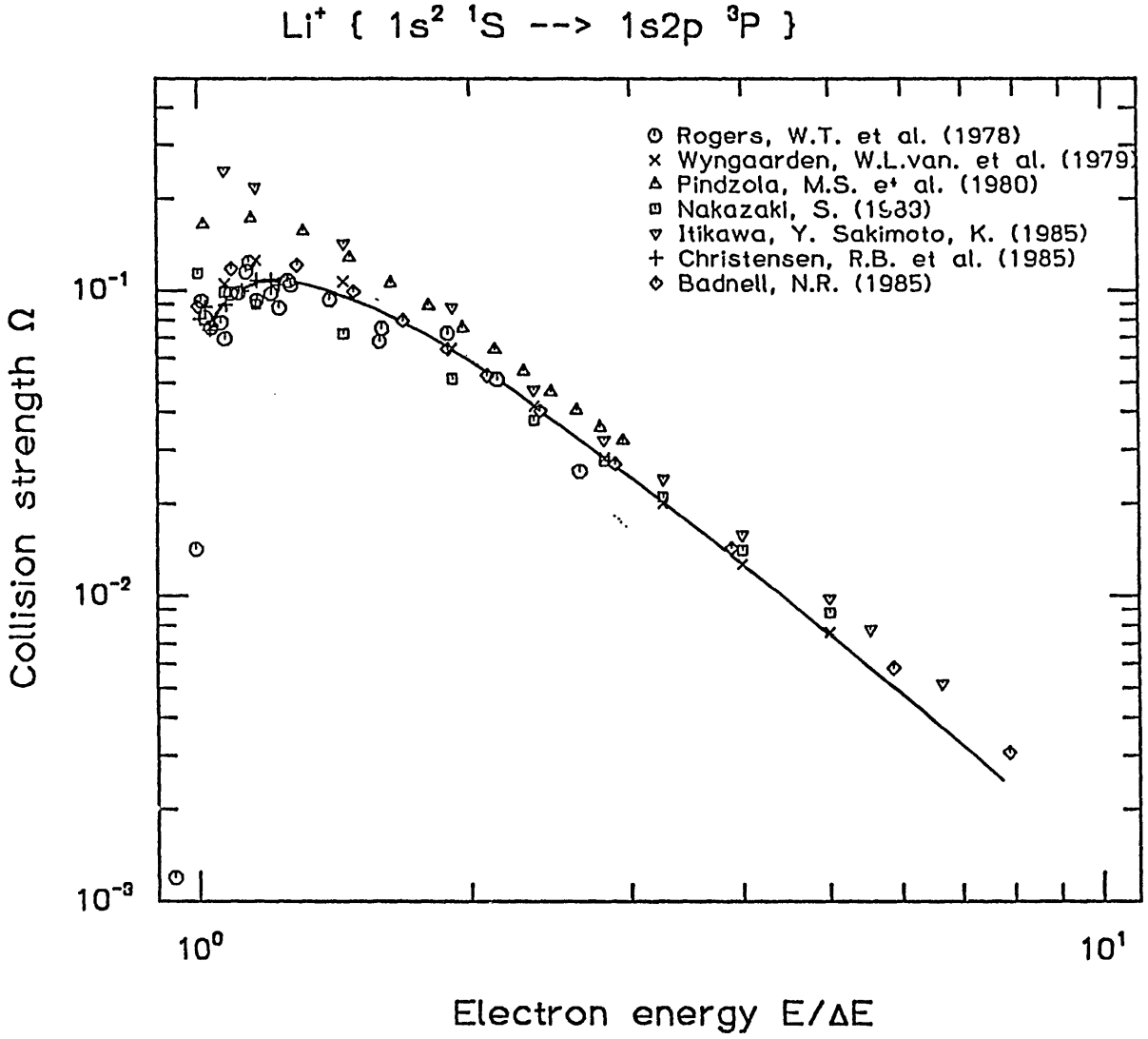

Li+ { 1s2 1S --> 1s2p 3P }
Rogers, W.T. et al. (1978)
Wyngaarden, W.L.van. et al. (1979)
Pindzola, M.S. et al. (1980)
Nakazaki, S. (1983)
Itikawa, Y. Sakimoto, K. (1985)
Christensen, R.B. et al. (1985)
Badnell, N.R. (1985)
Collision strength Ω
10-1
10-2
10-3
100
101
Electron energy E/ΔE

Fig.2

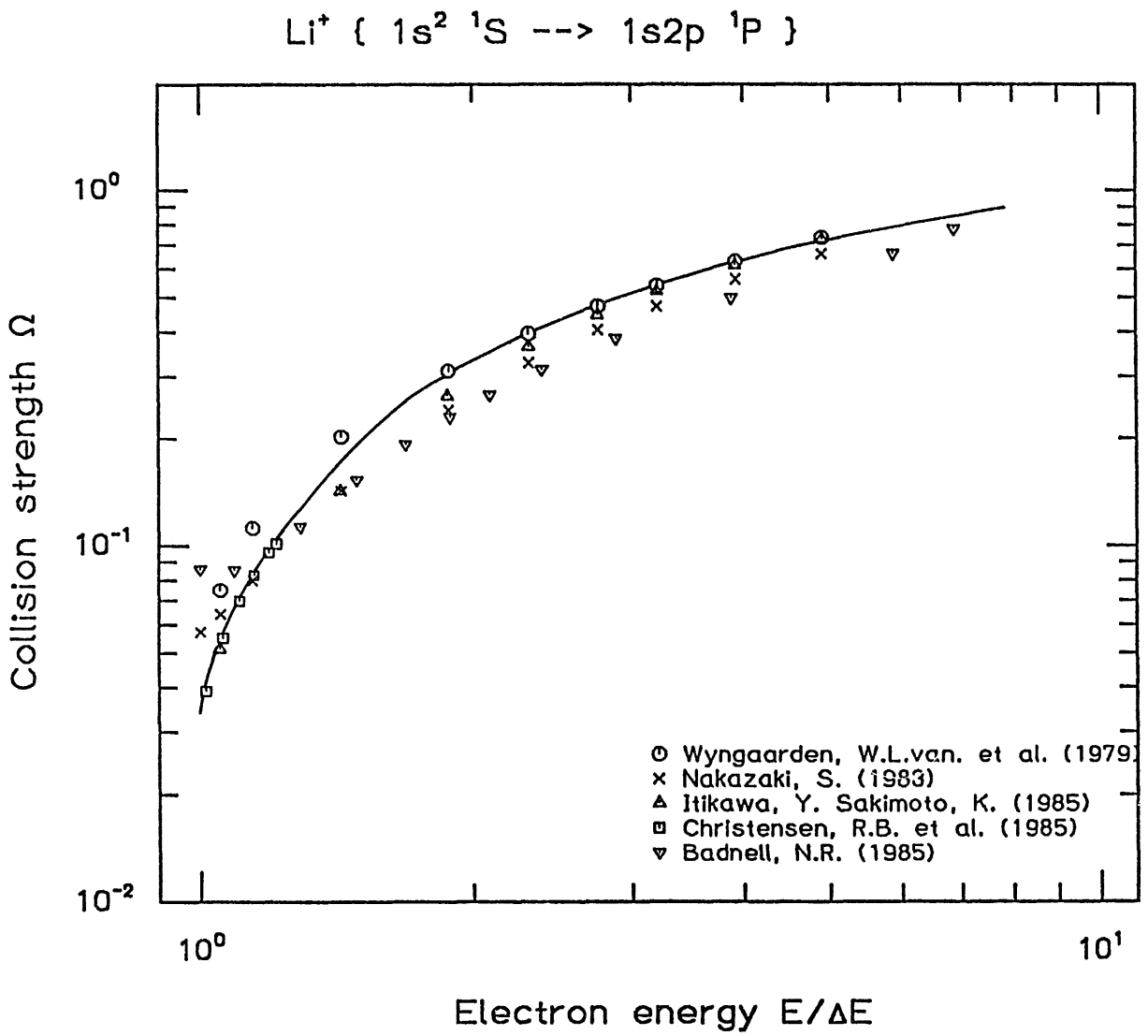

Li+ { 1s2 1S --> 1s2p 1P }
Collision strength Ω
10^0
10^-1
10^-2
10^0
10^1
Electron energy E/ΔE
Wyngaarden, W.L.van. et al. (1979)
Nakazaki, S. (1983)
Itikawa, Y. Sakimoto, K. (1985)
Christensen, R.B. et al. (1985)
Badnell, N.R. (1985)

Fig.3

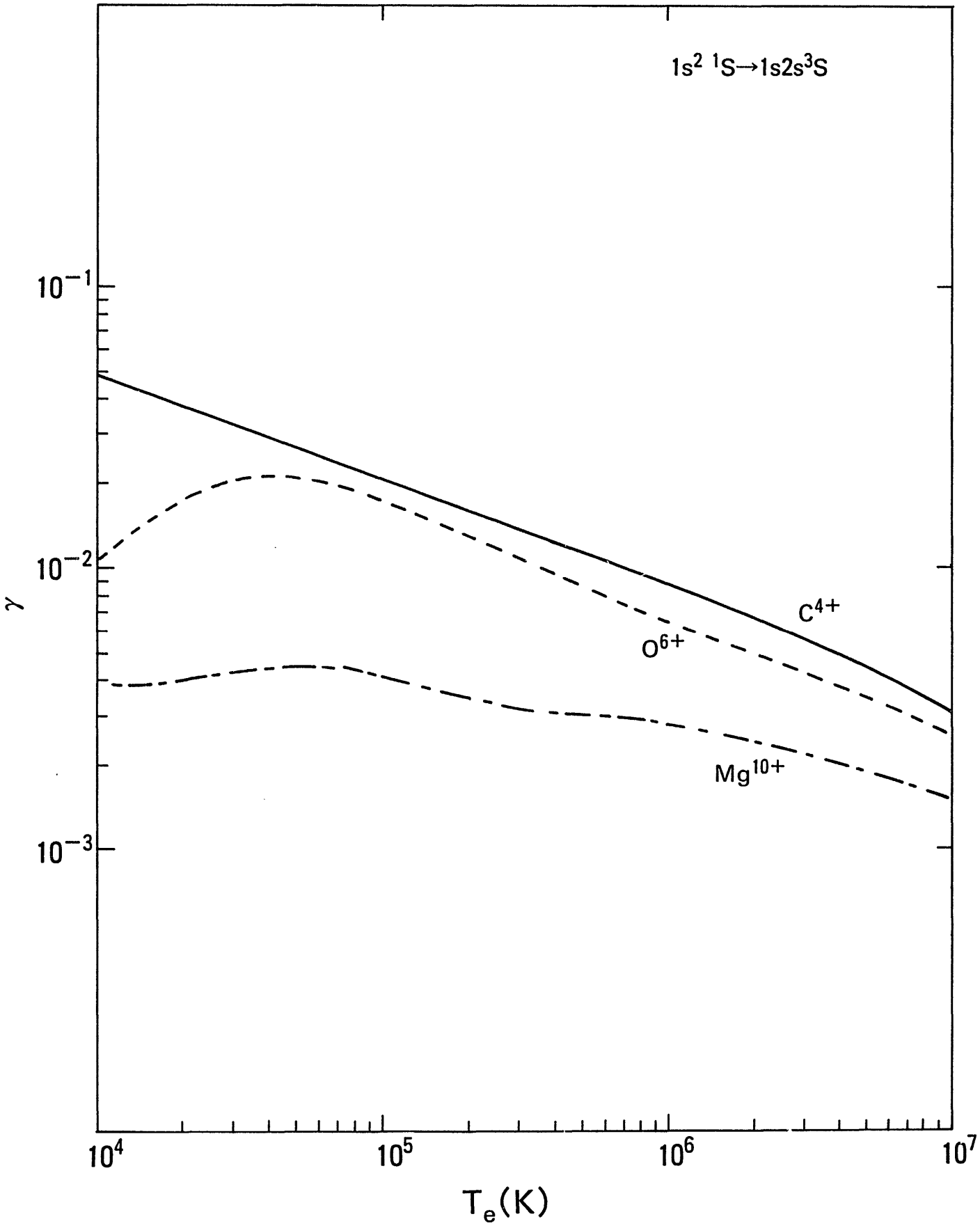

$1s^2\ ^1S \rightarrow 1s2s^3S$
10^{-1}
10^{-2}
10^{-3}
γ
C^{4+}
O^{6+}
Mg^{10+}
10^4
10^5
10^6
10^7
$T_e(K)$

Fig.4

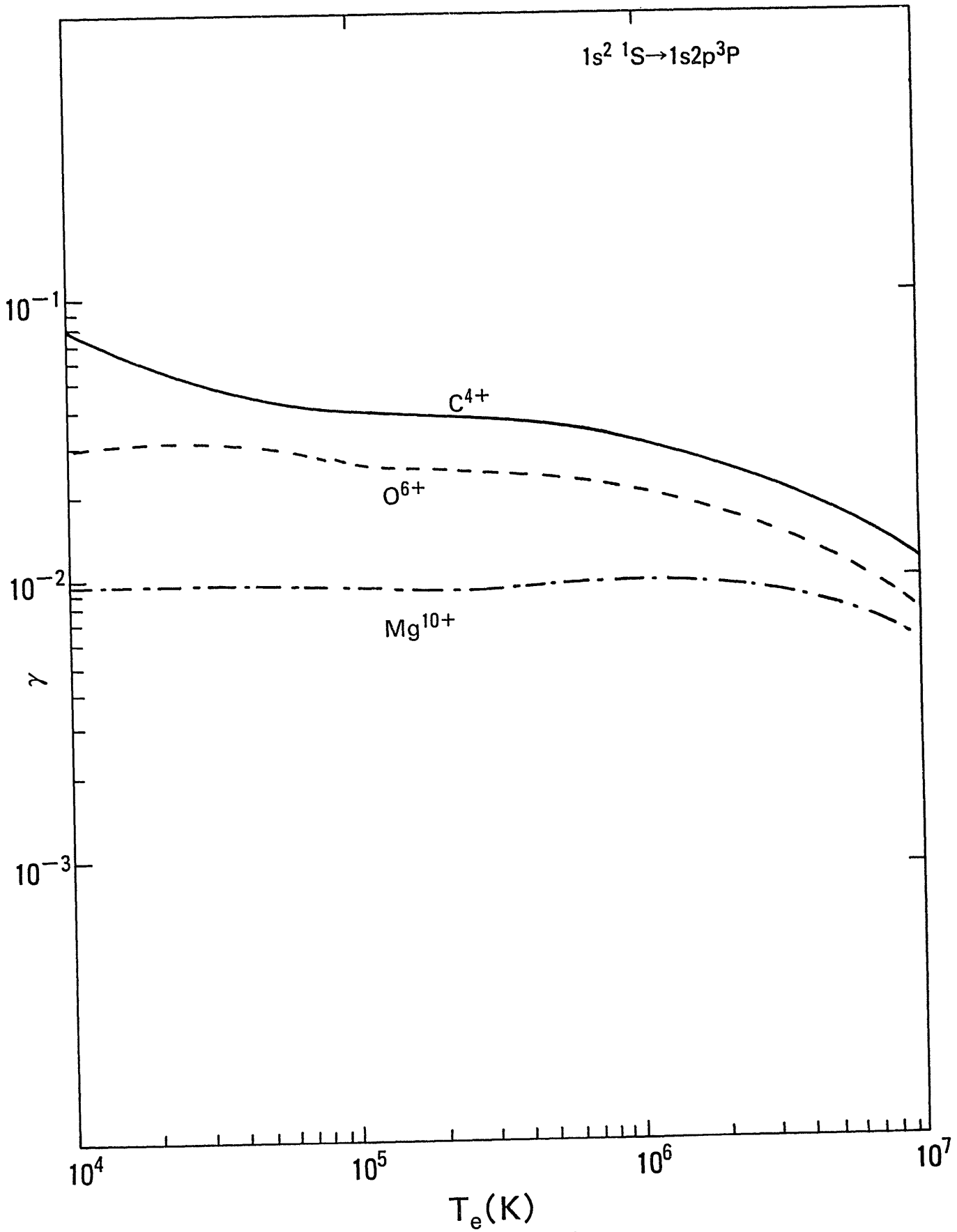

$1s^2\ ^1S \rightarrow 1s2p^3P$
10^{-1}
10^{-2}
10^{-3}
γ
C^{4+}
O^{6+}
Mg^{10+}
10^4
10^5
10^6
10^7
$T_e(K)$

Fig.5

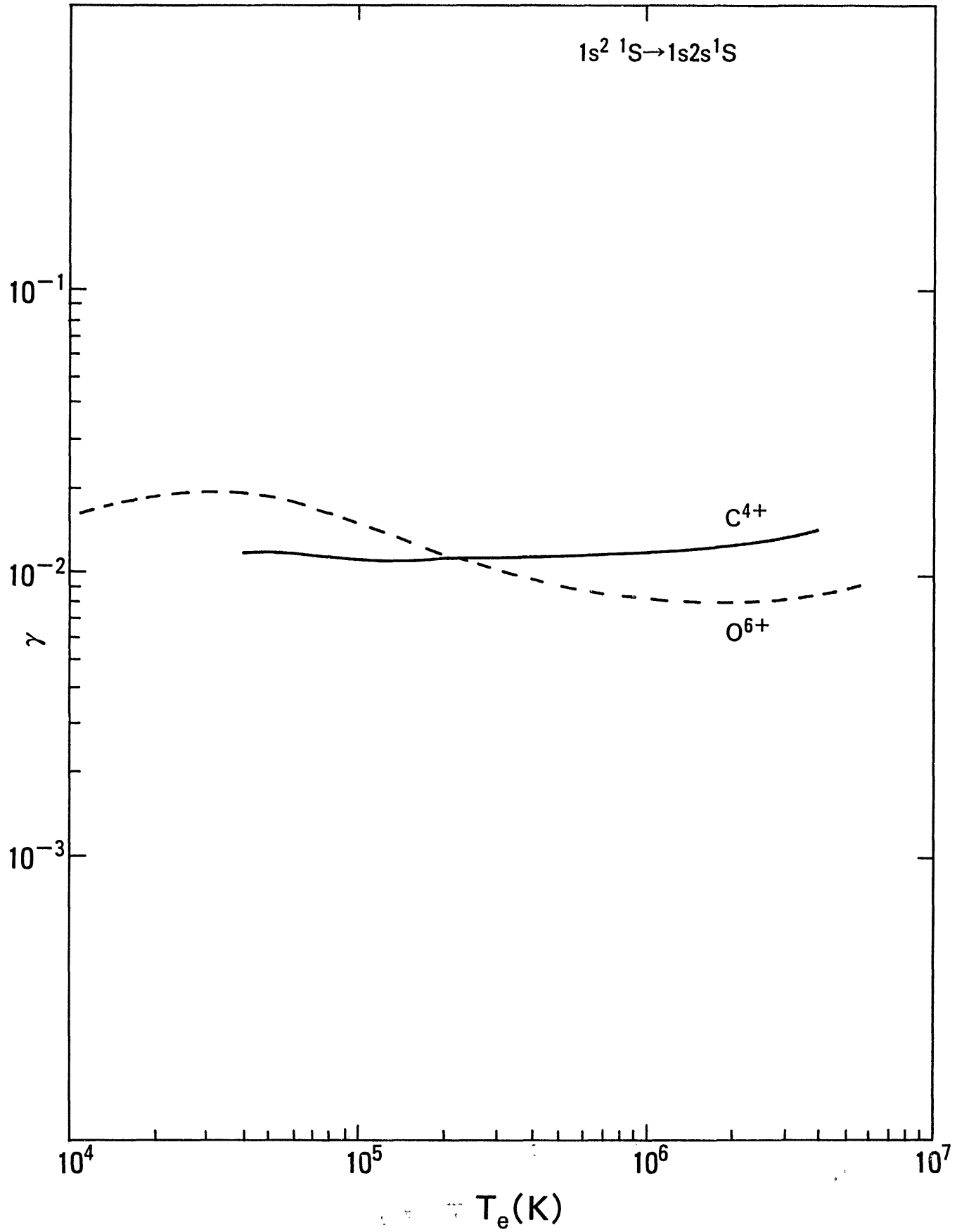

$1s^2\ ^1S \rightarrow 1s2s\ ^1S$
10^{-1}
10^{-2}
10^{-3}
γ
C^{4+}
O^{6+}
10^4
10^5
10^6
10^7
$T_e(K)$

Fig.6

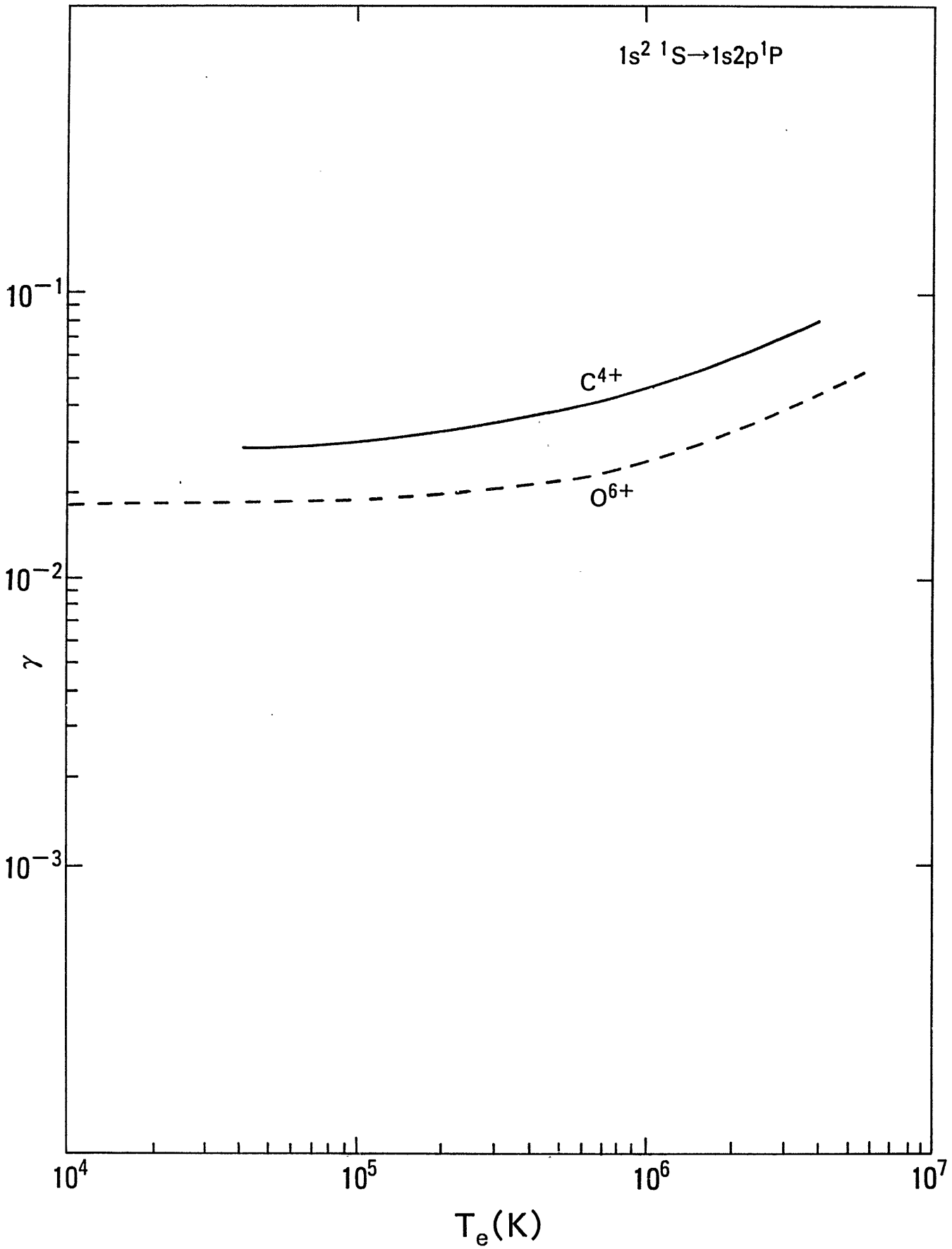

$1s^2\ ^1S \rightarrow 1s2p\ ^1P$
C^{4+}
O^{6+}
10^{-1}
10^{-2}
10^{-3}
γ
10^4
10^5
10^6
10^7
$T_e(K)$

Fig.7

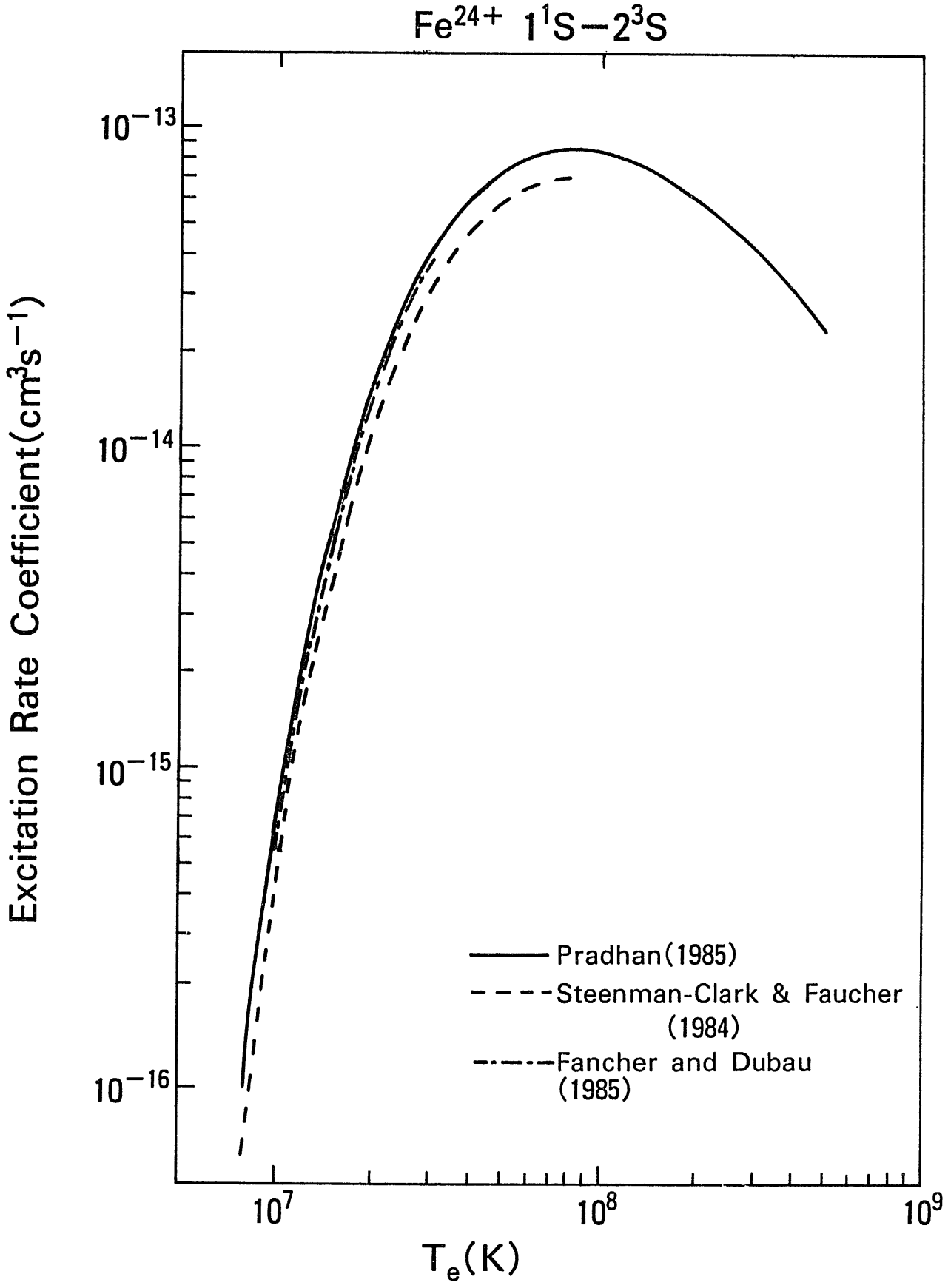

Fe^{24+} 1^1S-2^3S
10^{-13}
10^{-14}
10^{-15}
10^{-16}
Excitation Rate Coefficient(cm^3s^{-1})
10^7
10^8
10^9
T_e(K)
Pradhan(1985)
Steenman-Clark & Faucher (1984)
Fancher and Dubau (1985)

Fig.8

Explanation of Table III

Tables III. Fit Paramaters for the Recommended Rate Coefficients

Fit parameters in eq.(3) and eq.(5) are tabulated for each excitation process and each ion specie. For instance, $1s^2\ ^1S$ - $1s2s\ ^1S$ means the excitation from the lower state $1s^2\ ^1S$ to the upper state of $1s2s\ ^1S$.

ΔE	Excitation energy in (eV)
Accuracy	Estimated accuracy of the resulting rate coefficient.
	1 for the error within about 20%
	2 for about 50%
	3 for about a factor of 2
A, B, C, D, E,	Fit parameters
P, Q, X_1	Fit parameters for Ω_R and the upper energy of the resonance region, when considered (eq.(5)).

He	ΔE(eV)	A	B	C	D	E	P	Q	X_1	Accuracy
$1s^2\ ^1S$ - $1s2s\ ^3S$	1.98E+01	8.21E-04	4.22E-02	1.81E-01	-1.55E-01	0.0				1
$1s^2\ ^1S$ - $1s2p\ ^3P$	2.10E+01	-1.22E-03	4.75E-02	2.63E-01	-2.94E-01	0.0				1
$1s^2\ ^1S$ - $1s2s\ ^1S$	2.06E+01	1.72E-01	-3.46E-01	4.28E-01	-2.21E-01	0.0				1
$1s^2\ ^1S$ $1s2p\ ^1P$	2.12E+01	6.73E-02	-6.66E-01	6.08E-01	0.0	6.46E-01				1

Li^{1+}	ΔE(eV)	A	B	C	D	E	P	Q	X_1	Accuracy
$1s^2\ ^1S$ - $1s2s\ ^3S$	5.90E+01	-1.47E-03	1.70E-02	5.56E-02	-1.51E-02	0.0				1
$1s^2\ ^1S$ - $1s2p\ ^3P$	6.12E+01	4.68E-03	-9.41E-02	6.19E-01	-4.40E-01	0.0				1
$1s^2\ ^1S$ - $1s2s\ ^1S$	6.07E+01	2.17E-01	-3.02E-01	1.23E-01	0.0	-3.77E-02				1
$1s^2\ ^1S$ - $1s2p\ ^1P$	6.22E+01	1.49E-01	-3.03E-01	1.90E-01	0.0	4.00E-01				1

C^{4+}	ΔE(eV)	A	B	C	D	E	P	Q	X_1	Accuracy
$1s^2\ ^1S$ - $1s2s\ ^3S$	2.98E+02	-1.82E-05	1.09E-03	1.68E-02	-8.79E-03	0.0	-1.78E+00	1.83E+00	1.02	1
$1s^2\ ^1S$ - $1s2p\ ^3P$	3.03E+02	1.85E-05	-1.77E-03	6.15E-02	-1.57E-02	0.0				1
$1s^2\ ^1S$ - $1s2s\ ^1S$	3.04E+02	2.89E-02	-3.86E-02	1.58E-02	5.42E-03	0.0				1
$1s^2\ ^1S$ - $1s2p\ ^1P$	3.08E+02	4.59E-02	-1.17E-01	1.01E-01	0.0	1.14E-01				1

O^{6+}	ΔE(eV)	A	B	C	D	E	P	Q	X_1	Accuracy
$1s^2\ ^1S$ - $1s2s\ ^3S$	5.61E+02	-2.33E-05	1.03E-03	5.97E-03	-2.86E-03	0.0	-9.33E-02	1.09E-01	1.10	1
$1s^2\ ^1S$ - $1s2p\ ^3P$	5.68E+02	5.74E-05	-8.06E-04	3.32E-02	-9.39E-03	0.0	-2.37E-01	2.68E-01	1.04	1
$1s^2\ ^1S$ - $1s2s\ ^1S$	5.69E+02	1.61E-02	-2.41E-02	2.73E-02	-1.27E-02	0.0	-5.76E-04	1.83E-02	1.02	1
$1s^2\ ^1S$ - $1s2p\ ^1P$	5.74E+02	2.07E-02	-1.55E-02	1.30E-02	0.0	6.56E-02				1

Mg^{10+}	ΔE(eV)	A	B	C	D	E	P	Q	X_1	Accuracy
$1s^2\ ^1S$ - $1s2s\ ^3S$	1.34E+03	-7.35E-05	1.02E-03	1.79E-03	-1.12E-03	0.0	-1.29E-02	1.68E-02	1.25	1
$1s^2\ ^1S$ - $1s2p\ ^3P$	1.33E+03	1.19E-04	-1.64E-03	1.99E-02	-8.71E-03	0.0	1.28E-02	-3.53E-03	1.20	1
$1s^2\ ^1S$ - $1s2s\ ^1S$	1.34E+03	7.79E-03	-1.24E-02	1.48E-02	-6.68E-03	0.0				2
$1s^2\ ^1S$ - $1s2p\ ^1P$	1.34E+03	-8.77E-04	1.26E-02	-1.57E-03	0.0	3.02E-02				2

Ca^{18+}	ΔE(eV)	A	B	C	D	E	P	Q	X_1	Accuracy
$1s^2\ ^1S$ - $1s2s\ ^3S$	3.87E+03	-2.49E-05	4.05E-04	-1.13E-04	8.08E-04	0.0				2
$1s^2\ ^1S$ - $1s2p\ ^3P_0$	3.89E+03	-3.48E-08	-3.44E-05	6.92E-04	-2.04E-04	0.0				2
$1s^2\ ^1S$ - $1s2p\ ^3P_1$	3.89E+03	6.45E-04	-8.06E-04	1.40E-03	1.46E-04	0.0				2
$1s^2\ ^1S$ - $1s2p\ ^3P_2$	3.89E+03	-4.53E-07	-1.66E-04	3.41E-03	-9.82E-04	0.0				2
$1s^2\ ^1S$ - $1s2s\ ^1S$	3.89E+03	2.87E-03	-3.43E-03	1.95E-03	0.0	-1.97E-04				2
$1s^2\ ^1S$ - $1s2p\ ^1P$	3.91E+03	1.06E-03	-7.09E-05	3.06E-03	0.0	1.04E-02				1

Tl^{20+}	ΔE(eV)	A	B	C	D	E	P	Q	X_1	Accuracy
$1s^2\ ^1S$ - $1s2s\ ^3S$	4.70E+03	-3.02E-06	3.27E-04	-8.48E-05	5.03E-04	0.0				2
$1s^2\ ^1S$ - $1s2p\ ^3P_0$	4.73E+03	6.80E-06	-2.15E-05	4.10E-04	-1.89E-05	0.0				2
$1s^2\ ^1S$ - $1s2s\ ^3P_1$	4.73E+03	1.07E-03	-2.71E-03	4.10E-03	-1.25E-03	0.0				2
$1s^2\ ^1S$ - $1s2p\ ^3P_2$	4.74E+03	8.87E-05	-4.38E-04	2.66E-03	-4.35E-04	0.0				2
$1s^2\ ^1S$ - $1s2s\ ^1S$	4.73E+03	1.87E-03	-1.20E-03	2.59E-04	1.44E-04	0.0				2
$1s^2\ ^1S$ - $1s2p\ ^1P$	4.76E+03	1.72E-03	-7.93E-04	2.32E-03	0.0	8.41E-03				2

Fe^{24+}	ΔE(eV)	A	B	C	D	E	P	Q	X_1	Accuracy
$1s^2\ ^1S$ - $1s2s\ ^3S$	6.65E+03	-4.11E-05	6.25E-04	-1.13E-03	1.21E-03	0.0				2
$1s^2\ ^1S$ - $1s2p\ ^3P_0$	6.67E+03	-7.87E-06	8.78E-05	1.22E-04	7.41E-05	0.0				2
$1s^2\ ^1S$ - $1s2p\ ^3P_1$	6.68E+03	1.66E-03	-5.09E-03	7.74E-03	-3.56E-03	0.0				2
$1s^2\ ^1S$ - $1s2p\ ^3P_2$	6.69E+03	-4.46E-05	4.79E-04	4.81E-04	4.63E-04	0.0				2
$1s^2\ ^1S$ - $1s2s\ ^1S$	6.67E+03	1.59E-03	-1.53E-03	7.48E-04	0.0	-7.20E-05				2
$1s^2\ ^1S$ - $1s2p\ ^1P$	6.71E+03	7.22E-04	-4.34E-04	2.28E-03	0.0	5.72E-03				2

Ni^{26+}	ΔE(eV)	A	B	C	D	E	P	Q	X_1	Accuracy
$1s^2\ ^1S$ - $1s2s\ ^3S$	7.74E+03	-3.83E-05	4.60E-04	-5.42E-04	5.65E-04	0.0				2
$1s^2\ ^1S$ - $1s2p\ ^3P_0$	7.77E+03	-7.46E-06	7.28E-05	8.94E-05	7.16E-05	0.0				2
$1s^2\ ^1S$ - $1s2p\ ^3P_1$	7.77E+03	1.67E-03	-4.24E-03	5.32E-03	-1.96E-03	0.0				2
$1s^2\ ^1S$ - $1s2p\ ^3P_2$	7.80E+03	-6.09E-05	5.39E-04	7.80E-05	5.94E-04	0.0				2
$1s^2\ ^1S$ - $1s2s\ ^1S$	7.77E+03	1.12E-03	-4.88E-04	-3.21E-04	3.56E-04	0.0				2
$1s^2\ ^1S$ - $1s2p\ ^1P$	7.82E+03	9.56E-04	-3.90E-04	1.38E-03	0.0	4.91E-03				2

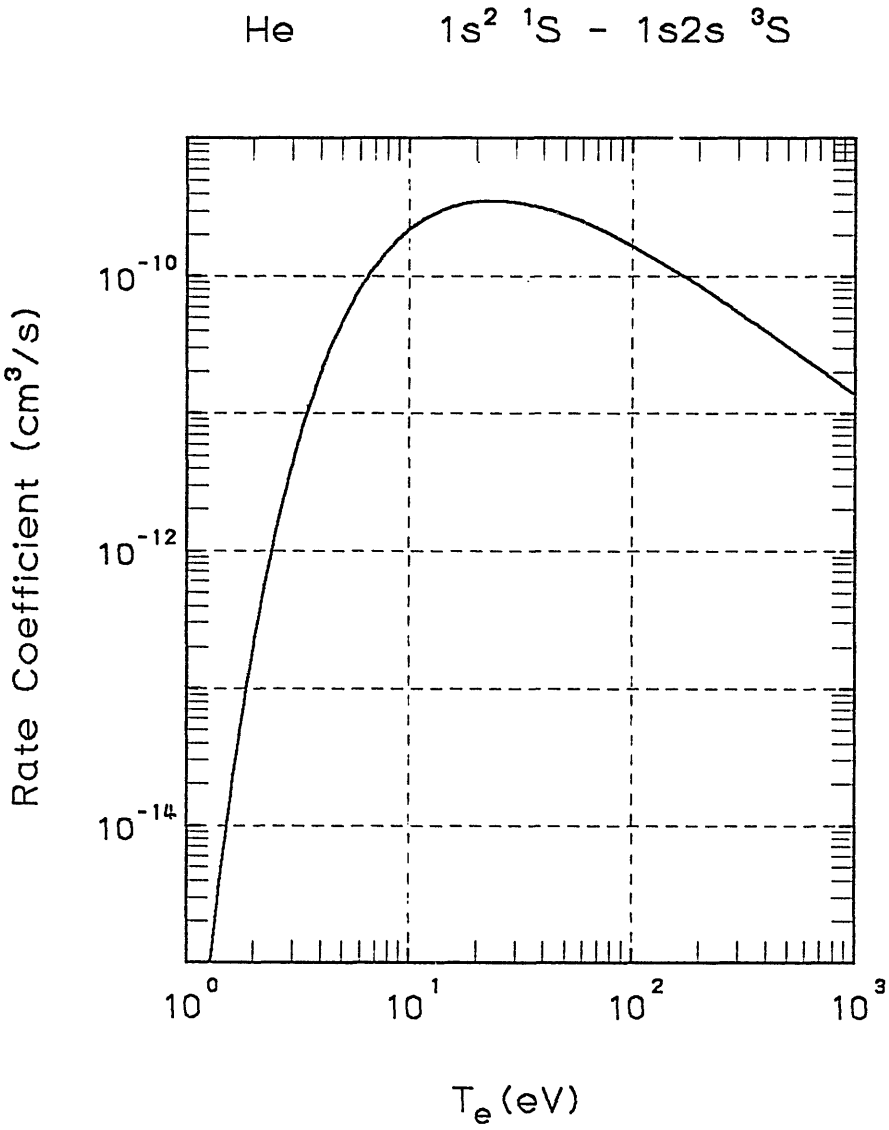
Se^{32+}	ΔE(eV)	A	B	C	D	E	P	Q	X_1	Accuracy
$1s^2\ ^1S$ - $1s2s\ ^3S$	1.16E+04	-1.66E-06	4.95E-05	3.58E-04	-2.16E-04	0.0				2
$1s^2\ ^1S$ - $1s2p\ ^3P_0$	1.16E+04	-1.92E-07	-3.43E-06	2.11E-04	-7.20E-05	0.0				2
$1s^2\ ^1S$ - $1s2p\ ^3P_1$	1.16E+04	2.13E-03	-6.87E-03	1.04E-02	-5.35E-03	0.0				2
$1s^2\ ^1S$ - $1s2p\ ^3P_2$	1.16E+04	1.02E-06	-2.90E-05	1.05E-03	-3.59E-04	0.0				2
$1s^2\ ^1S$ - $1s2s\ ^1S$	1.16E+04	7.78E-04	-4.16E-04	3.90E-05	0.0	-5.74E-08				2
$1s^2\ ^1S$ - $1s2p\ ^1P$	1.17E+04	6.22E-04	1.57E-04	7.08E-04	0.0	2.94E-03				2

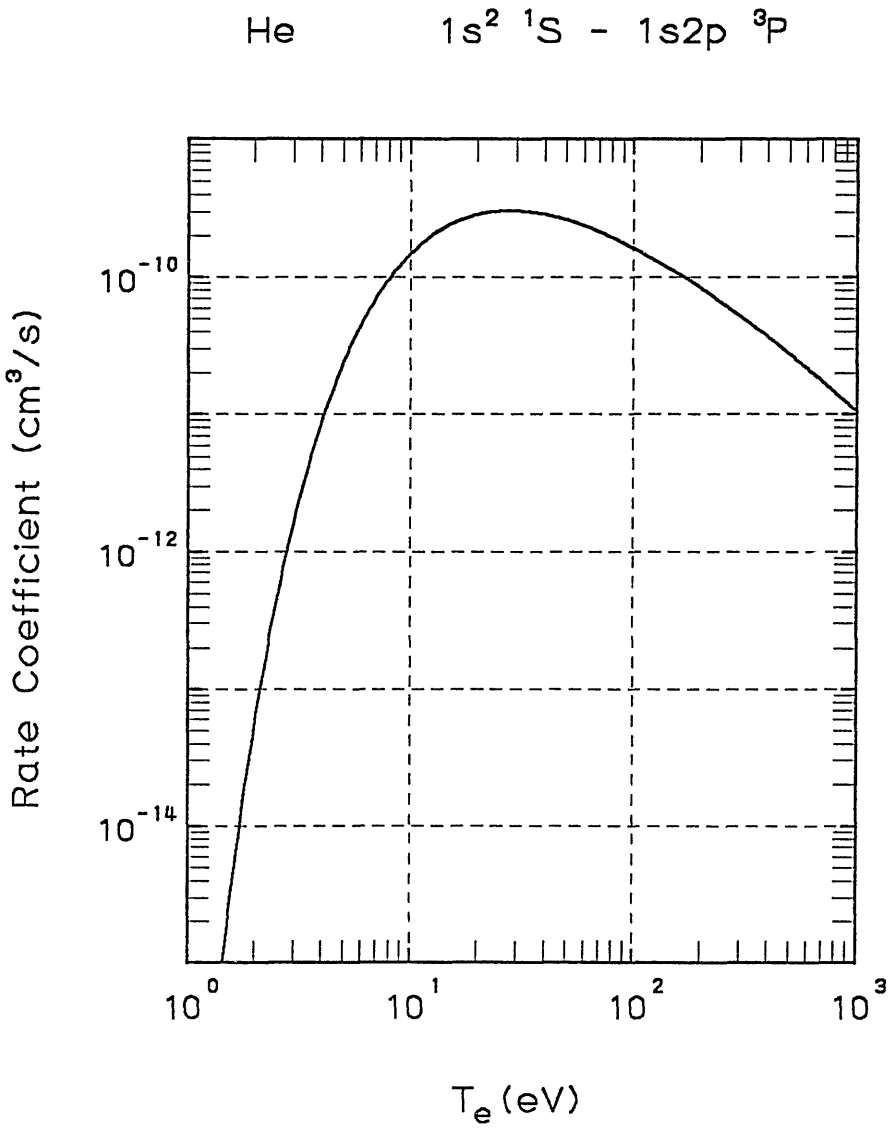
Mo^{40+}	ΔE(eV)	A	B	C	D	E	P	Q	X_1	Accuracy
$1s^2\ {}^1S$ - $1s2s\ {}^3S$	1.79E+04	-3.74E-06	6.72E-05	1.13E-04	-4.49E-05	0.0	-9.28E-05	2.66E-04	1.90	2
$1s^2\ {}^1S$ - $1s2p\ {}^3P_0$	1.79E+04	-1.13E-07	3.11E-06	1.10E-04	-2.08E-05	0.0				2
$1s^2\ {}^1S$ - $1s2p\ {}^3P_1$	1.79E+04	1.95E-03	-6.32E-03	9.10E-03	-4.46E-03	0.0				2
$1s^2\ {}^1S$ - $1s2p\ {}^3P_2$	1.81E+04	-1.02E-06	6.25E-06	5.84E-04	-1.52E-04	0.0				2
$1s^2\ {}^1S$ - $1s2s\ {}^1S$	1.79E+04	4.40E-04	-9.05E-05	-9.55E-05	0.0	2.22E-05				2
$1s^2\ {}^1S$ - $1s2p\ {}^1P$	1.81E+04	4.27E-04	-7.14E-05	3.87E-04	0.0	1.69E-03				2

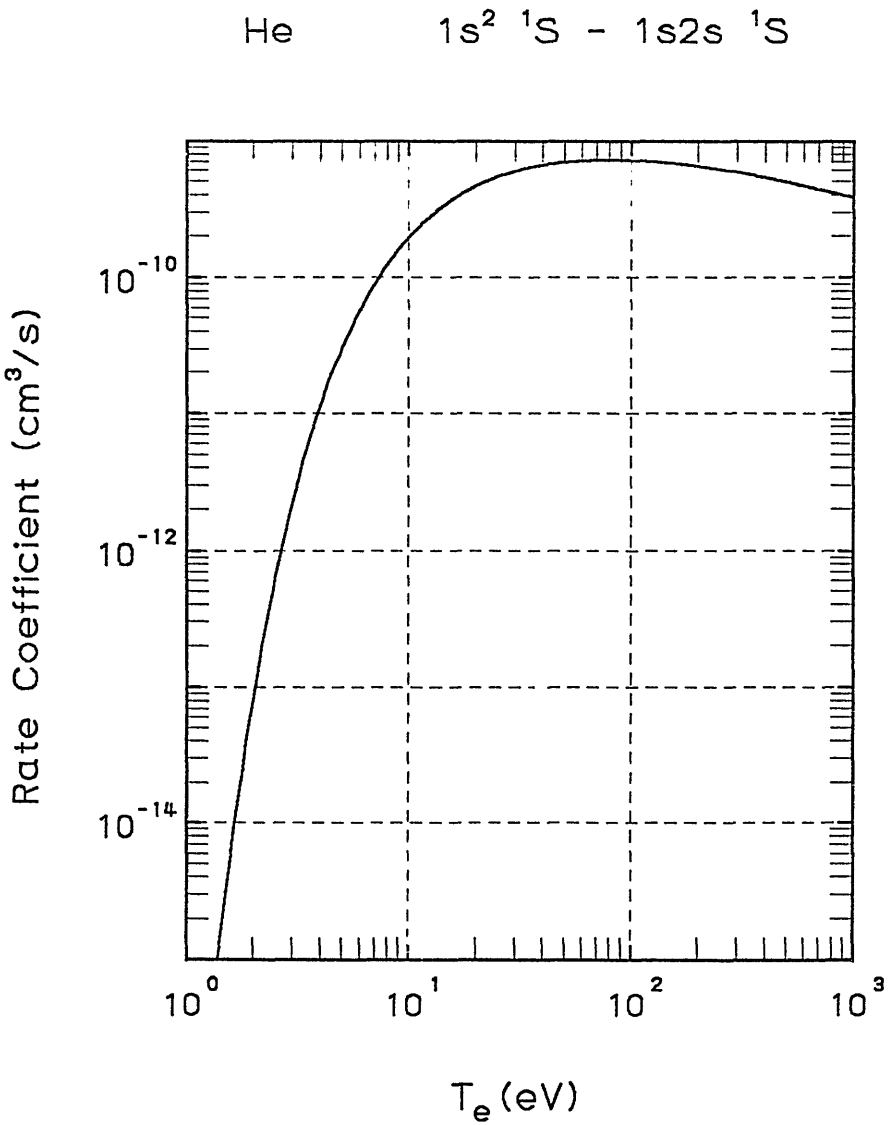
Explanation of Graphs

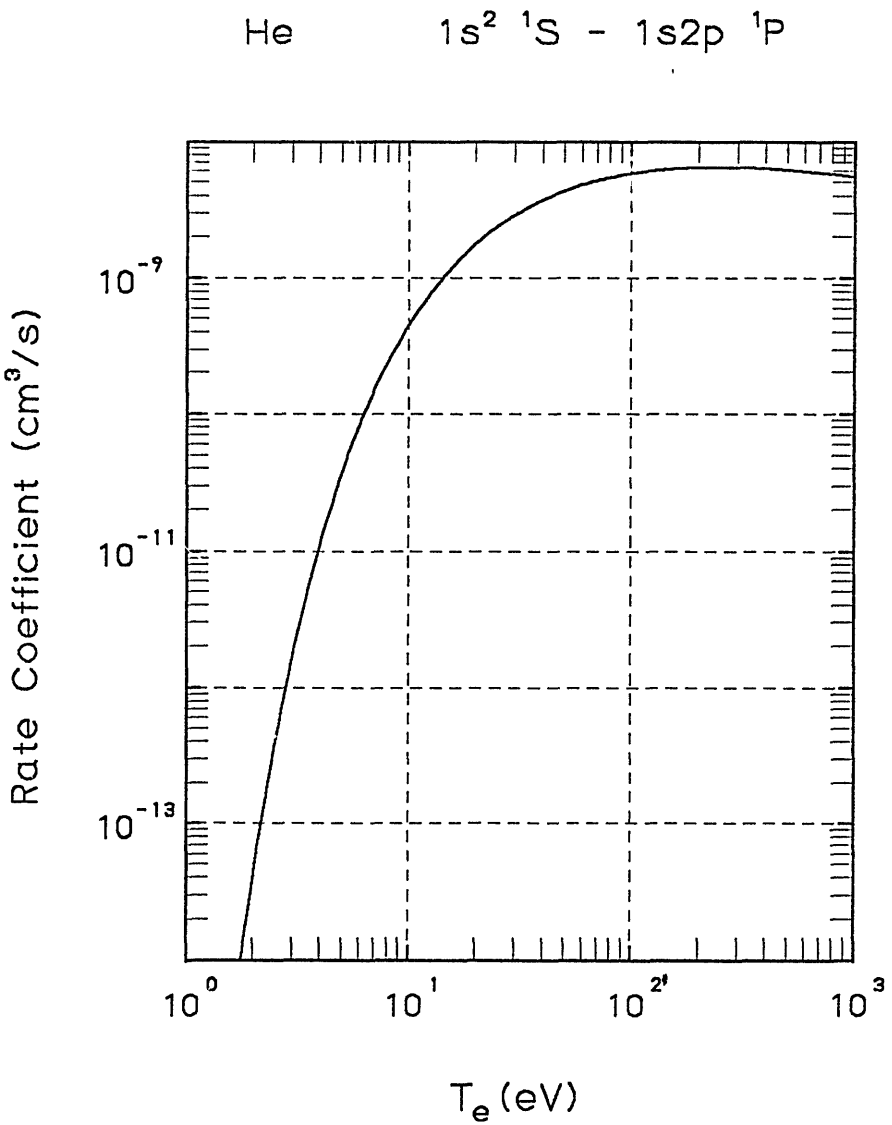
Graphs. Excitation Rate Coefficients

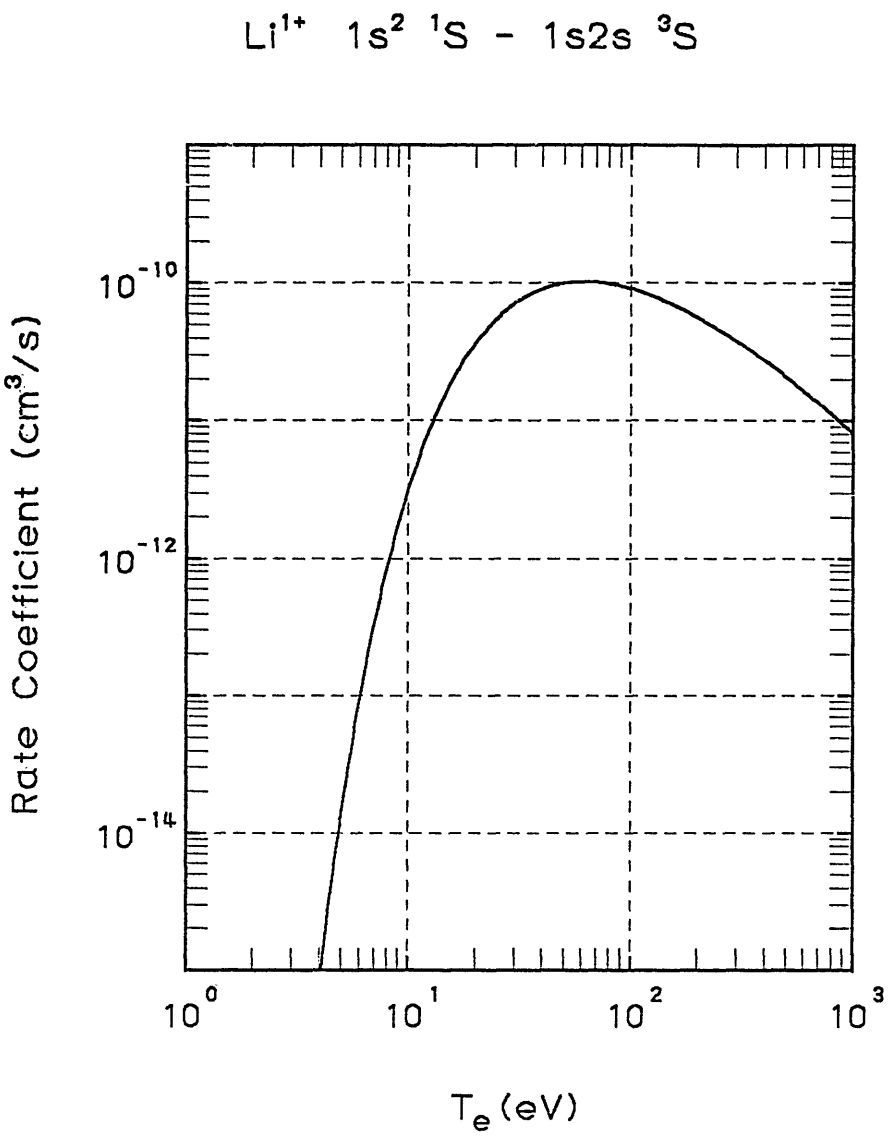
Excitation rate coefficient ($cm^3\ s^{-1}$) against electron temperature T_e(eV). The initial and final states are given at the top of each figure using the same notation as in Table III together with the ion species. Calculated rate coefficients are given for the whole temperature range displayed. The validity ranges of temperature are given in Table II for each transition.

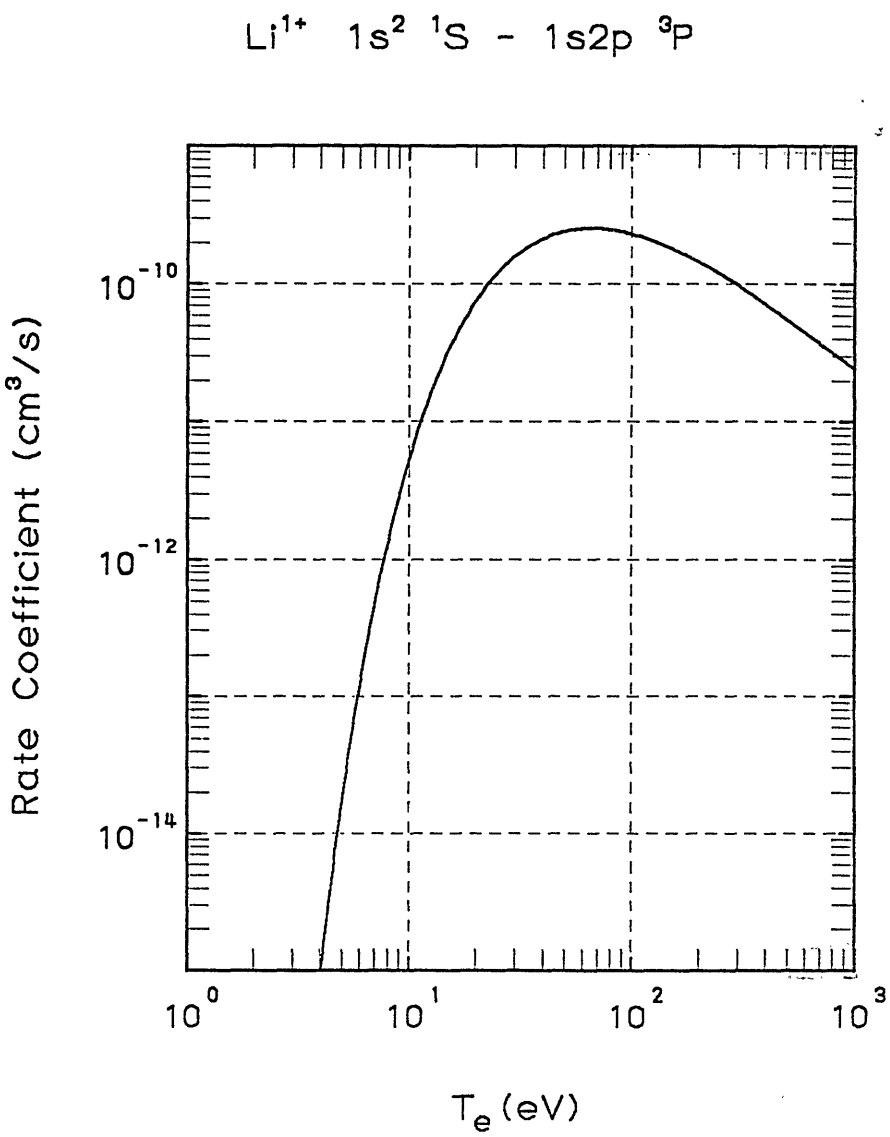

He 1s² ¹S - 1s2s ³S
Rate Coefficient (cm³/s)
10⁻¹⁰
10⁻¹²
10⁻¹⁴
10⁰
10¹
10²
10³
Tₑ (eV)

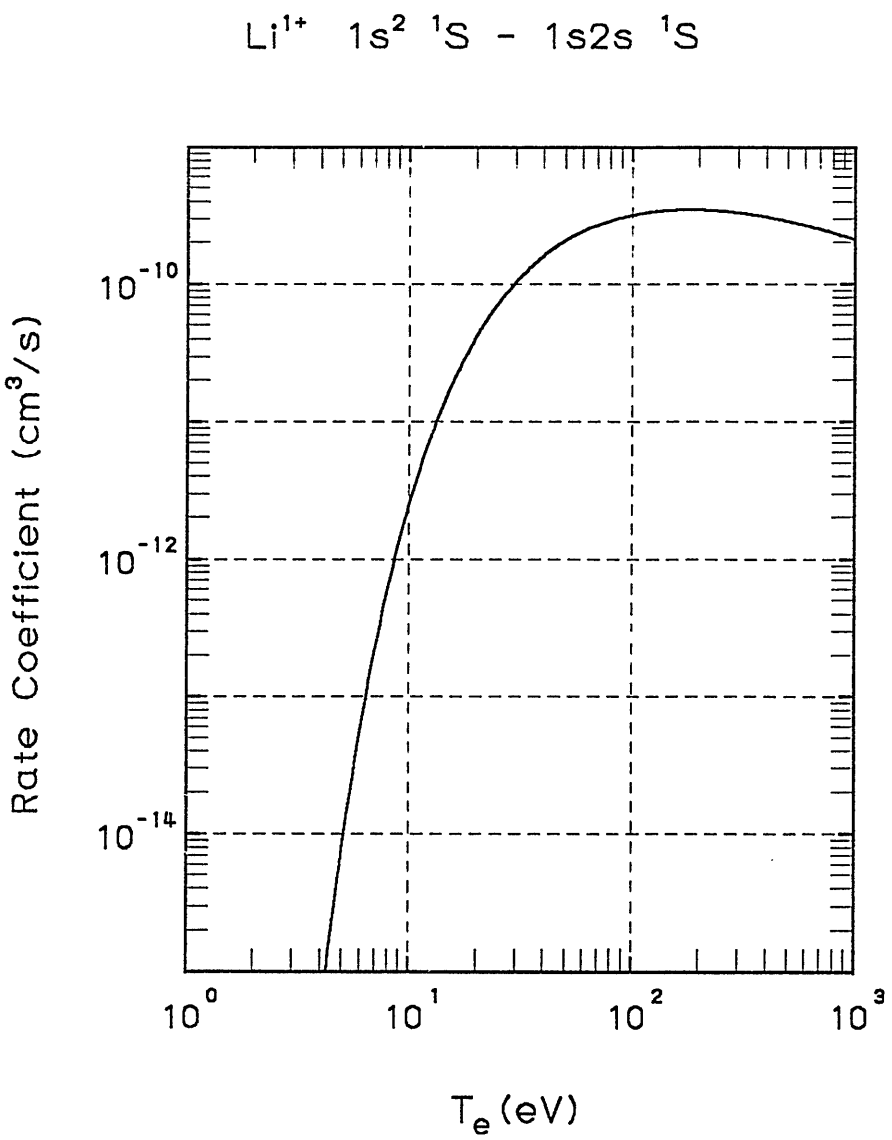

He 1s² ¹S - 1s2p ³P
Rate Coefficient (cm³/s)
10⁻¹⁰
10⁻¹²
10⁻¹⁴
10⁰
10¹
10²
10³
Tₑ (eV)

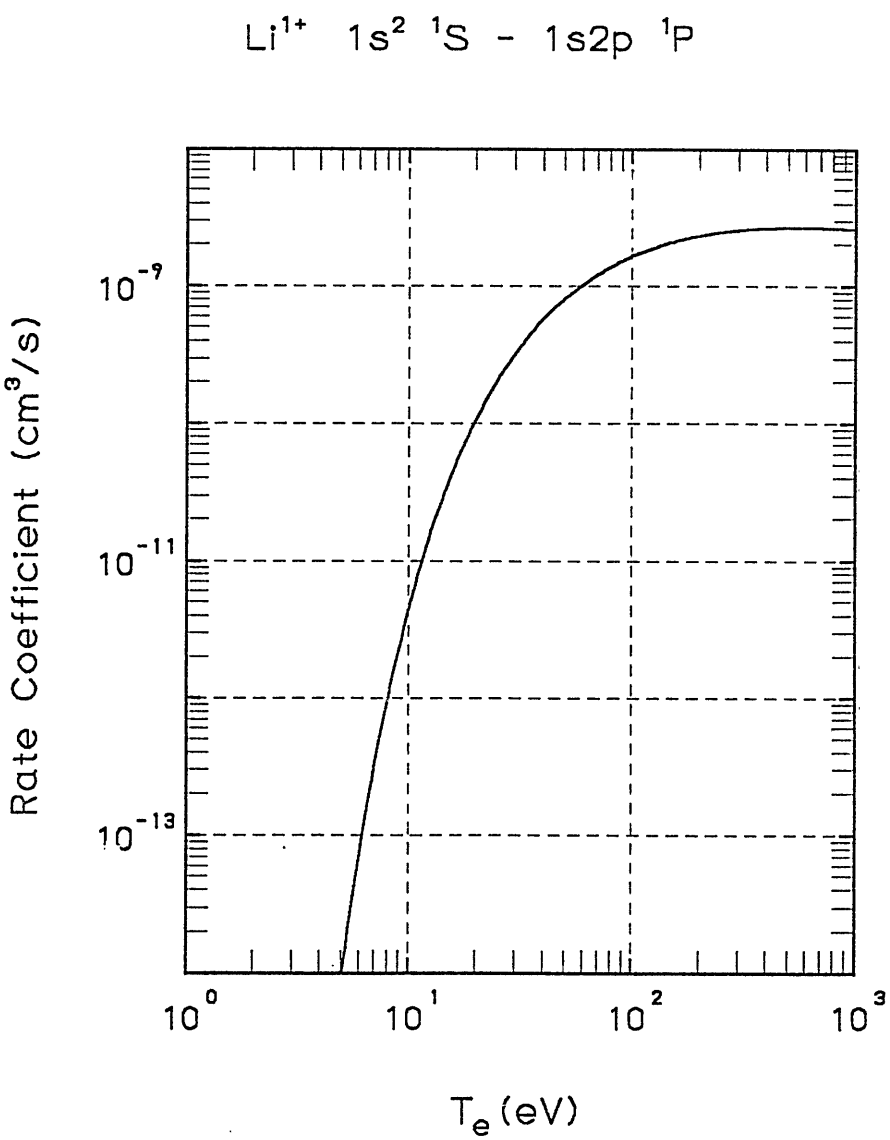

He 1s² ¹S - 1s2s ¹S
Rate Coefficient (cm³/s)
10⁻¹⁰
10⁻¹²
10⁻¹⁴
10⁰
10¹
10²
10³
Tₑ (eV)

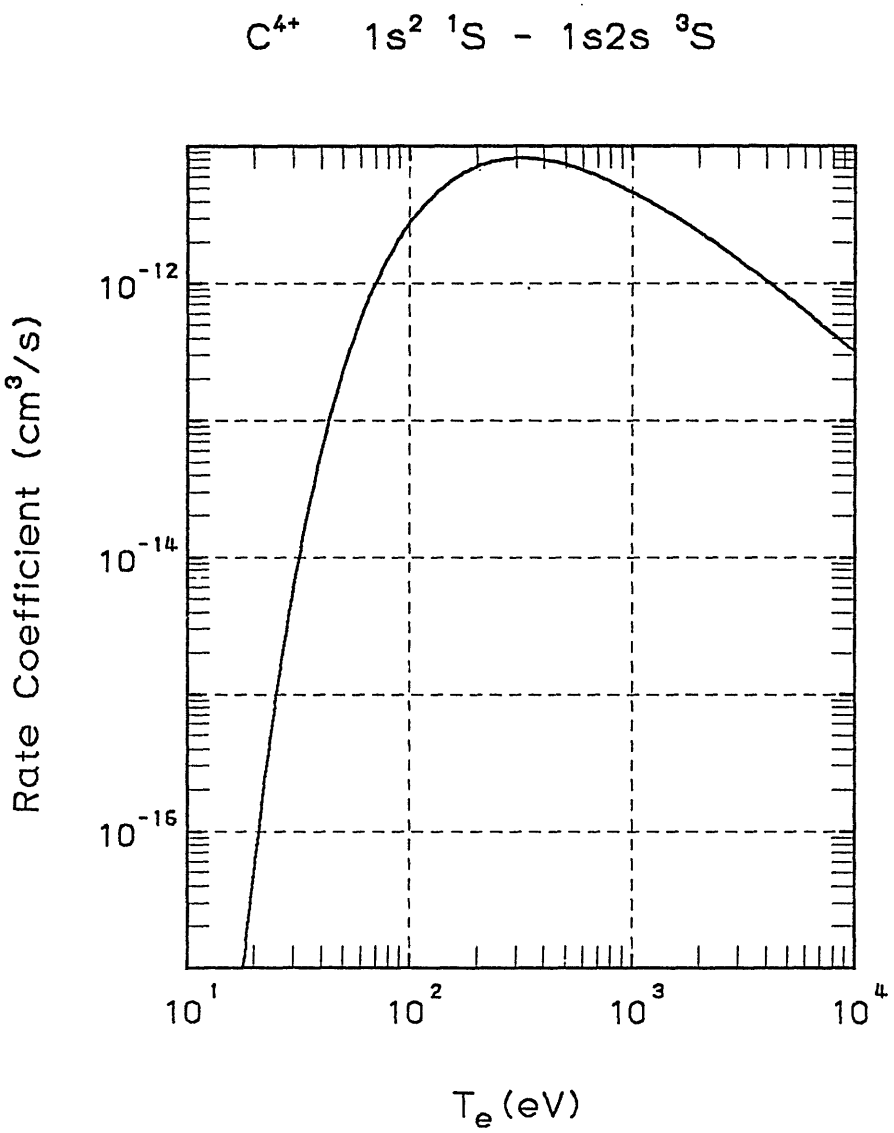

He 1s² ¹S - 1s2p ¹P
Rate Coefficient (cm³/s)
10⁻⁹
10⁻¹¹
10⁻¹³
10⁰
10¹
10²
10³
Tₑ (eV)

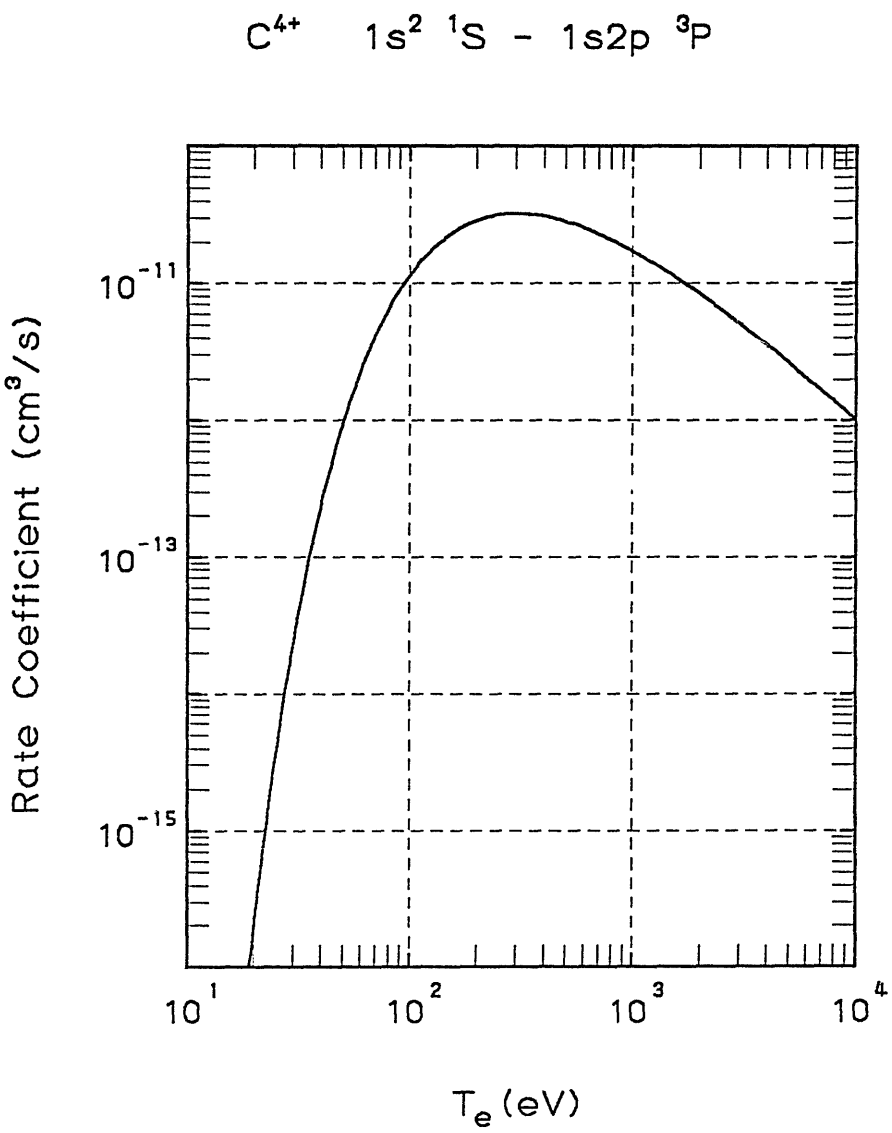

Li1+ 1s2 1S - 1s2s 3S
Rate Coefficient (cm3/s)
10-10
10-12
10-14
100
101
102
103
Te (eV)

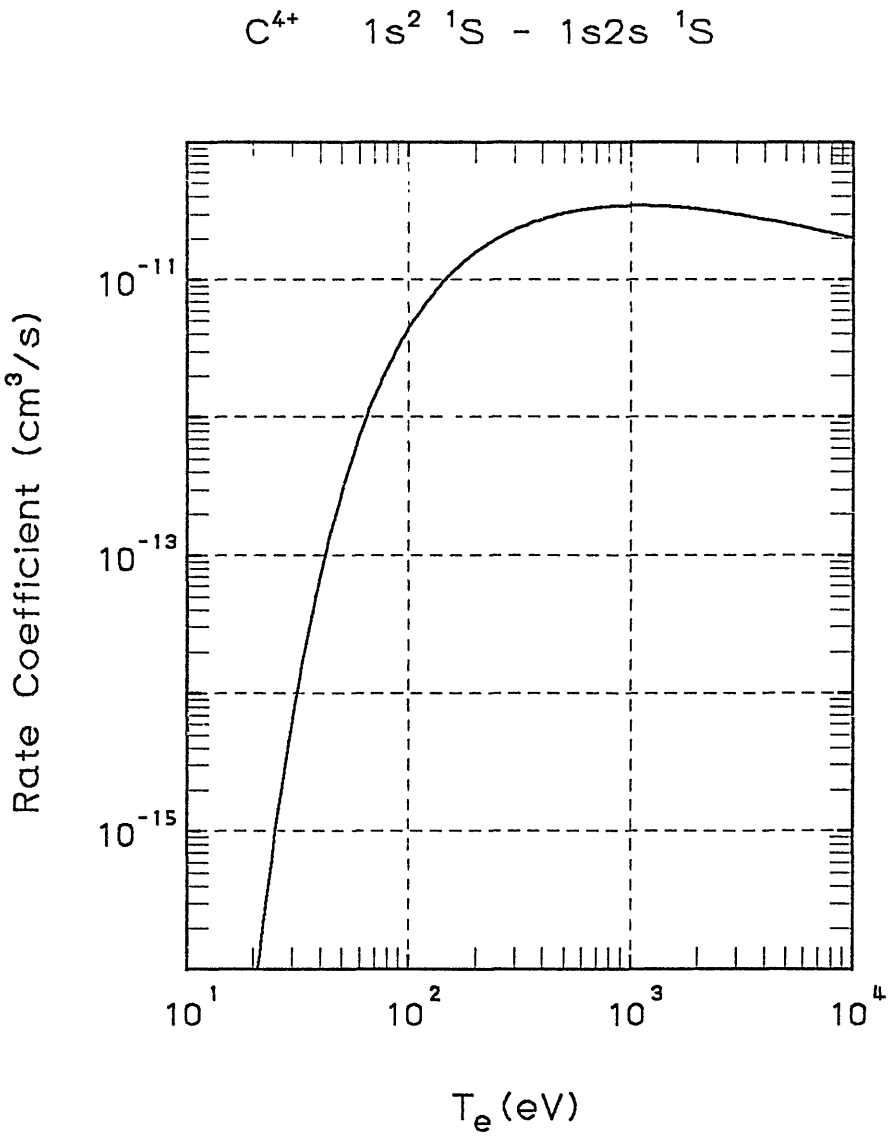

Li1+ 1s2 1S - 1s2p 3P
Rate Coefficient (cm3/s)
10-10
10-12
10-14
100
101
102
103
Te (eV)

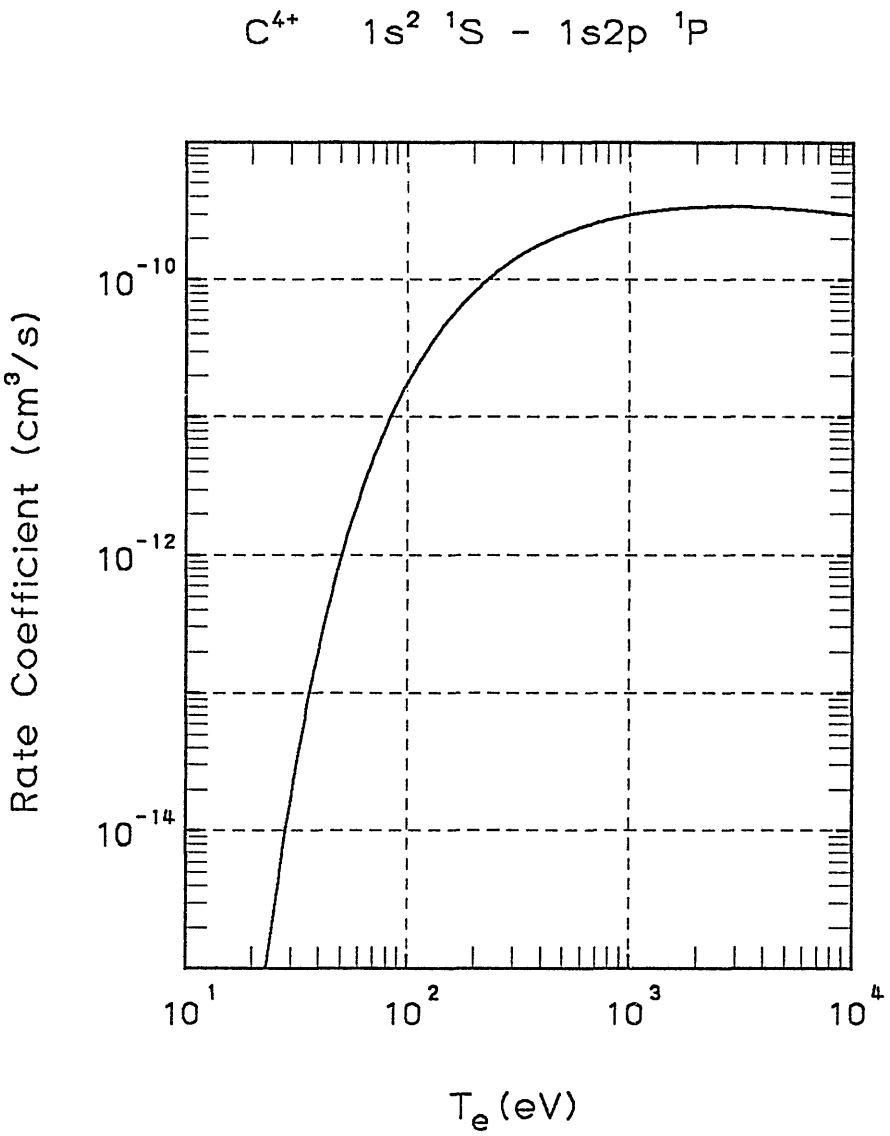

Li1+ 1s2 1S - 1s2s 1S
Rate Coefficient (cm3/s)
10-10
10-12
10-14
100
101
102
103
Te (eV)

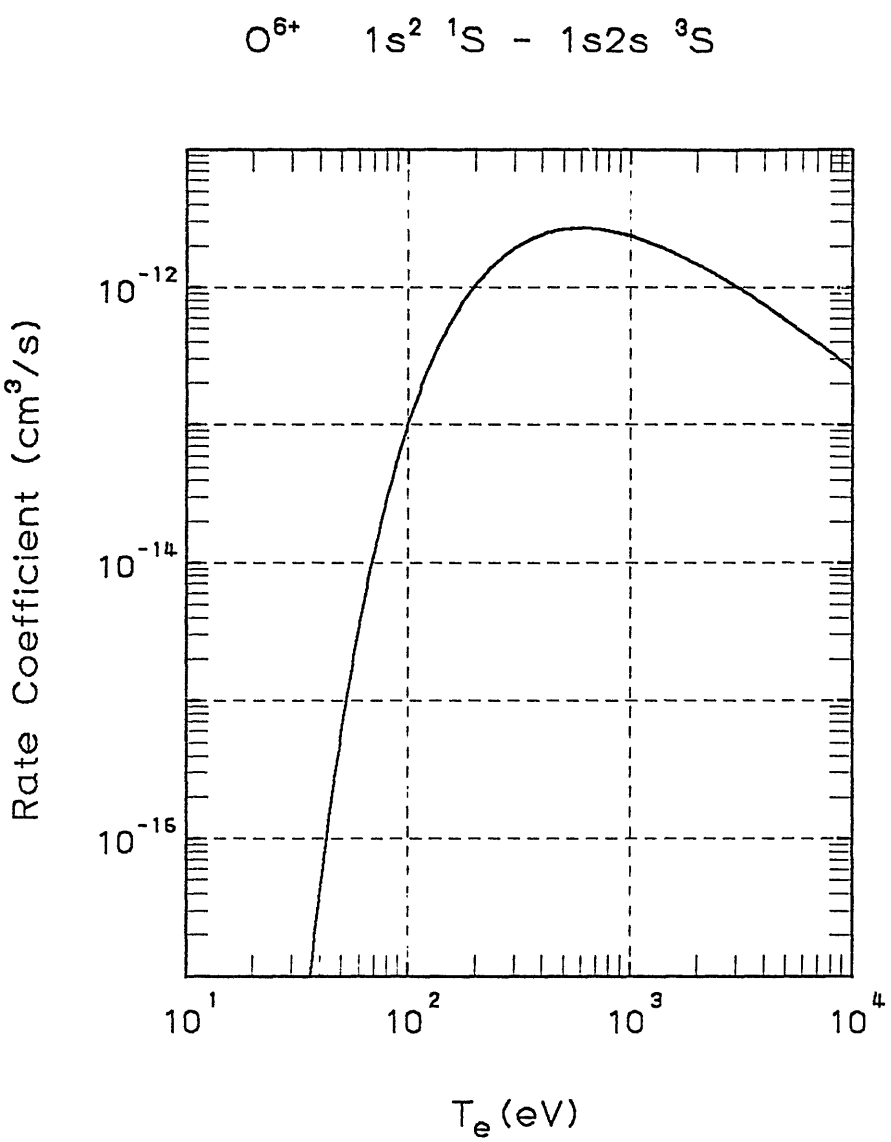

Li1+ 1s2 1S - 1s2p 1P
Rate Coefficient (cm3/s)
10-9
10-11
10-13
100
101
102
103
Te (eV)

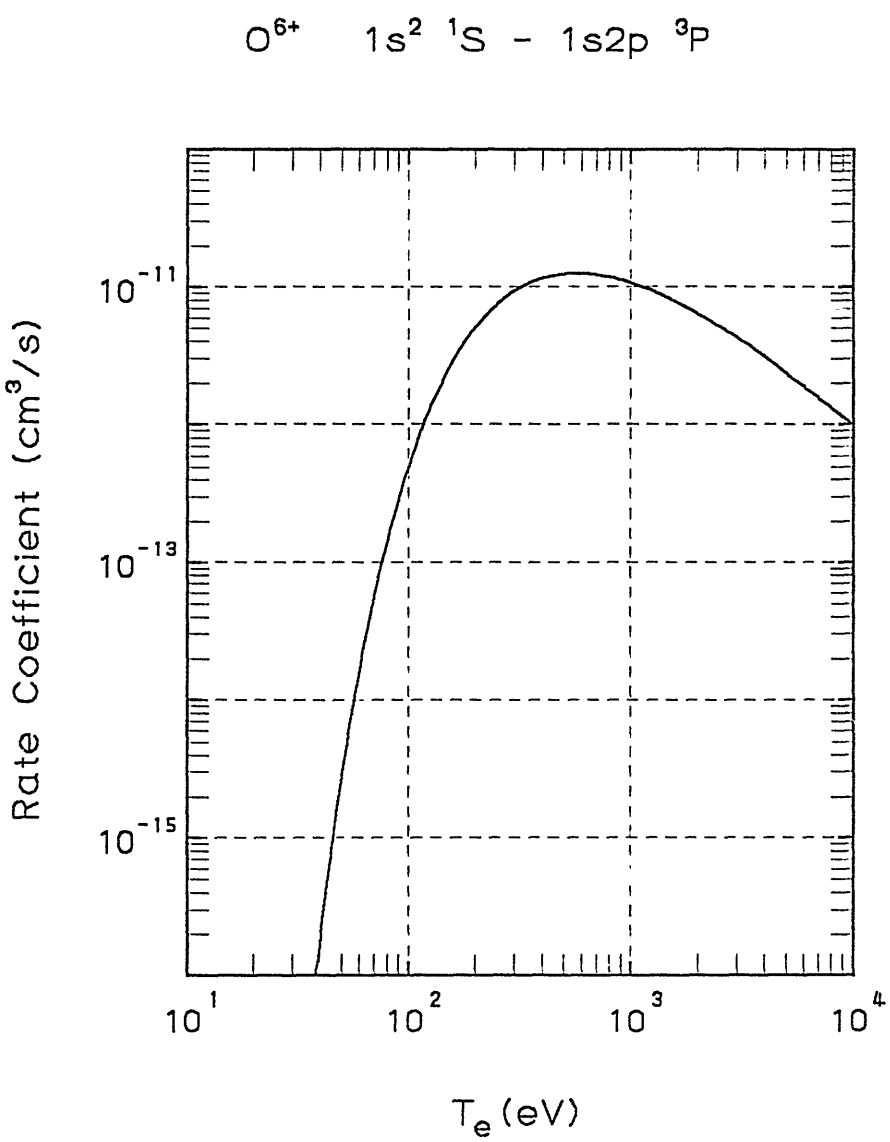

C4+ 1s2 1S - 1s2s 3S
Rate Coefficient (cm3/s)
10-12
10-14
10-16
101
102
103
104
Te (eV)

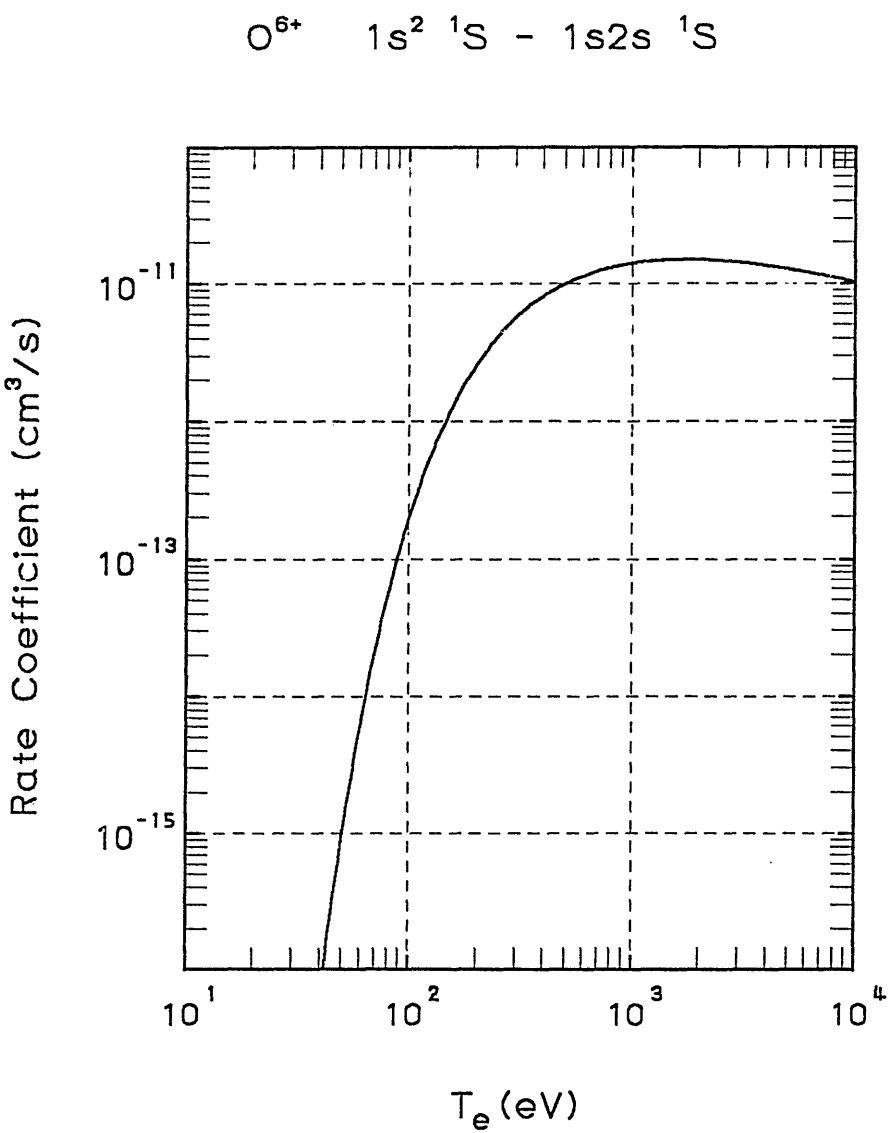

C4+ 1s2 1S - 1s2p 3P
Rate Coefficient (cm3/s)
10-11
10-13
10-15
101
102
103
104
Te (eV)

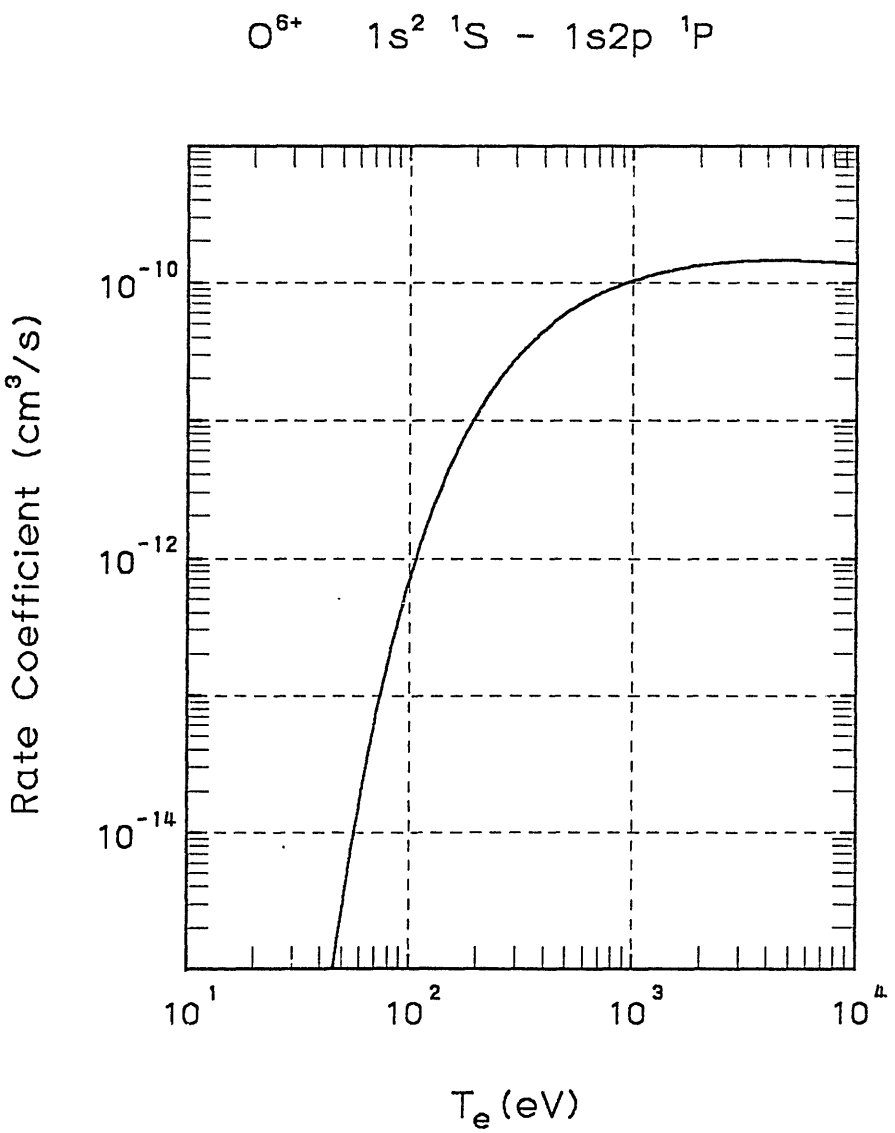

C4+ 1s2 1S - 1s2s 1S
Rate Coefficient (cm3/s)
10-11
10-13
10-15
101
102
103
104
Te (eV)

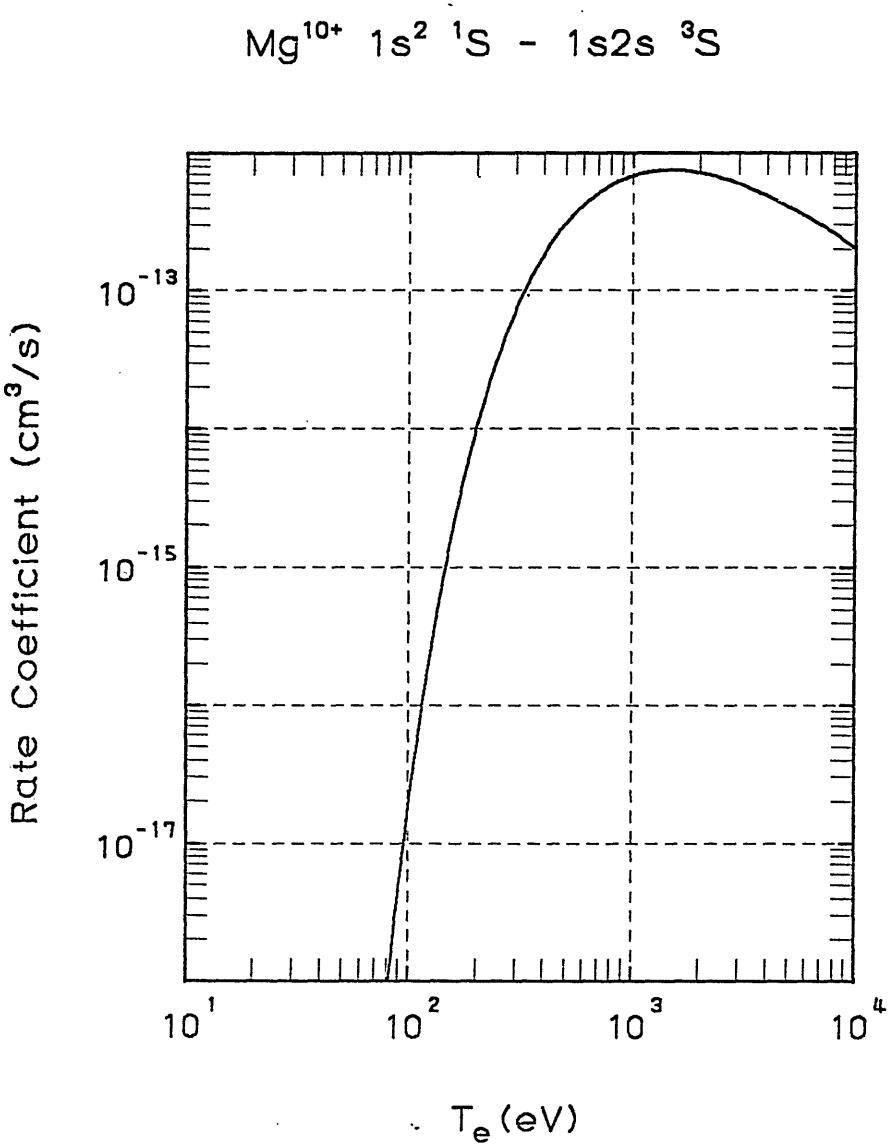

C4+ 1s2 1S - 1s2p 1P
Rate Coefficient (cm3/s)
10-10
10-12
10-14
101
102
103
104
Te (eV)

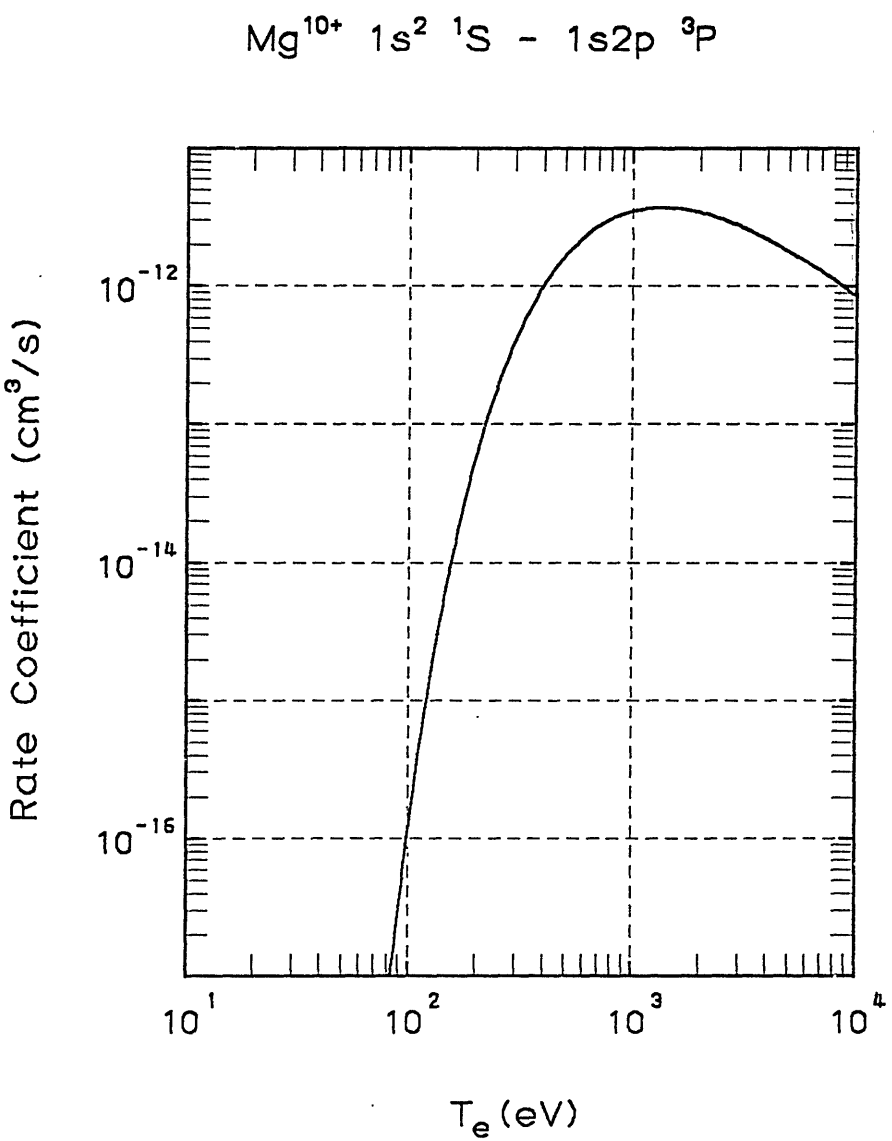

O^{6+} $1s^2\ ^1S$ - $1s2s\ ^3S$
Rate Coefficient (cm^3/s)
10^{-12}
10^{-14}
10^{-16}
10^1
10^2
10^3
10^4
T_e (eV)

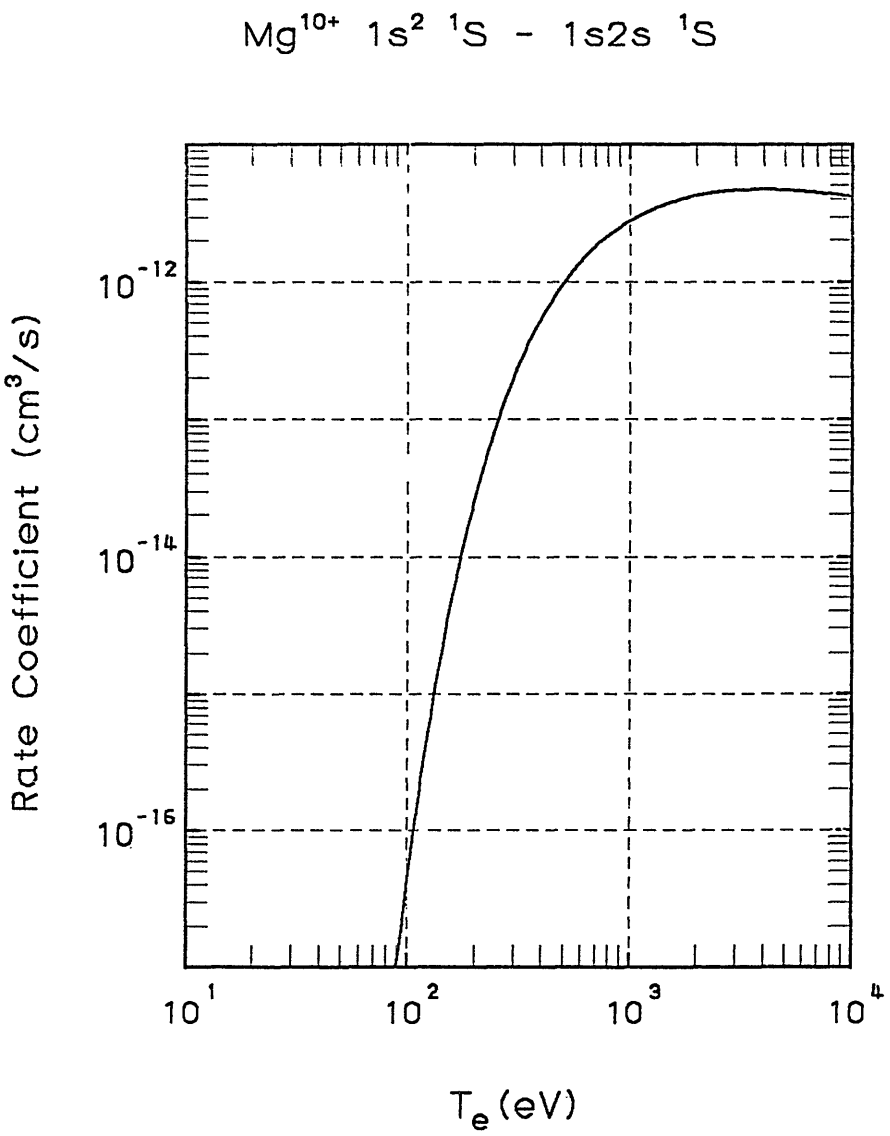

O^{6+} $1s^2\ ^1S$ - $1s2p\ ^3P$
Rate Coefficient (cm^3/s)
10^{-11}
10^{-13}
10^{-15}
10^1
10^2
10^3
10^4
T_e (eV)

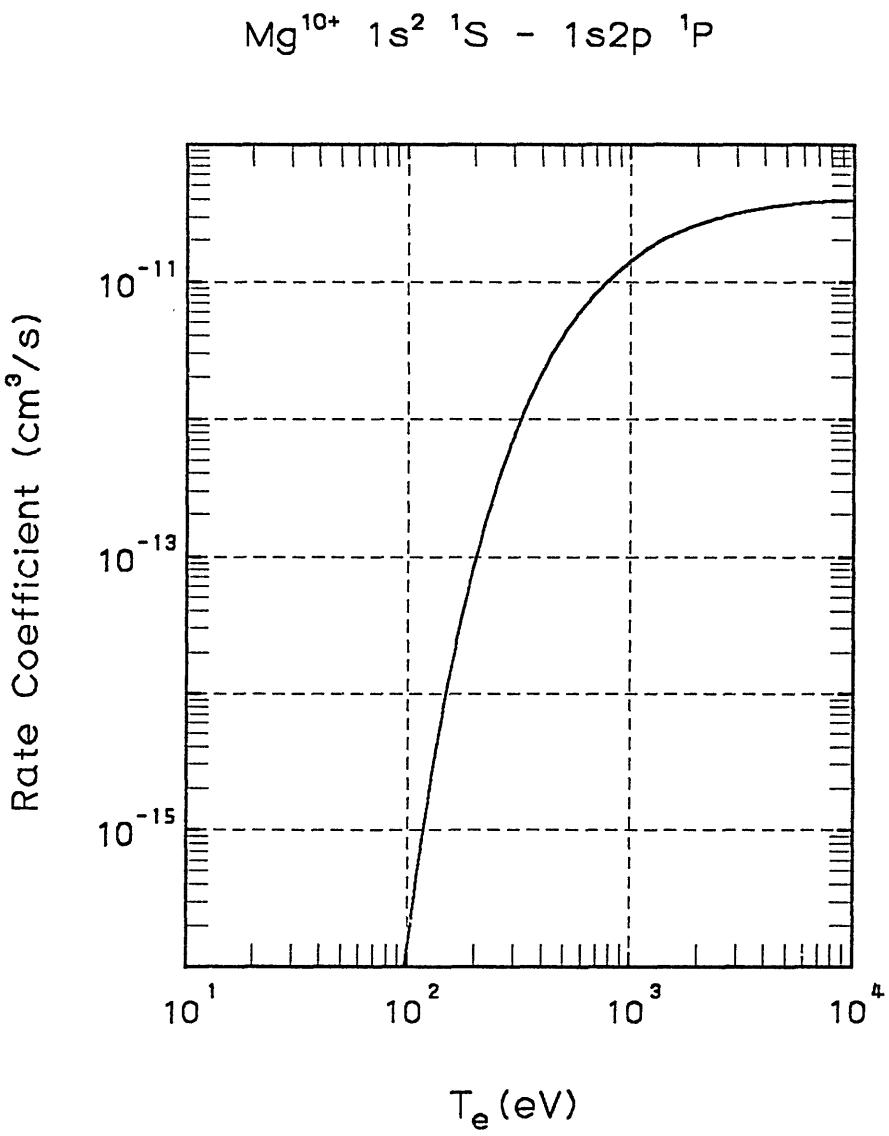

O6+ 1s2 1S - 1s2s 1S
Rate Coefficient (cm3/s)
10-11
10-13
10-15
101
102
103
104
Te (eV)

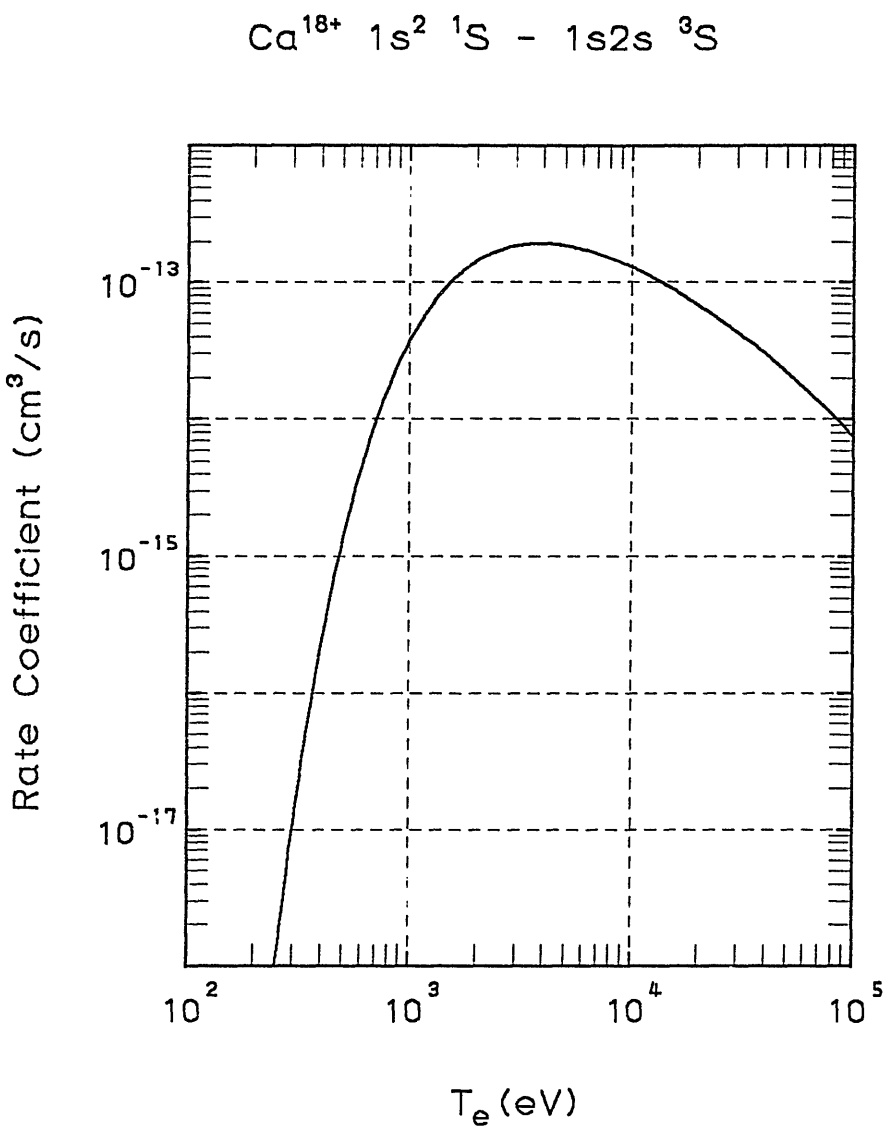

O6+ 1s2 1S - 1s2p 1P
Rate Coefficient (cm3/s)
10-10
10-12
10-14
101
102
103
104
Te (eV)

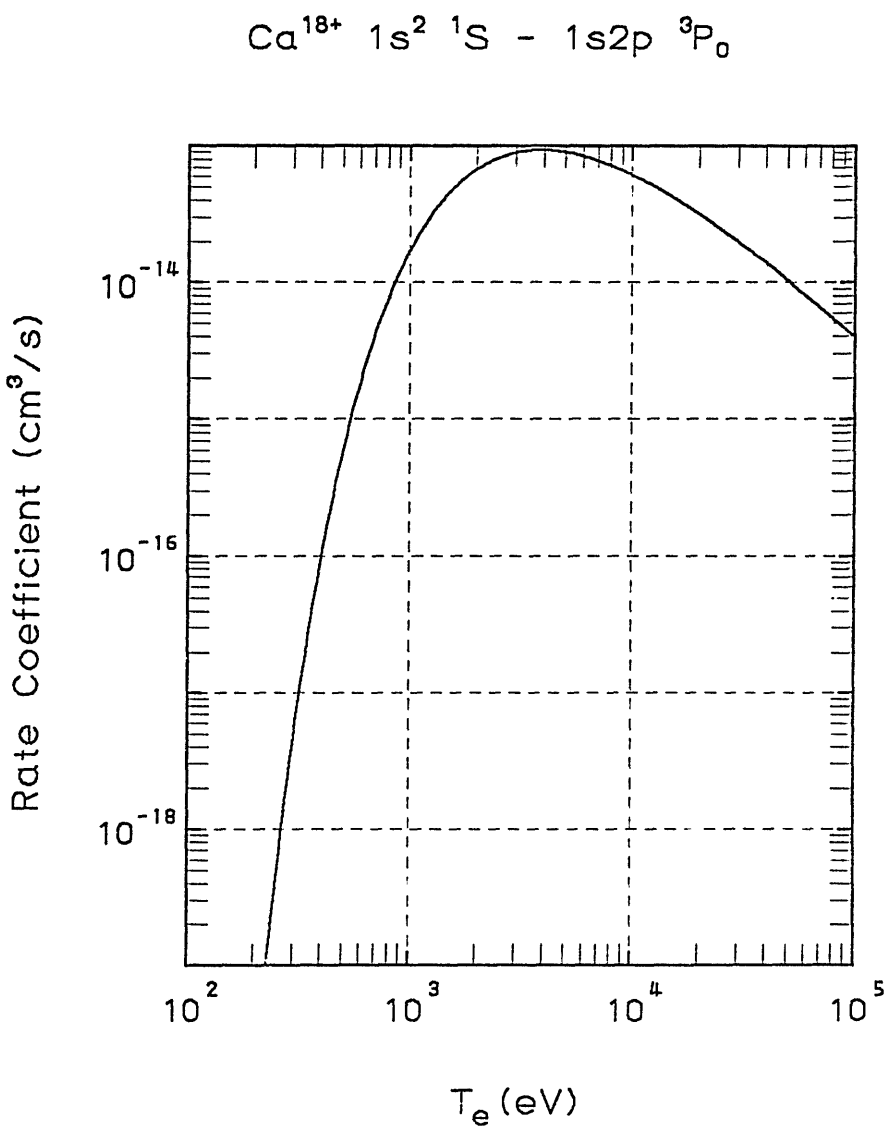

Mg10+ 1s2 1S - 1s2s 3S
Rate Coefficient (cm3/s)
10-13
10-15
10-17
101
102
103
104
Te (eV)

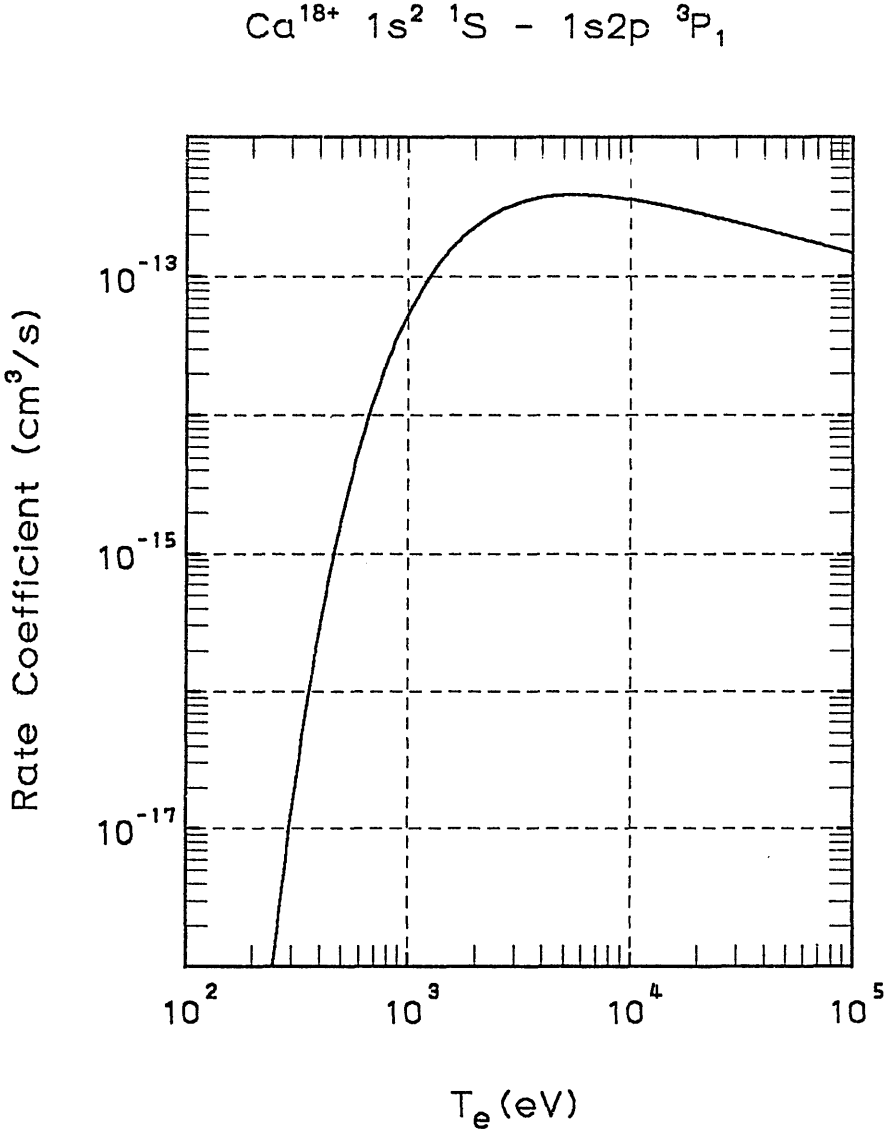

Mg10+ 1s2 1S - 1s2p 3P
Rate Coefficient (cm3/s)
10-12
10-14
10-16
101
102
103
104
Te (eV)

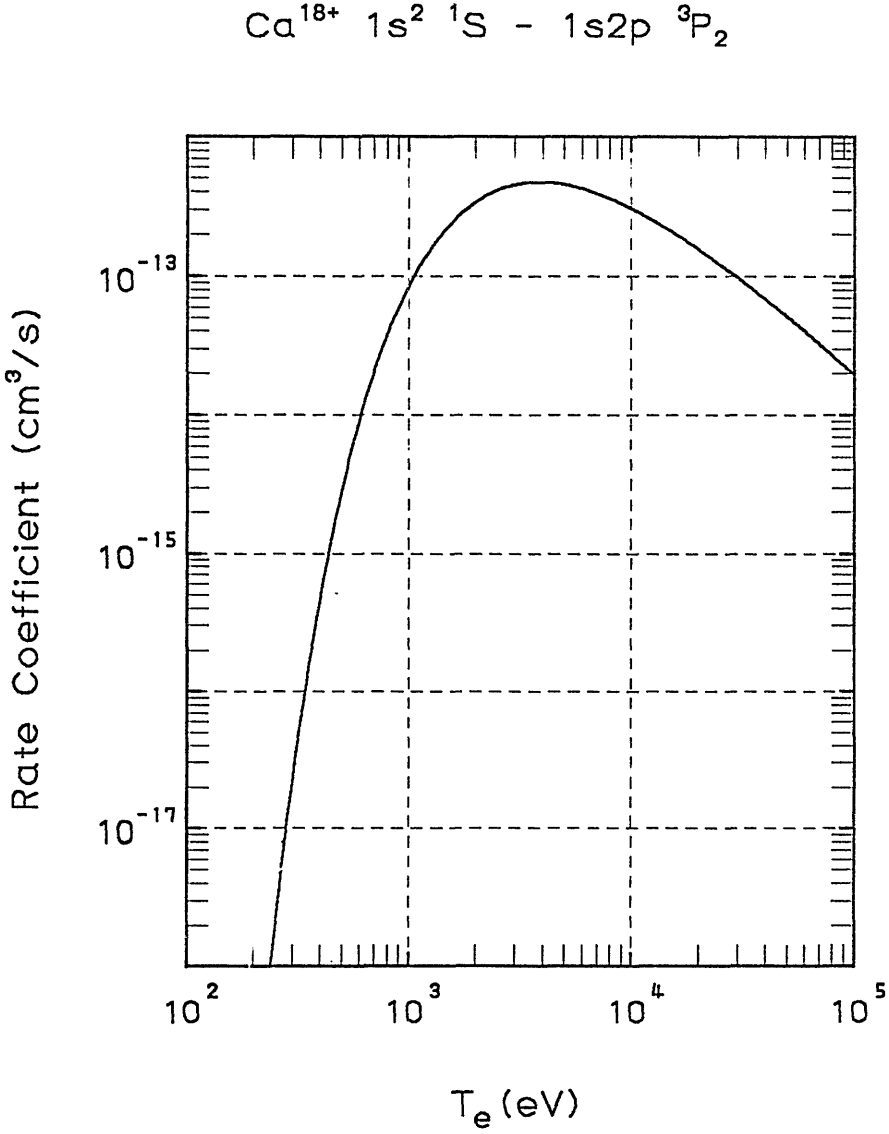

Mg10+ 1s2 1S - 1s2s 1S
Rate Coefficient (cm3/s)
10-12
10-14
10-16
10 1
10 2
10 3
10 4
Te (eV)

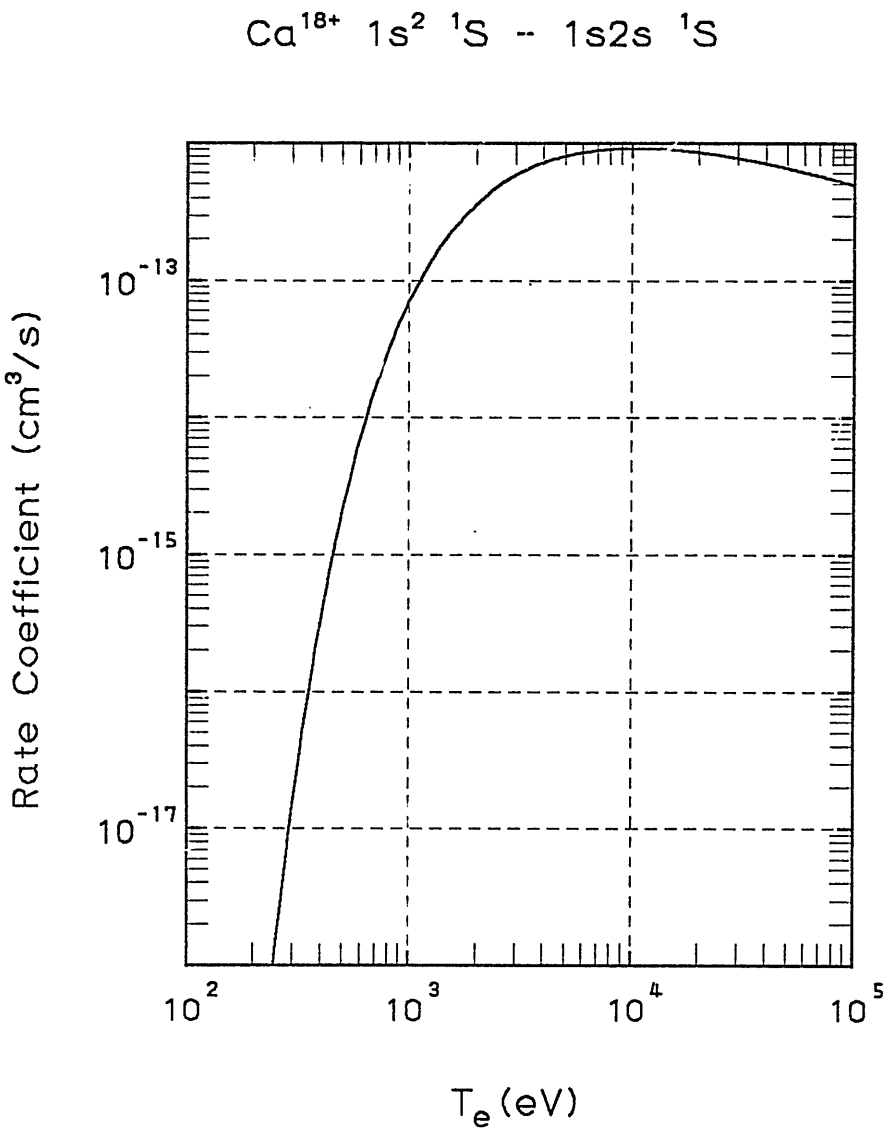

Mg10+ 1s2 1S - 1s2p 1P
Rate Coefficient (cm3/s)
10-11
10-13
10-15
10 1
10 2
10 3
10 4
Te (eV)

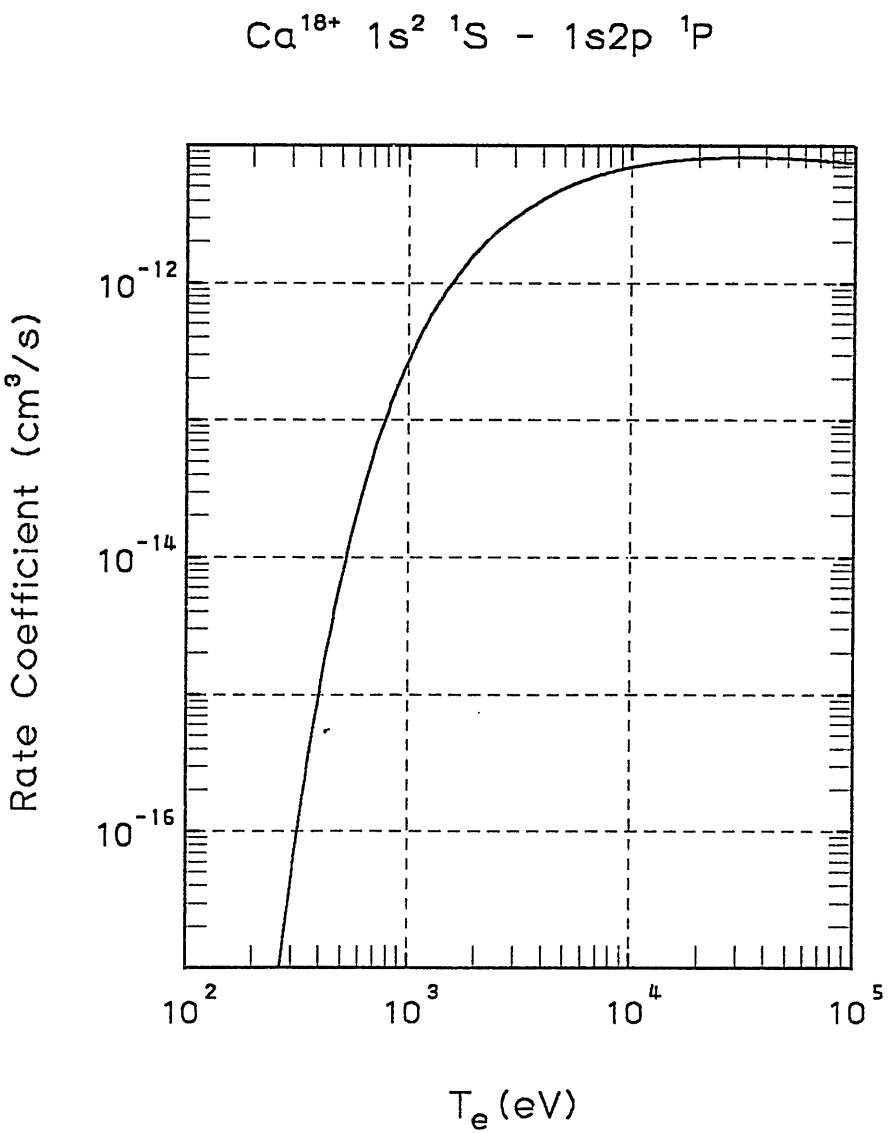

Ca18+ 1s2 1S - 1s2s 3S
Rate Coefficient (cm3/s)
10-13
10-15
10-17
10 2
10 3
10 4
10 5
Te (eV)

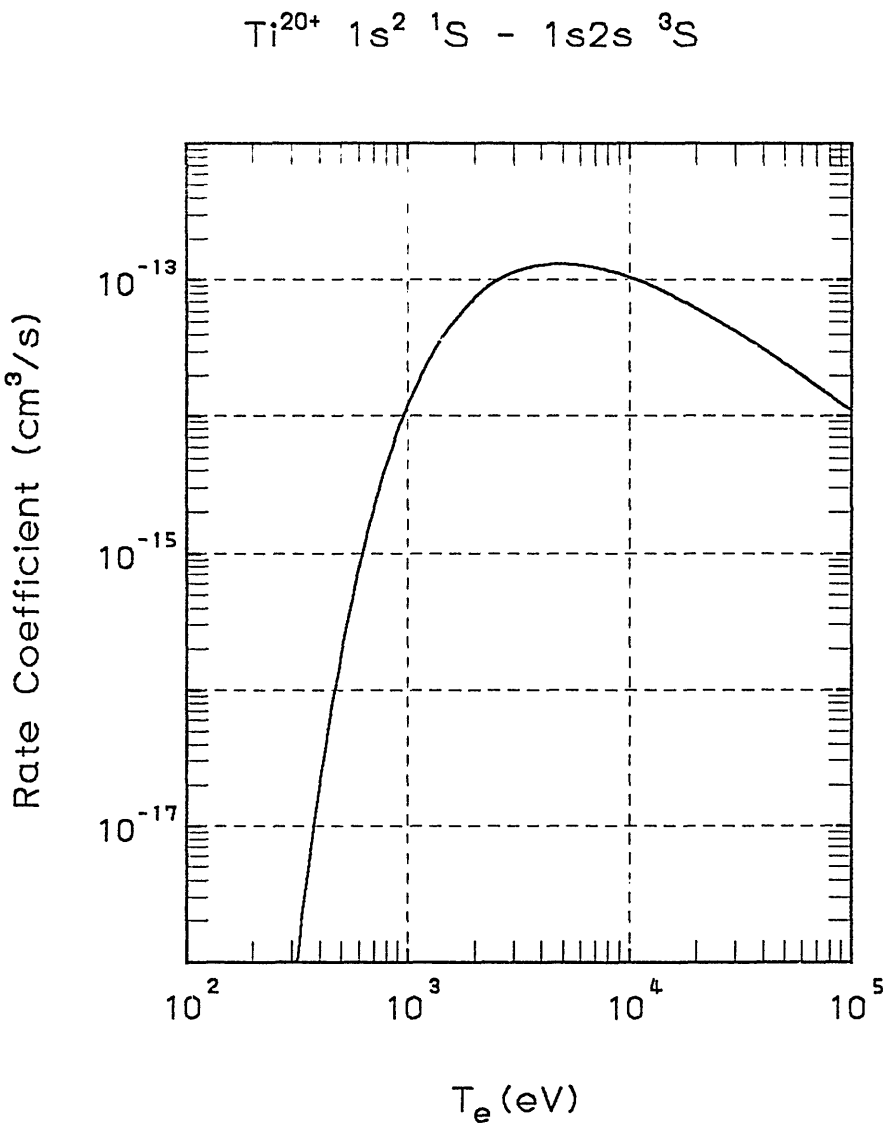

Ca18+ 1s2 1S - 1s2p 3P0
Rate Coefficient (cm3/s)
10-14
10-16
10-18
10 2
10 3
10 4
10 5
Te (eV)

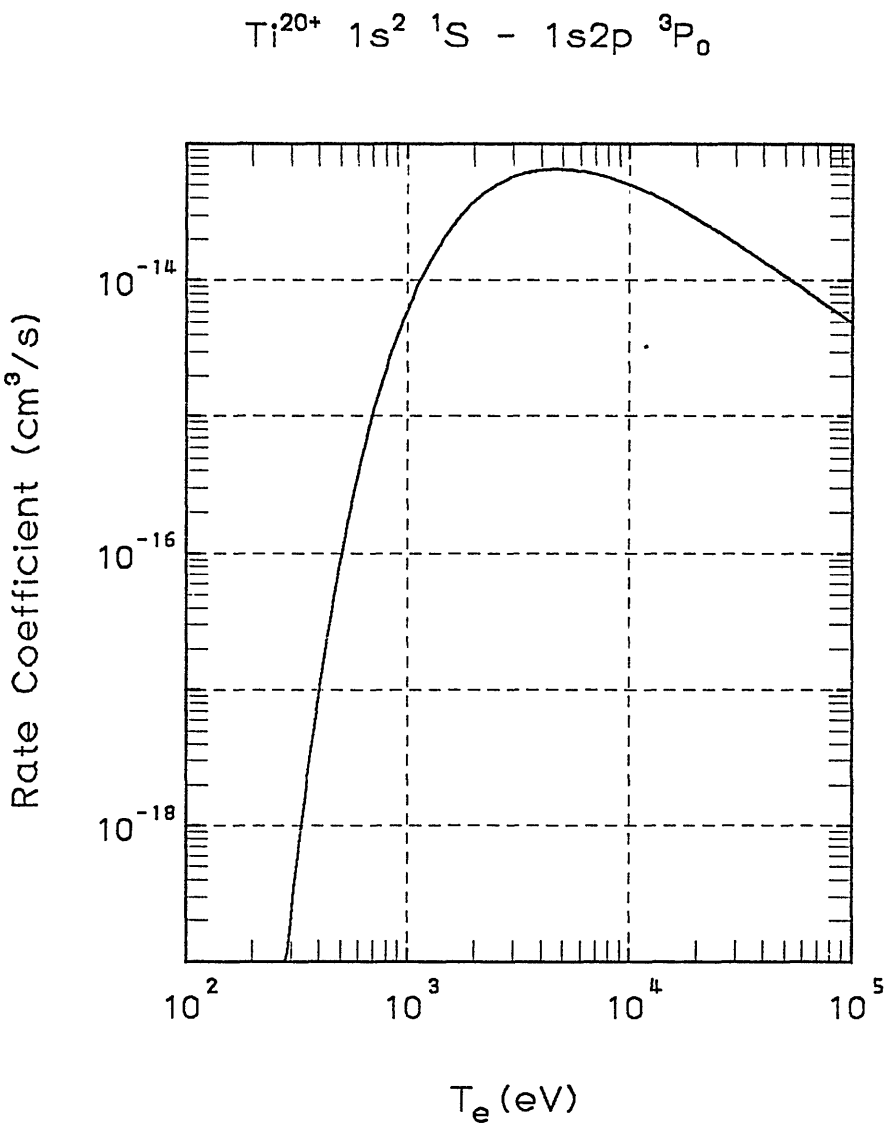

Ca18+ 1s2 1S - 1s2p 3P1
Rate Coefficient (cm3/s)
10-13
10-15
10-17
102
103
104
105
Te (eV)

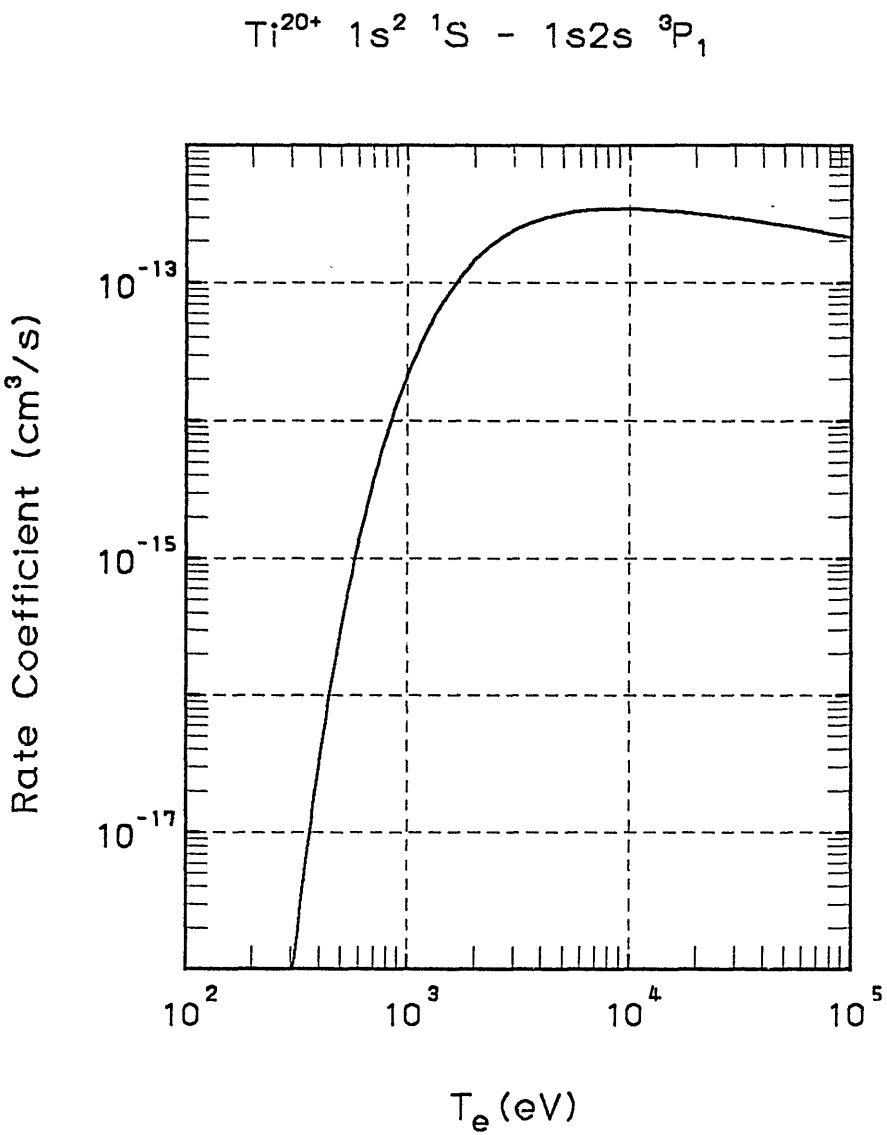

Ca18+ 1s2 1S - 1s2p 3P2
Rate Coefficient (cm3/s)
10-13
10-15
10-17
102
103
104
105
Te (eV)

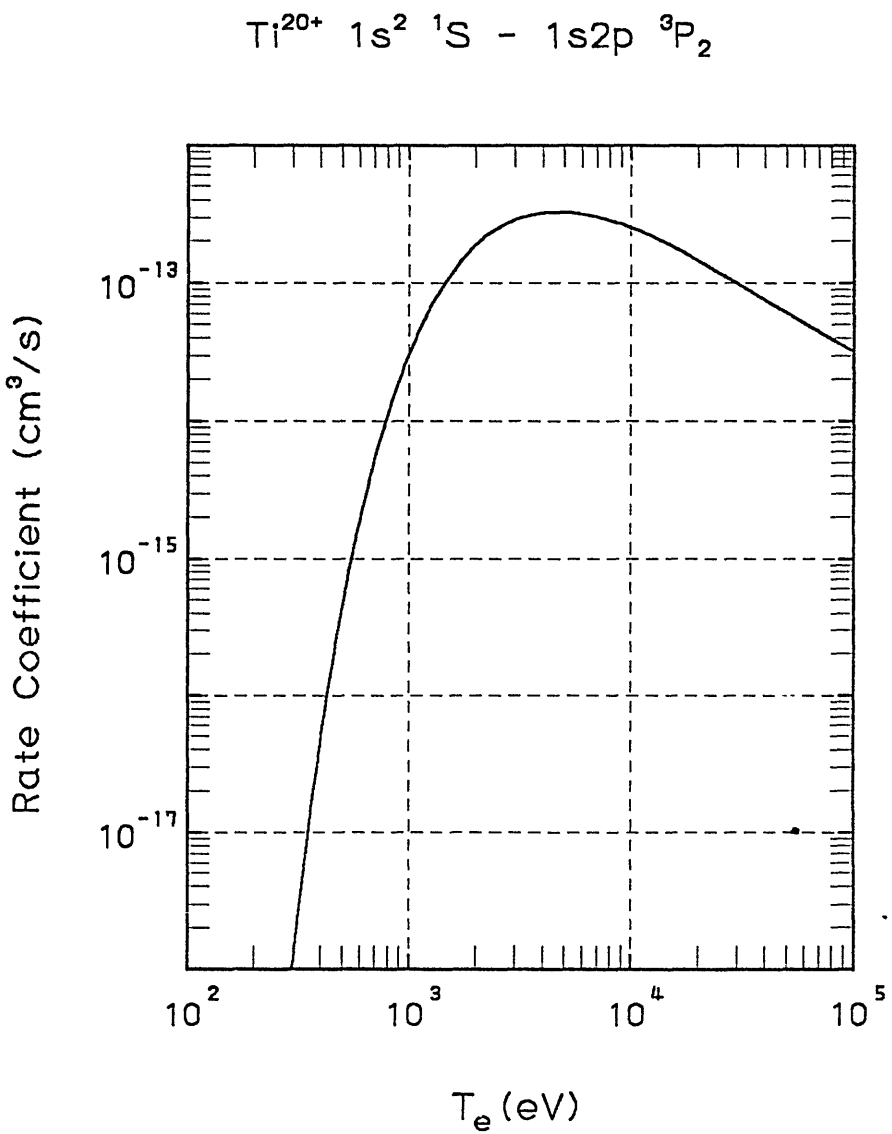

Ca18+ 1s2 1S - 1s2s 1S
Rate Coefficient (cm3/s)
10-13
10-15
10-17
10 2
10 3
10 4
10 5
Te (eV)

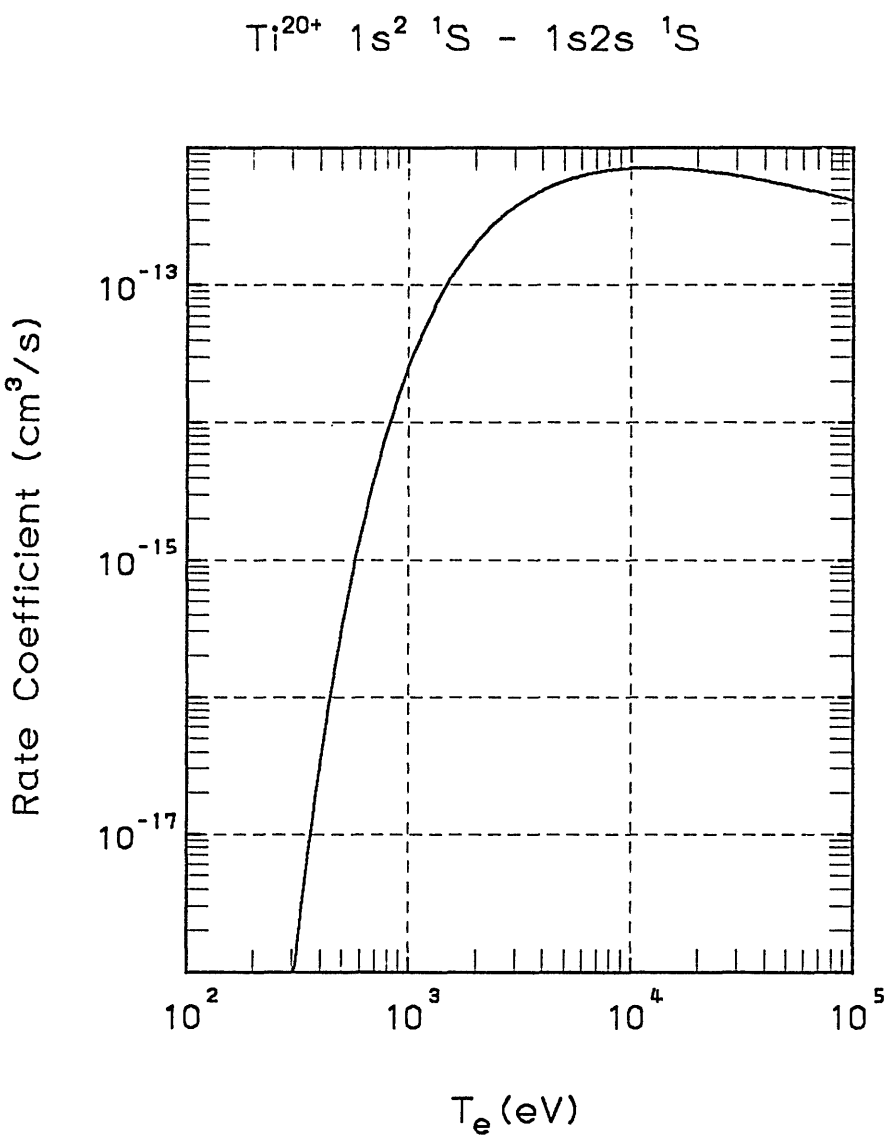

Ca18+ 1s2 1S - 1s2p 1P
Rate Coefficient (cm3/s)
10-12
10-14
10-16
10 2
10 3
10 4
10 5
Te (eV)

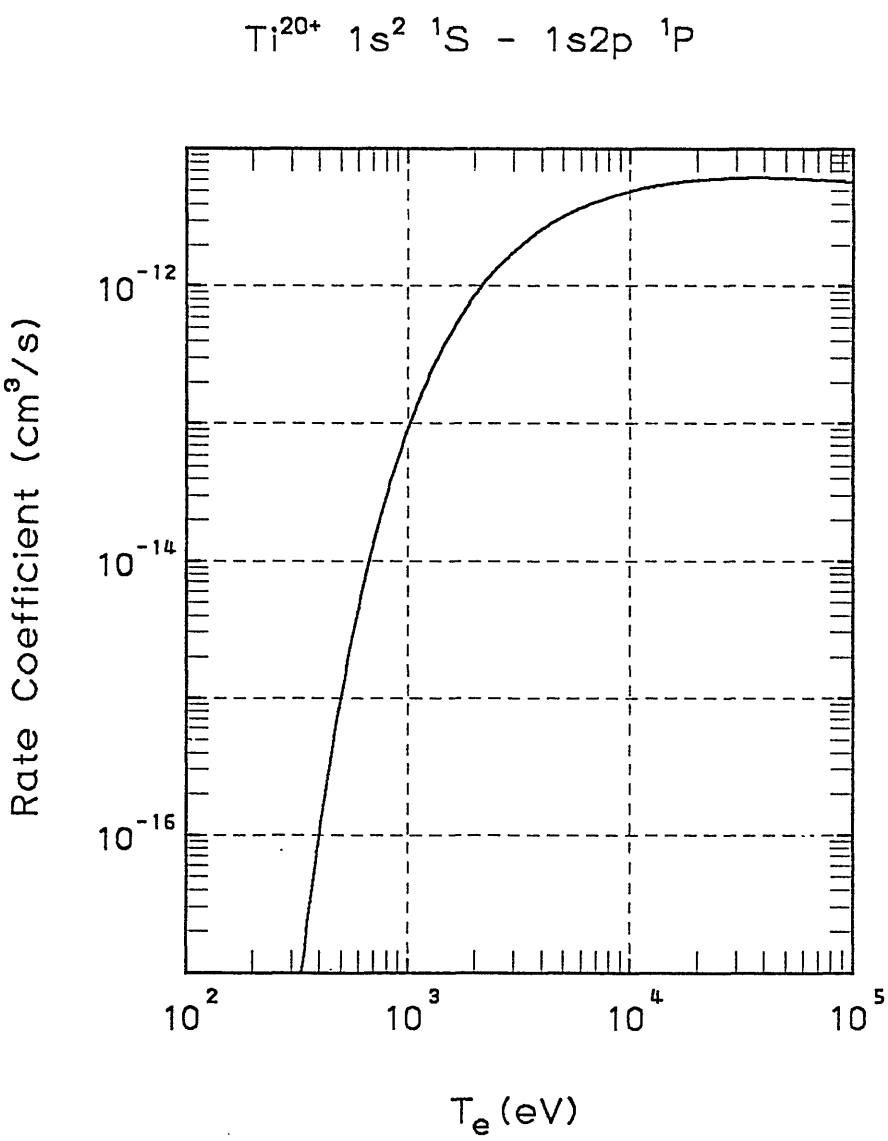

Ti^{20+} $1s^2$ ^1S - 1s2s ^3S
Rate Coefficient (cm^3/s)
10^{-13}
10^{-15}
10^{-17}
10^2
10^3
10^4
10^5
T_e (eV)

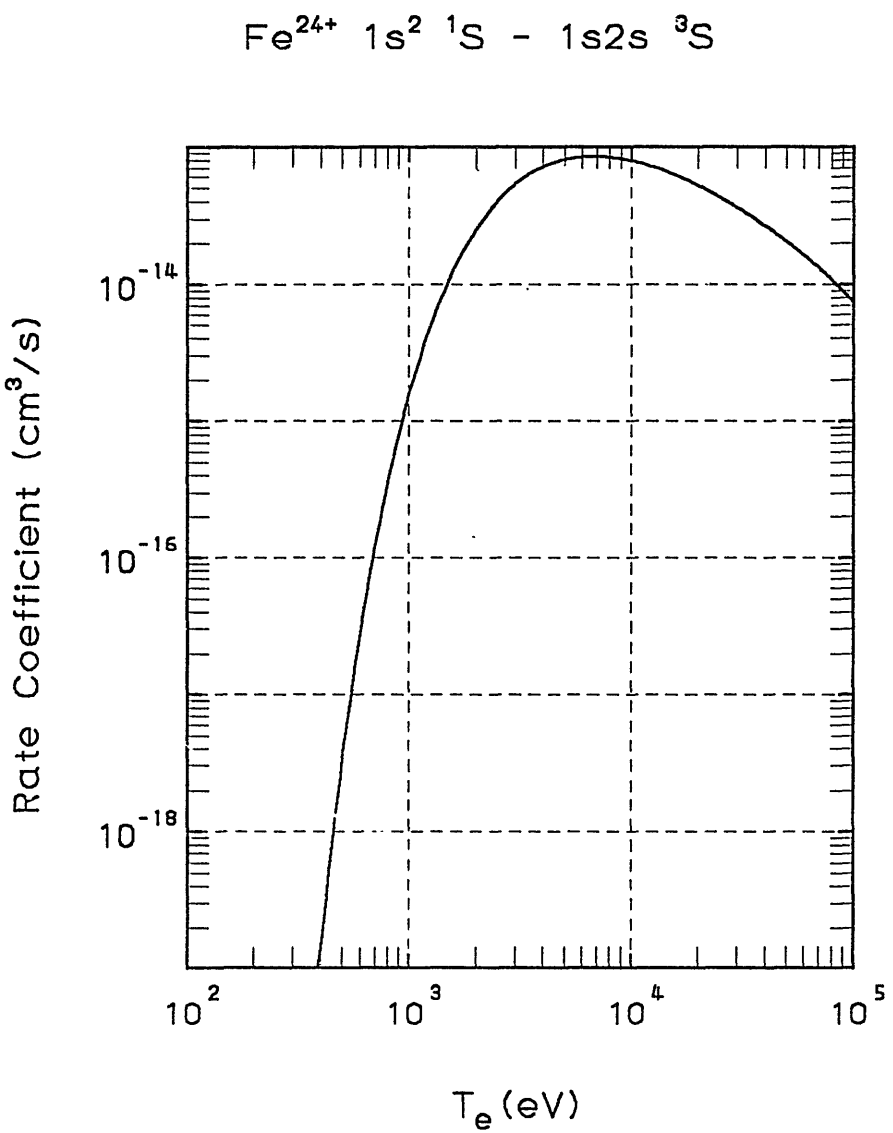

Ti^{20+} $1s^2$ ^1S - 1s2p $^3P_0$
Rate Coefficient (cm^3/s)
10^{-14}
10^{-16}
10^{-18}
10^2
10^3
10^4
10^5
T_e (eV)

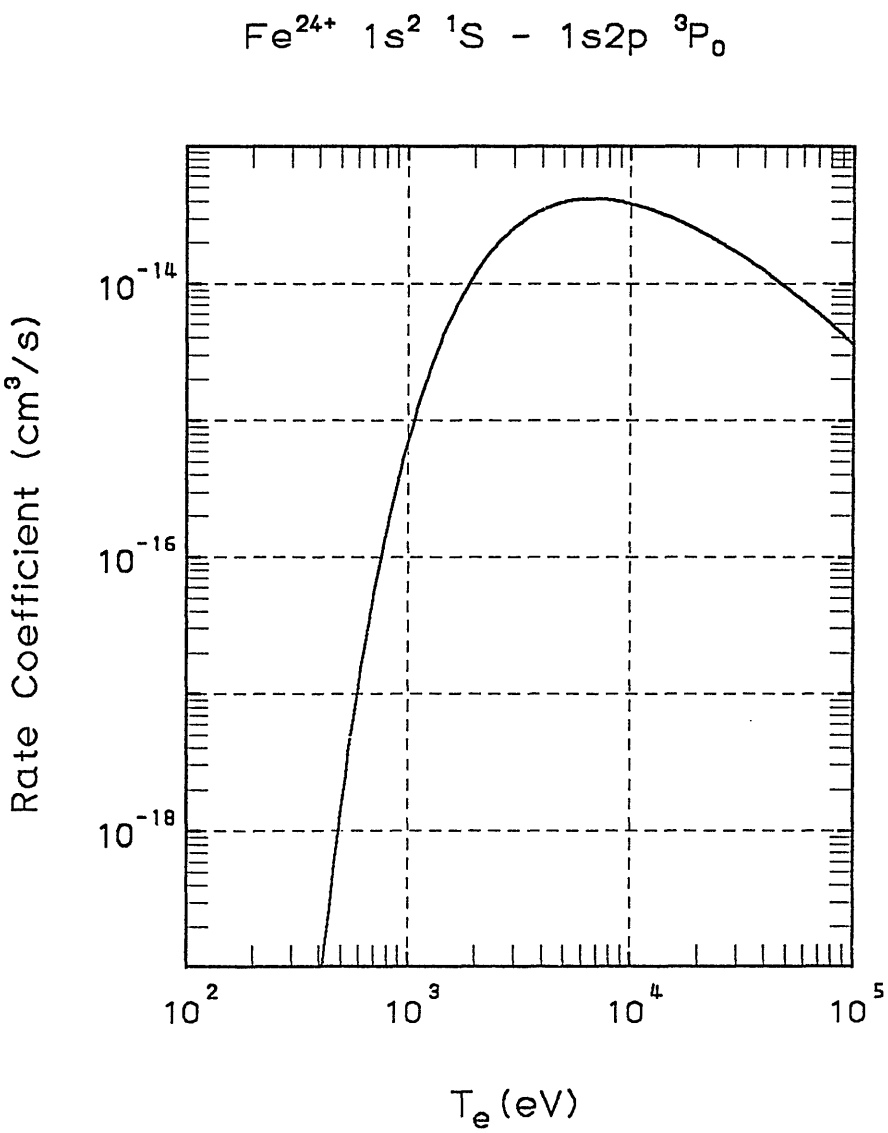

Ti20+ 1s2 1S - 1s2s 3P1
Rate Coefficient (cm3/s)
10-13
10-15
10-17
10 2
10 3
10 4
10 5
Te (eV)

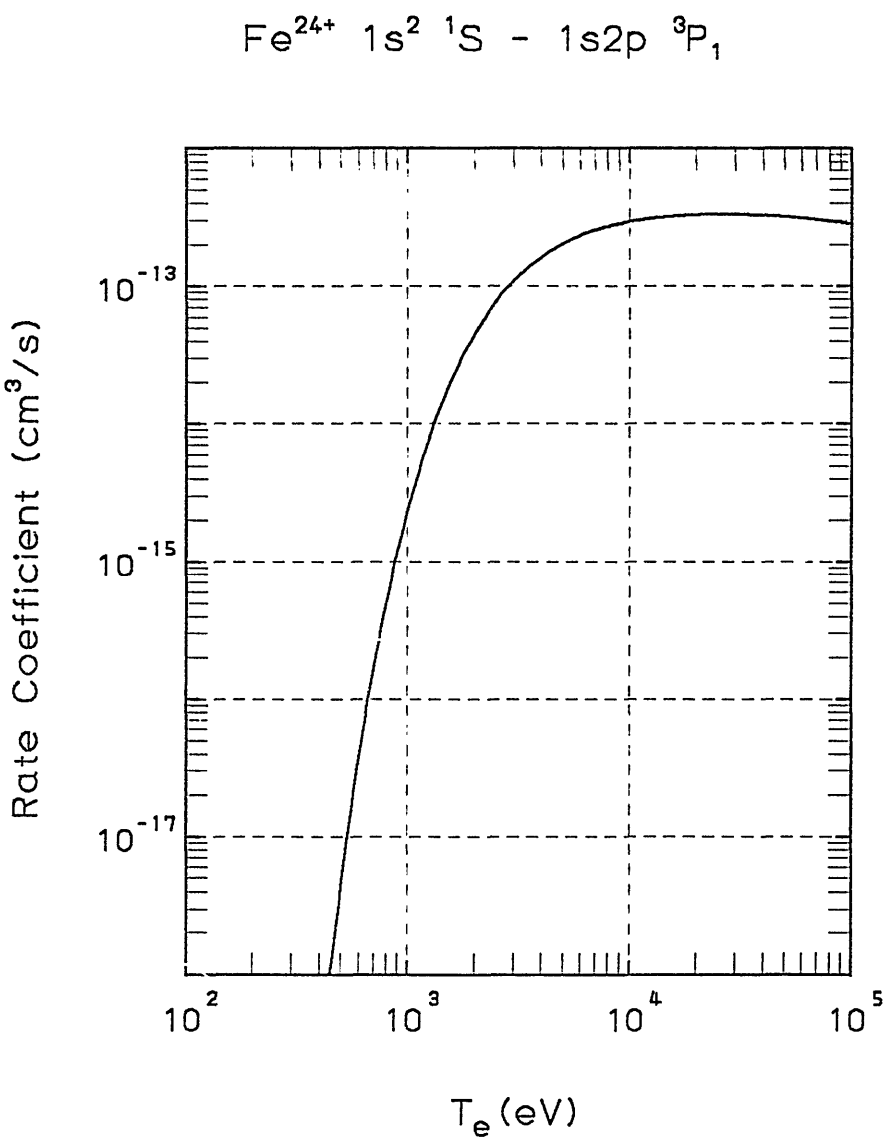

Ti20+ 1s2 1S - 1s2p 3P2
Rate Coefficient (cm3/s)
10-13
10-15
10-17
10 2
10 3
10 4
10 5
Te (eV)

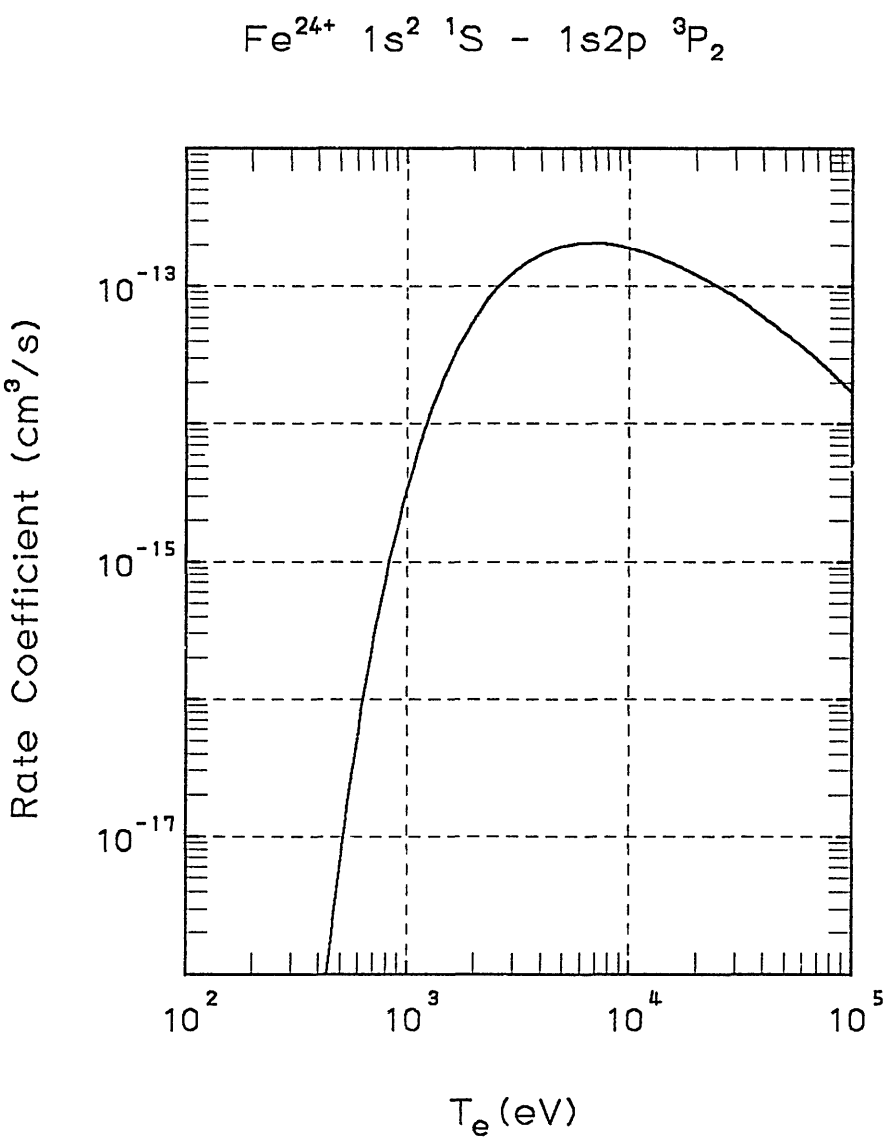

Ti20+ 1s2 1S - 1s2s 1S
Rate Coefficient (cm3/s)
10-13
10-15
10-17
10 2
10 3
10 4
10 5
Te (eV)

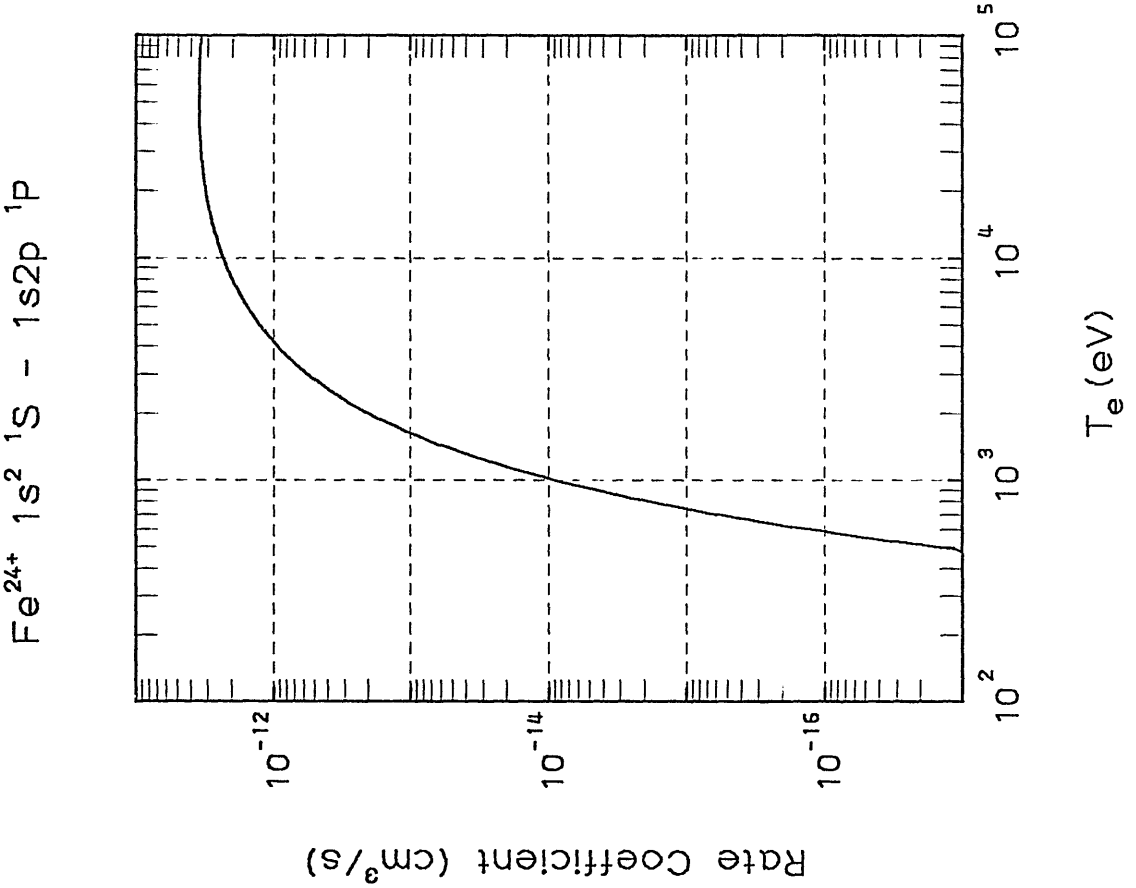

Ti20+ 1s2 1S - 1s2p 1P
Rate Coefficient (cm3/s)
10-12
10-14
10-16
10 2
10 3
10 4
10 5
Te (eV)

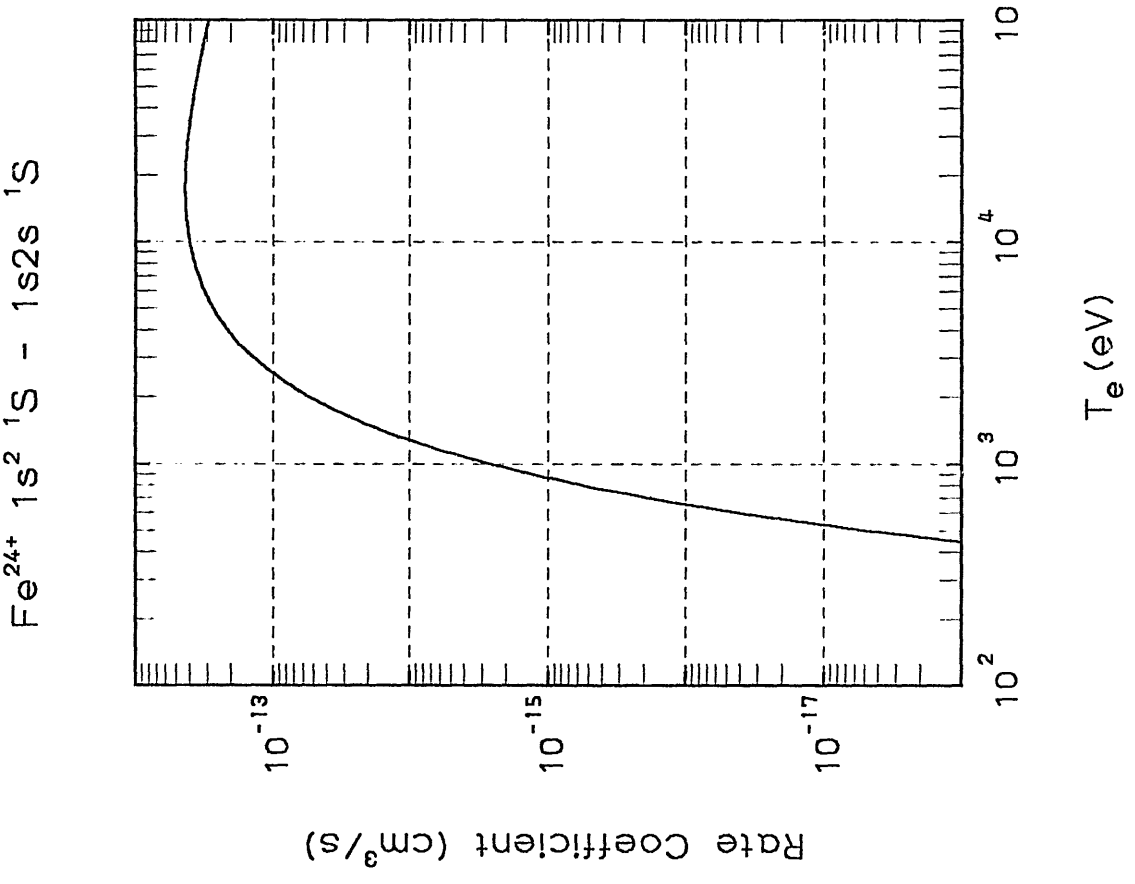

Fe24+ 1s2 1S - 1s2s 3S
Rate Coefficient (cm3/s)
10-14
10-16
10-18
10 2
10 3
10 4
10 5
Te (eV)

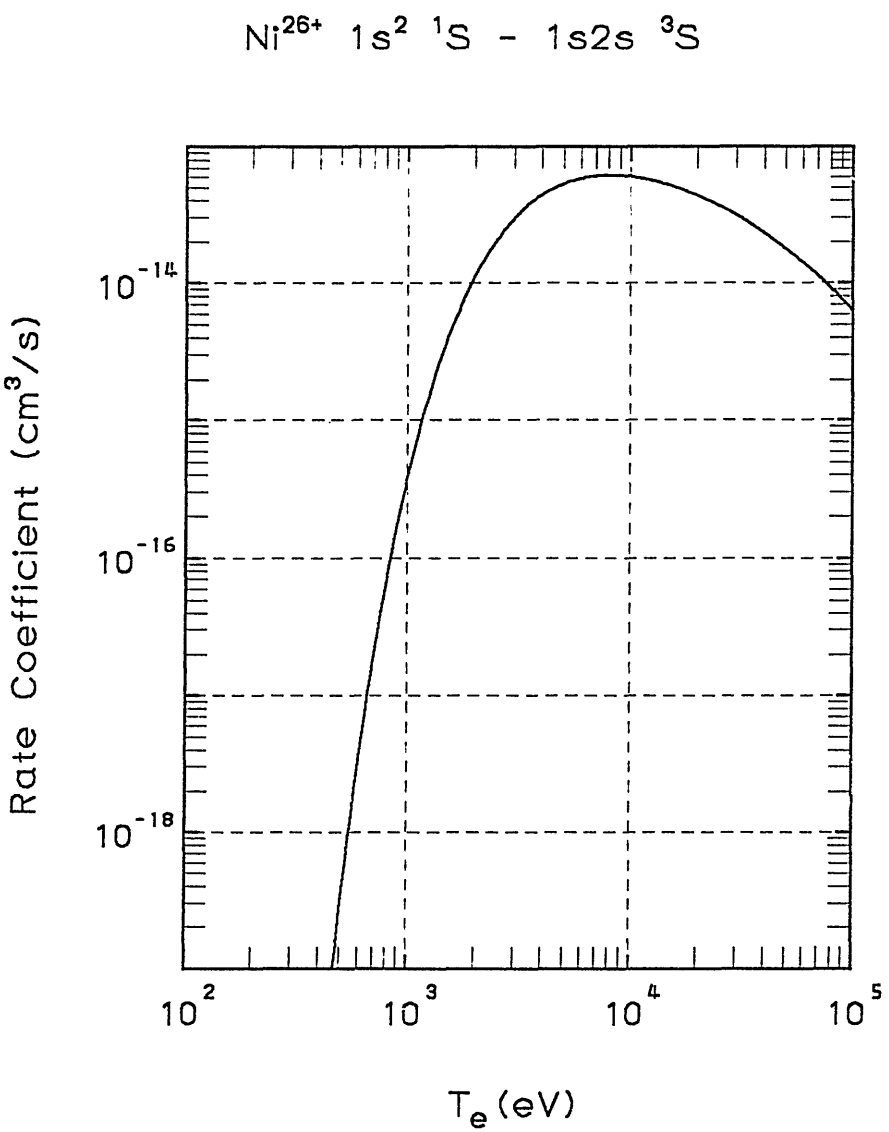

Fe24+ 1s2 1S - 1s2p 3P0
Rate Coefficient (cm3/s)
10-14
10-16
10-18
10 2
10 3
10 4
10 5
Te (eV)

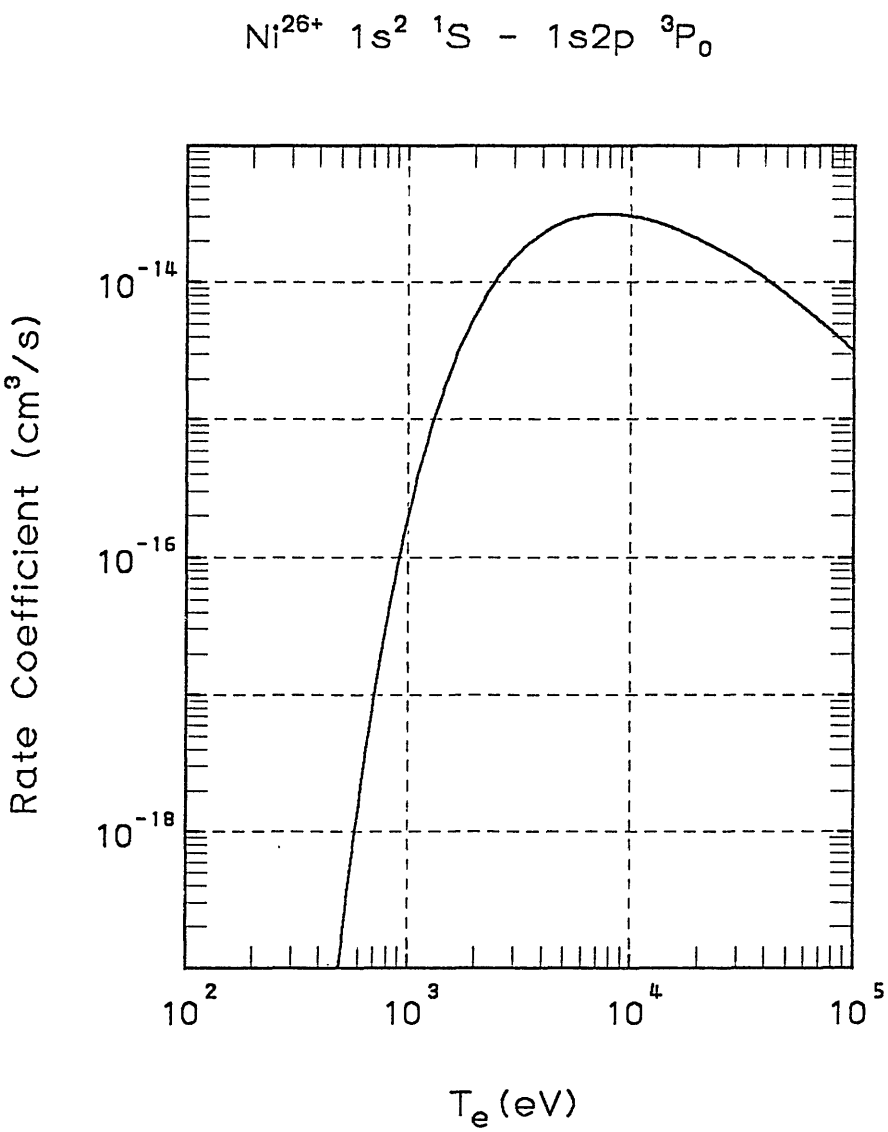

Fe24+ 1s2 1S - 1s2p 3P1
Rate Coefficient (cm3/s)
10-13
10-15
10-17
10 2
10 3
10 4
10 5
Te (eV)

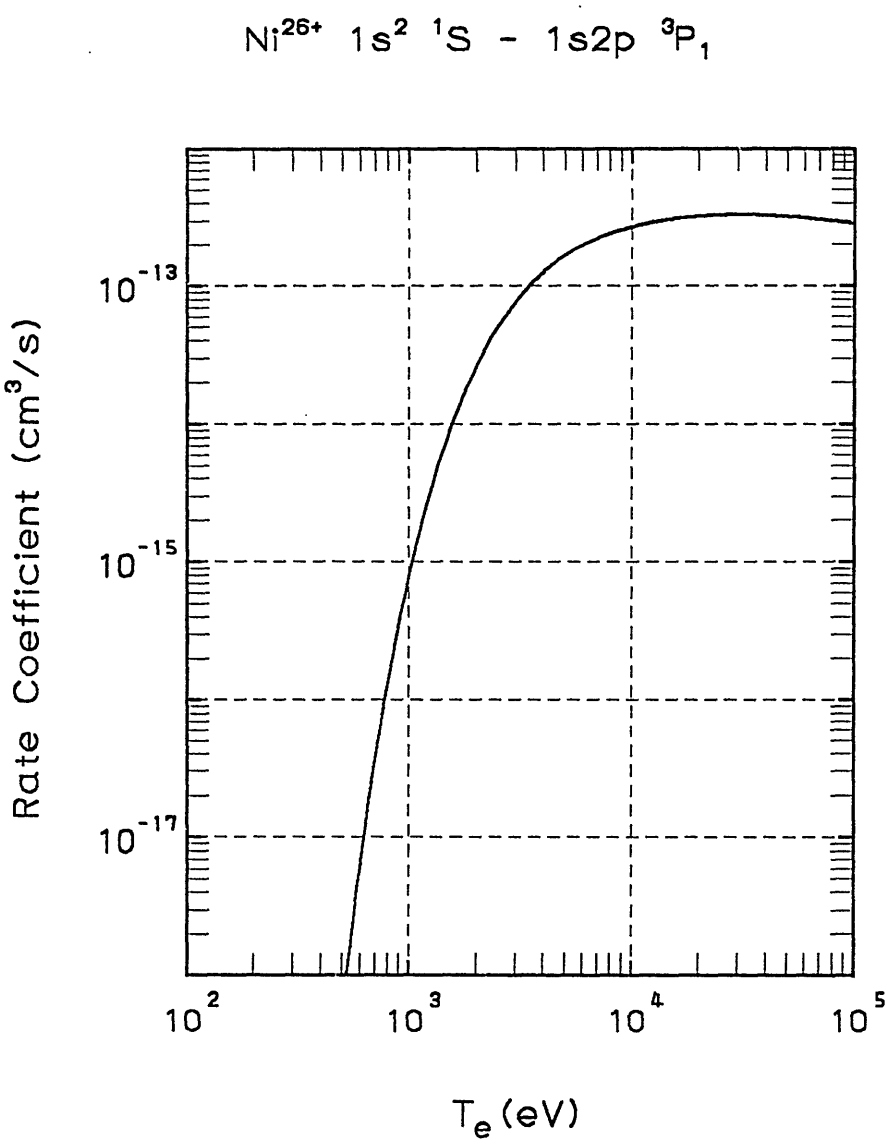

Fe24+ 1s2 1S - 1s2p 3P2
Rate Coefficient (cm3/s)
10-13
10-15
10-17
10 2
10 3
10 4
10 5
Te (eV)

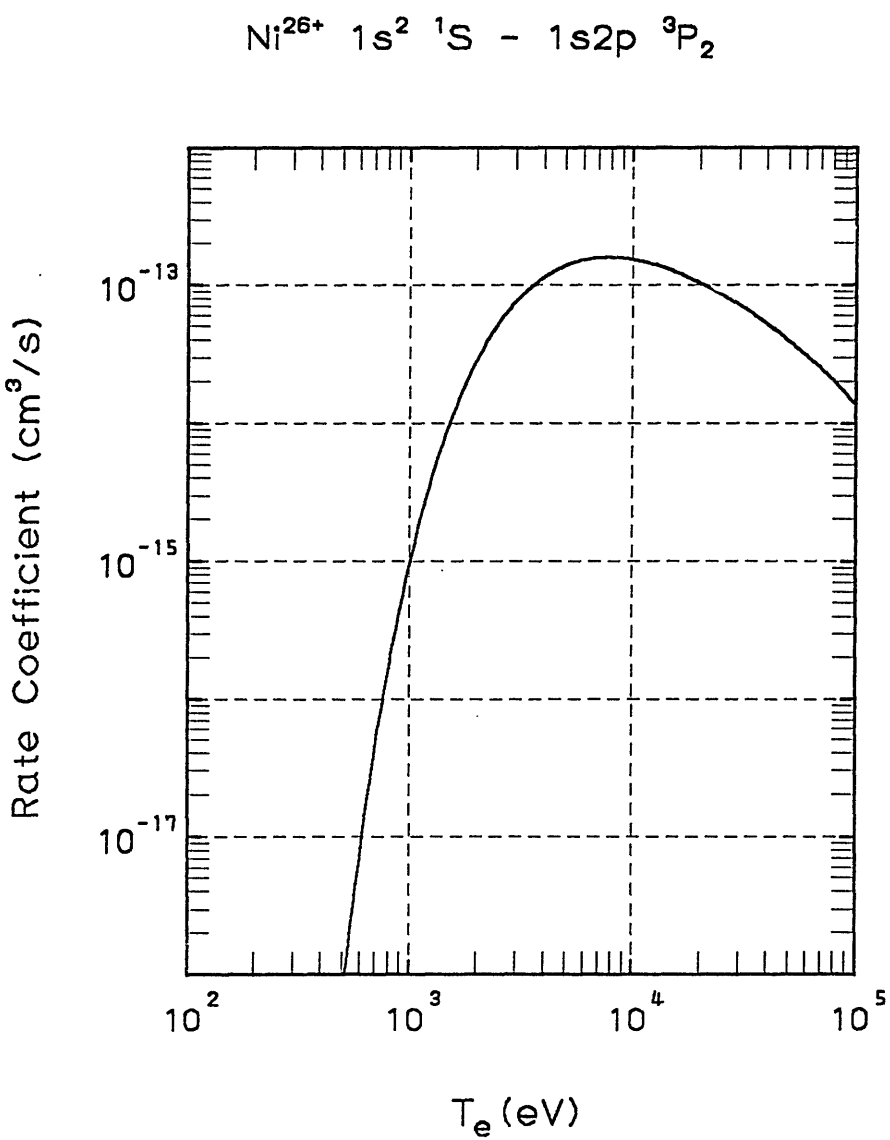

Fe^{24+} $1s^2$ ^1S - 1s2p ^1P
Rate Coefficient (cm^3/s)
10^{-12}
10^{-14}
10^{-16}
10^2
10^3
10^4
10^5
T_e (eV)

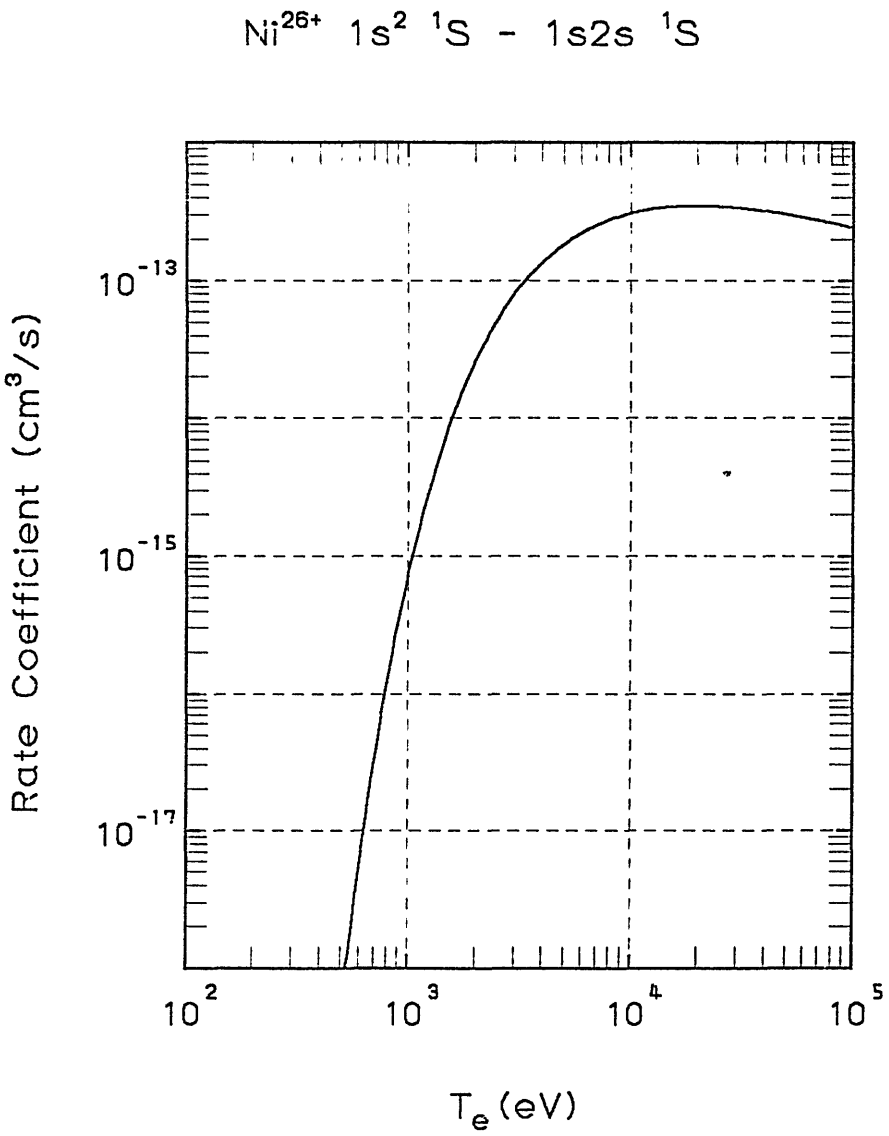

Fe^{24+} $1s^2$ ^1S - 1s2s ^1S
Rate Coefficient (cm^3/s)
10^{-13}
10^{-15}
10^{-17}
10^2
10^3
10^4
10^5
T_e (eV)

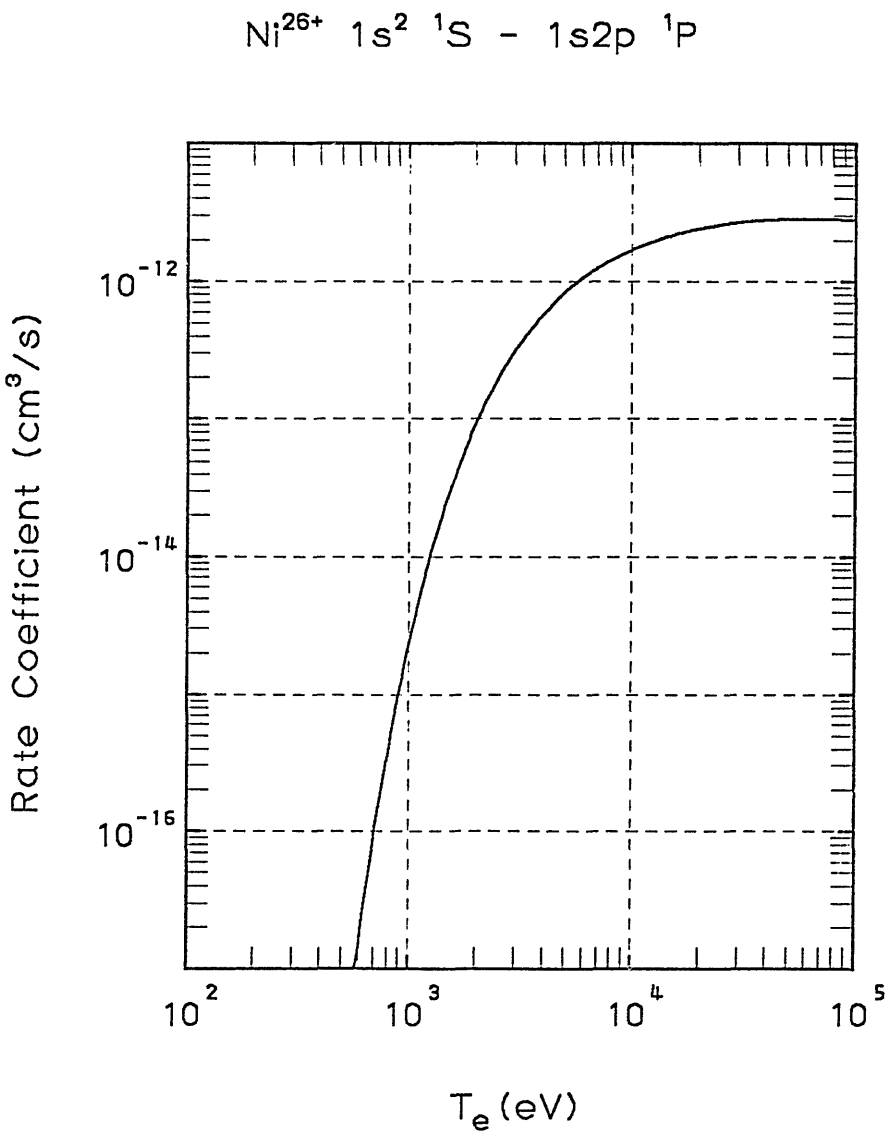

Ni26+ 1s2 1S - 1s2s 3S
Rate Coefficient (cm3/s)
10-14
10-16
10-18
10 2
10 3
10 4
10 5
Te (eV)

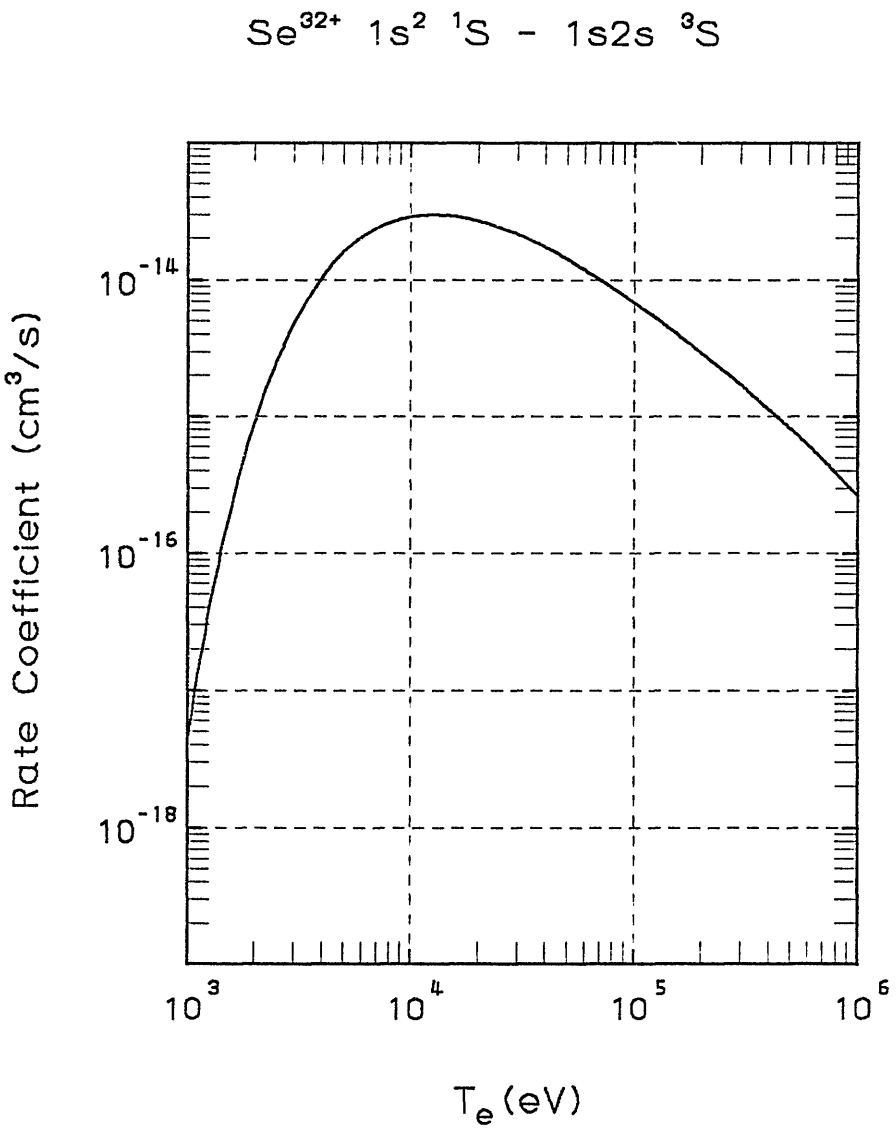

Ni26+ 1s2 1S - 1s2p 3P0
Rate Coefficient (cm3/s)
10-14
10-16
10-18
10 2
10 3
10 4
10 5
Te (eV)

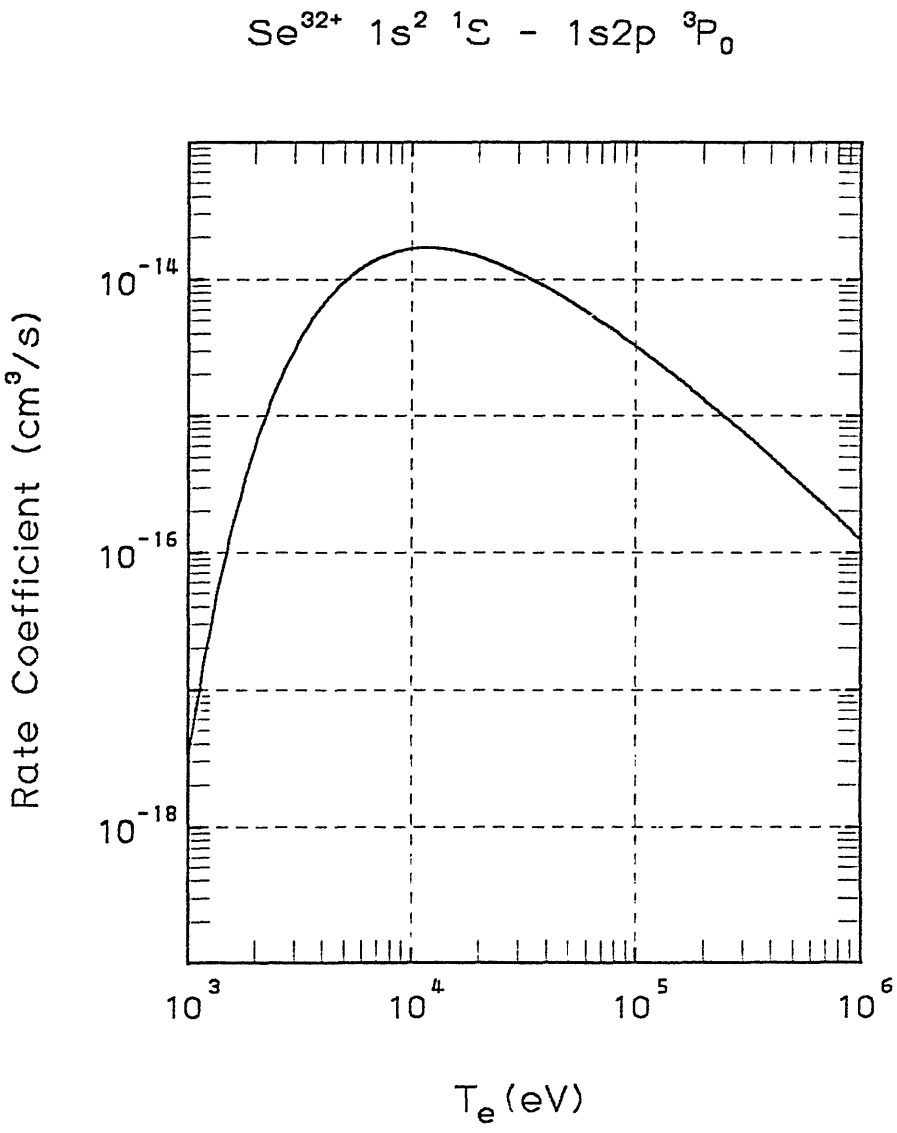

Ni26+ 1s2 1S - 1s2p 3P1
Rate Coefficient (cm3/s)
10-13
10-15
10-17
102
103
104
105
Te (eV)

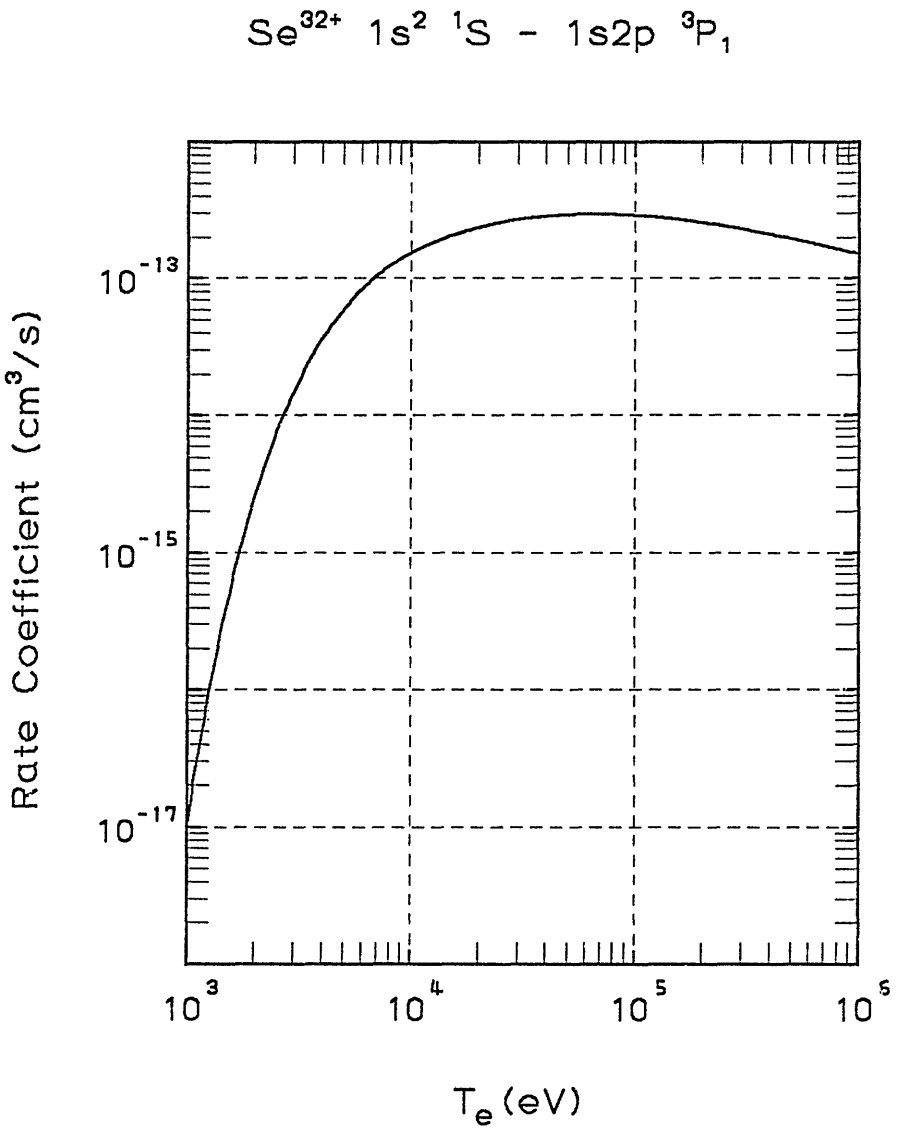

Ni26+ 1s2 1S - 1s2p 3P2
Rate Coefficient (cm3/s)
10-13
10-15
10-17
102
103
104
105
Te (eV)

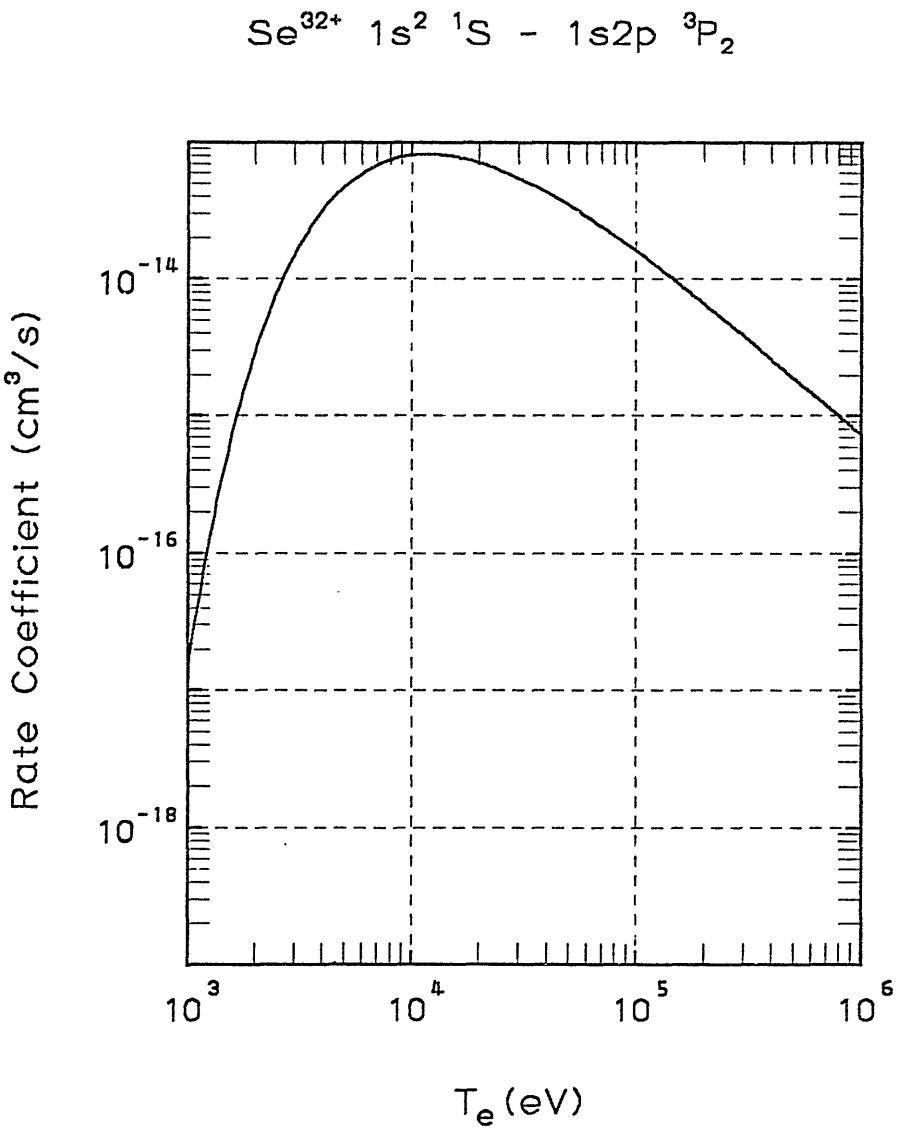

Ni26+ 1s2 1S - 1s2s 1S
Rate Coefficient (cm3/s)
10-13
10-15
10-17
10 2
10 3
10 4
10 5
Te (eV)

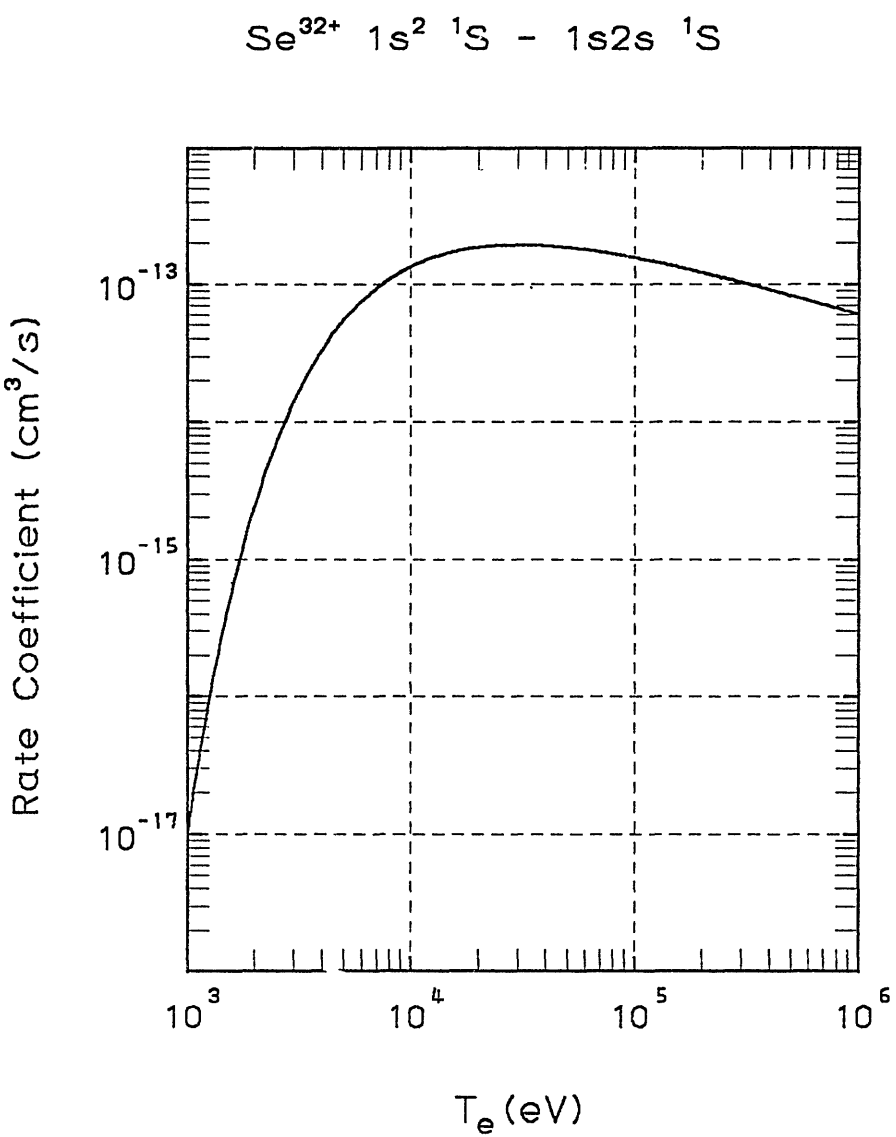

Ni26+ 1s2 1S - 1s2p 1P
Rate Coefficient (cm3/s)
10-12
10-14
10-16
10 2
10 3
10 4
10 5
Te (eV)

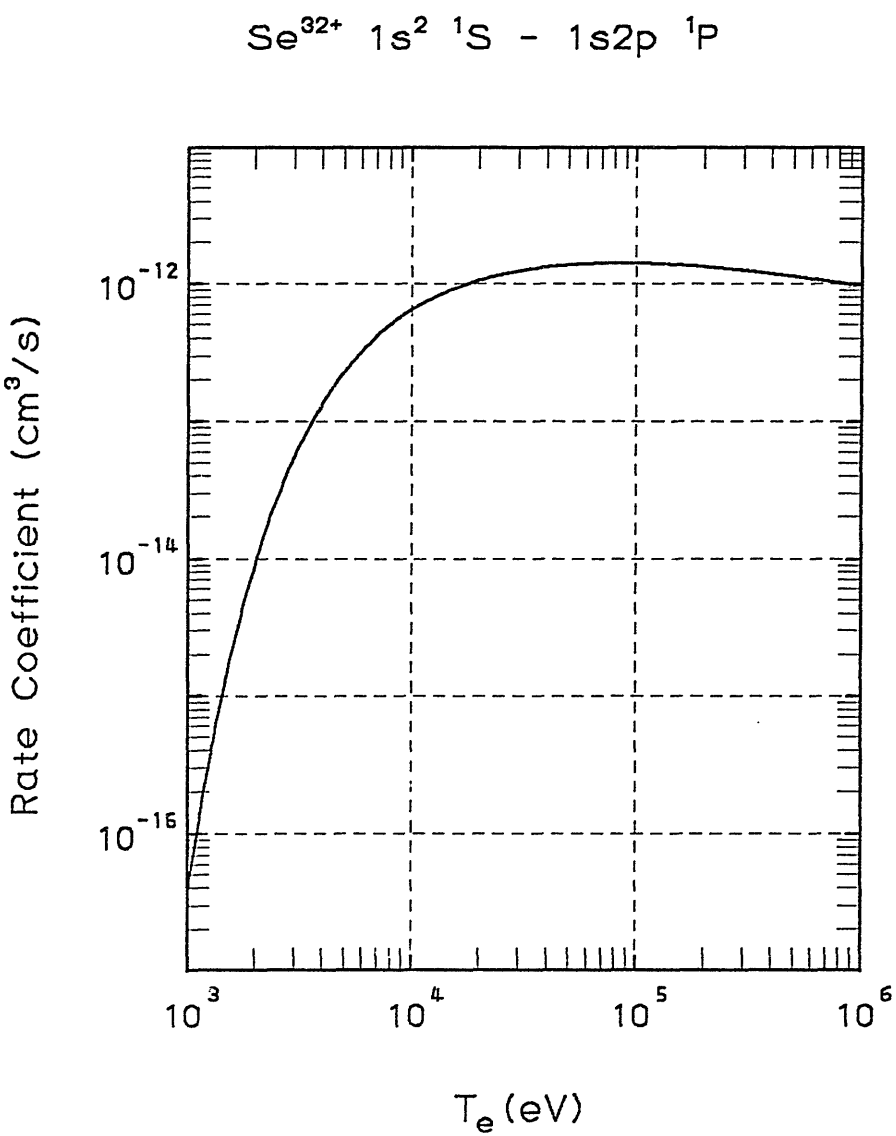

Se32+ 1s2 1S - 1s2s 3S
Rate Coefficient (cm3/s)
10-14
10-16
10-18
10 3
10 4
10 5
10 6
Te (eV)

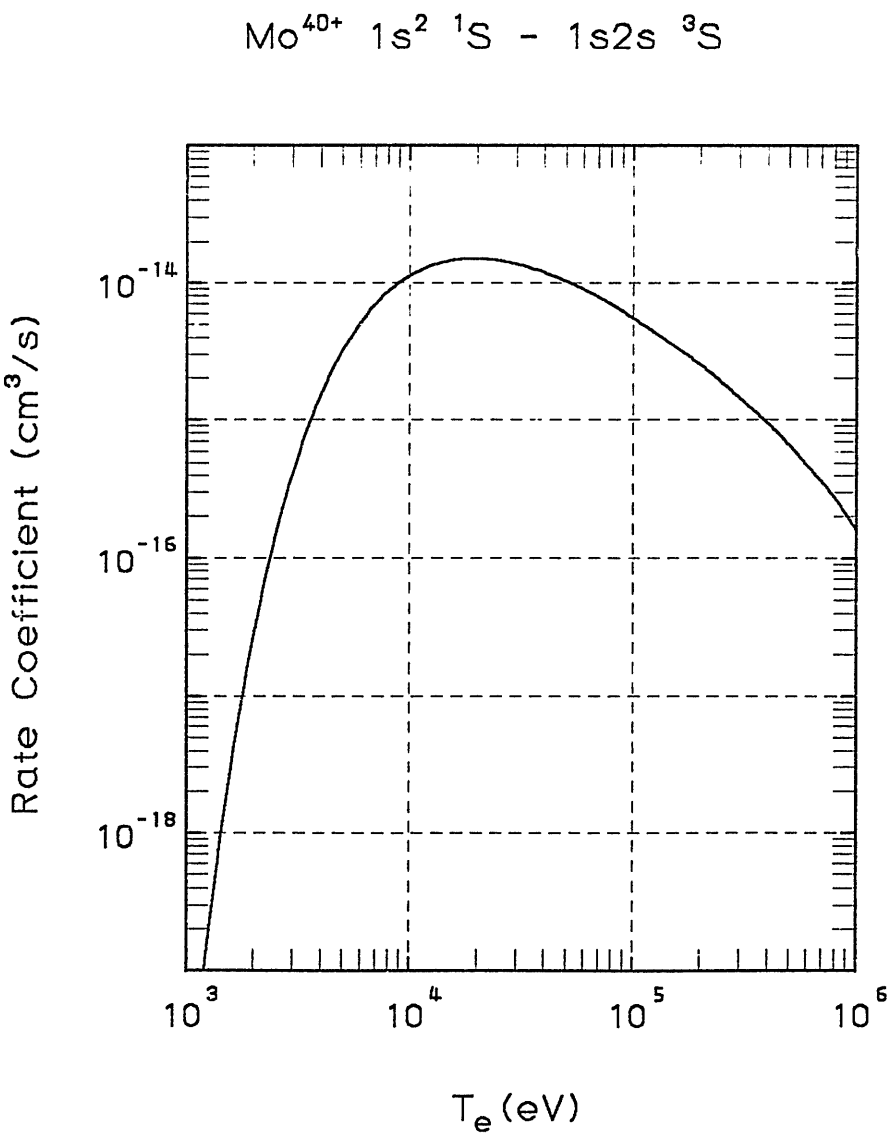

Se32+ 1s2 1S - 1s2p 3P0
Rate Coefficient (cm3/s)
10-14
10-16
10-18
10 3
10 4
10 5
10 6
Te (eV)

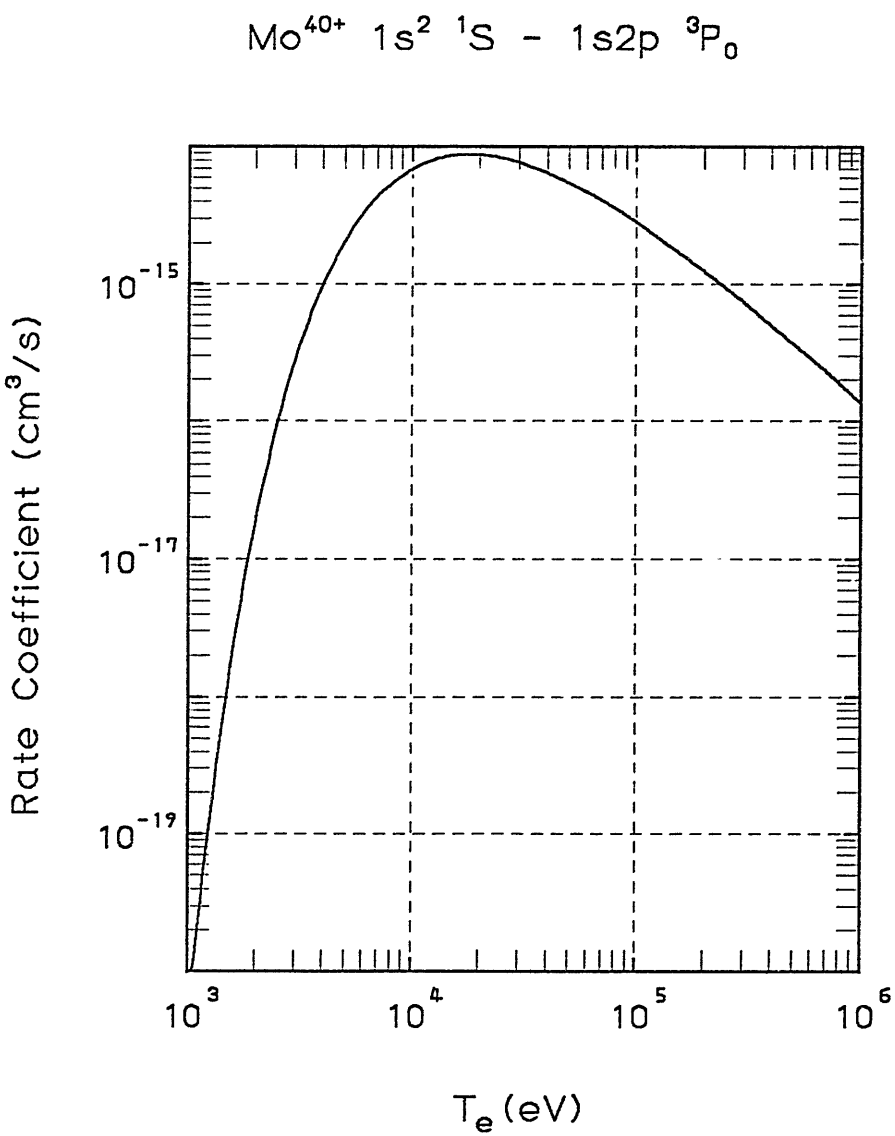

Se32+ 1s2 1S - 1s2p 3P1
Rate Coefficient (cm3/s)
10-13
10-15
10-17
10³
10⁴
10⁵
10⁶
Te (eV)

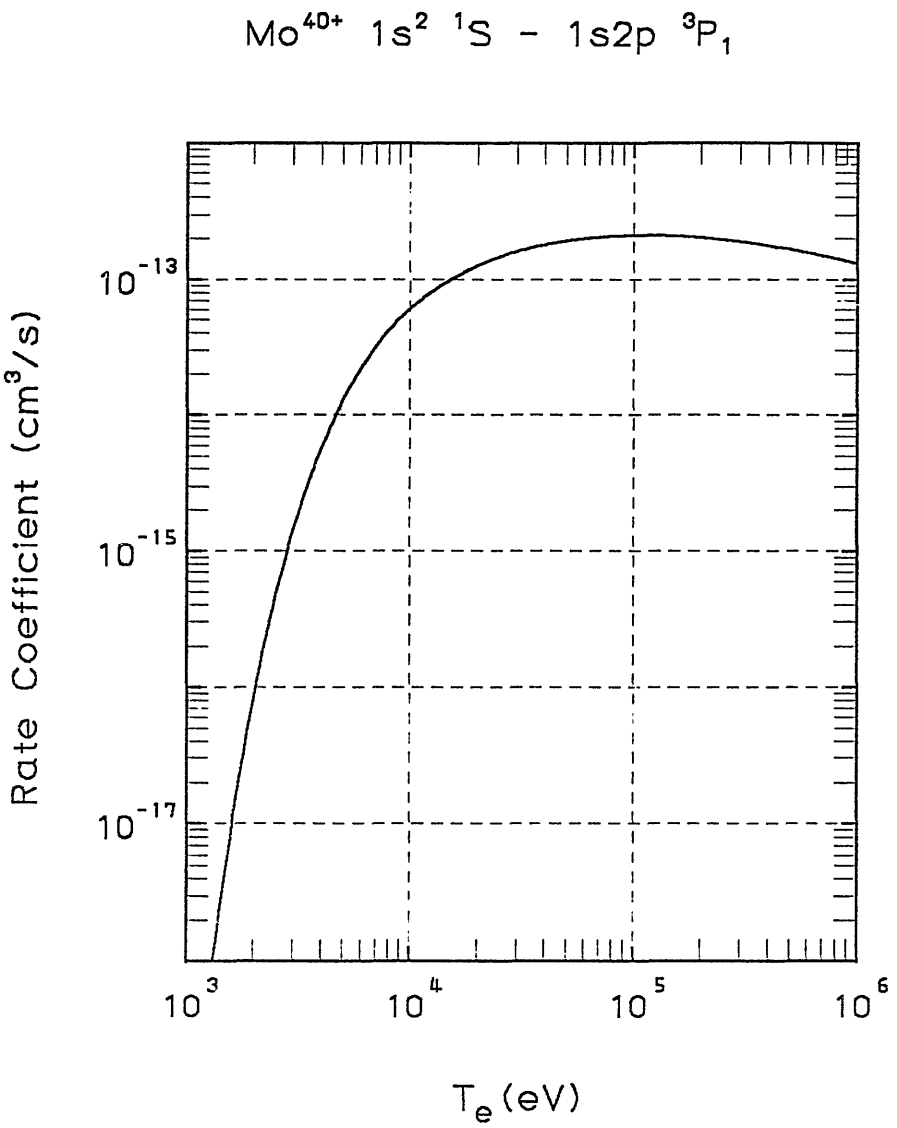

Se32+ 1s2 1S - 1s2p 3P2
Rate Coefficient (cm3/s)
10-14
10-16
10-18
10³
10⁴
10⁵
10⁶
Te (eV)


Se32+ 1s2 1S - 1s2s 1S
Rate Coefficient (cm3/s)
10-13
10-15
10-17
10 3
10 4
10 5
10 6
Te (eV)


Se32+ 1s2 1S - 1s2p 1P
Rate Coefficient (cm3/s)
10-12
10-14
10-16
10 3
10 4
10 5
10 6
Te (eV)


Mo40+ 1s2 1S - 1s2s 3S
Rate Coefficient (cm3/s)
10-14
10-16
10-18
10 3
10 4
10 5
10 6
Te (eV)


Mo40+ 1s2 1S - 1s2p 3P0
Rate Coefficient (cm3/s)
10-15
10-17
10-19
10 3
10 4
10 5
10 6
Te (eV)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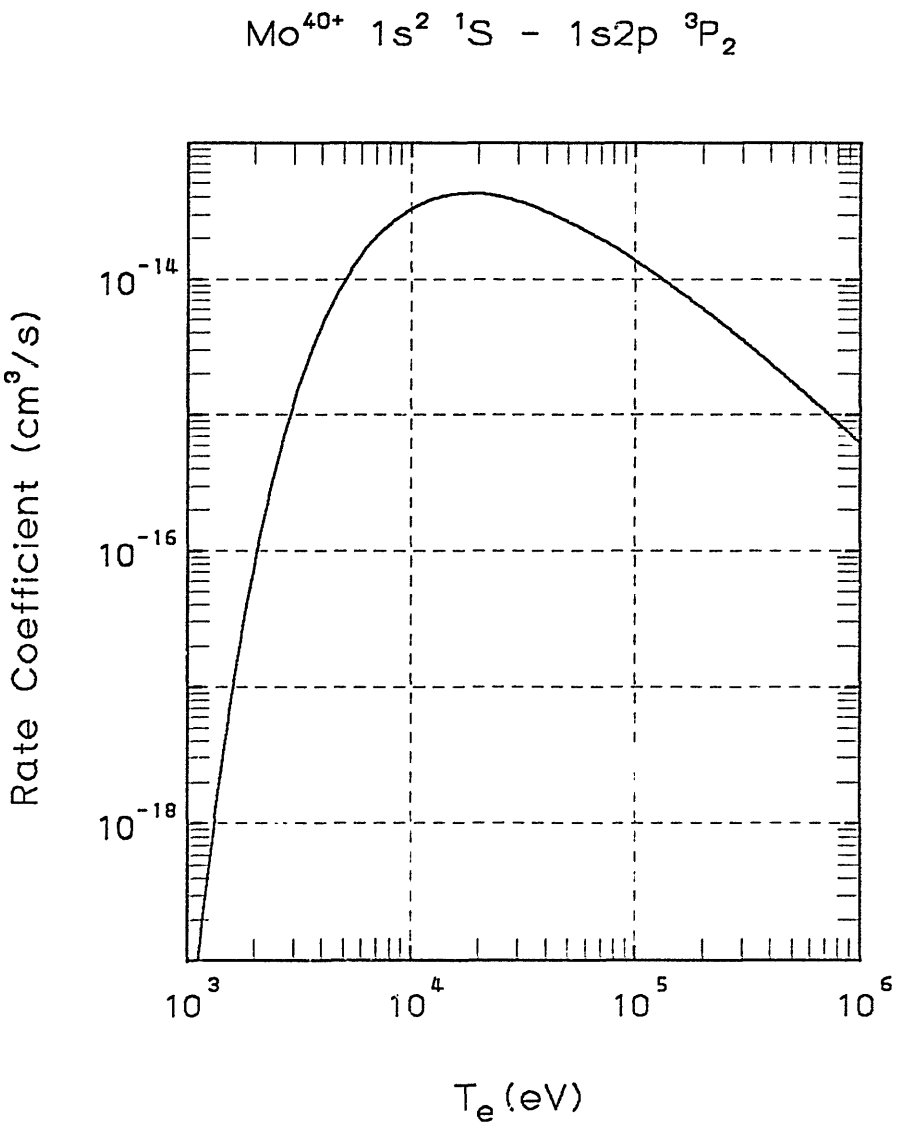
Rate Coefficient (cm3/s)
10-13
10-15
10-17
10 3
10 4
10 5
10 6
Te (eV)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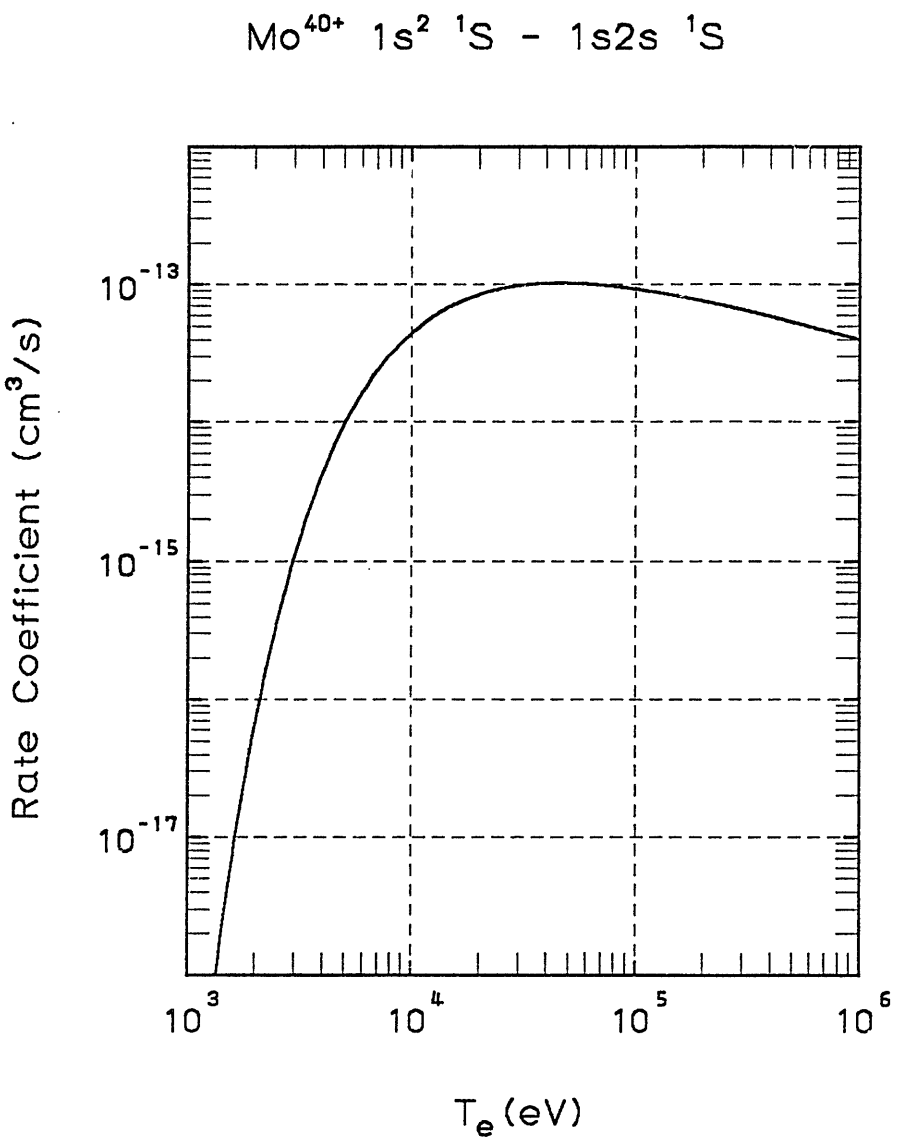
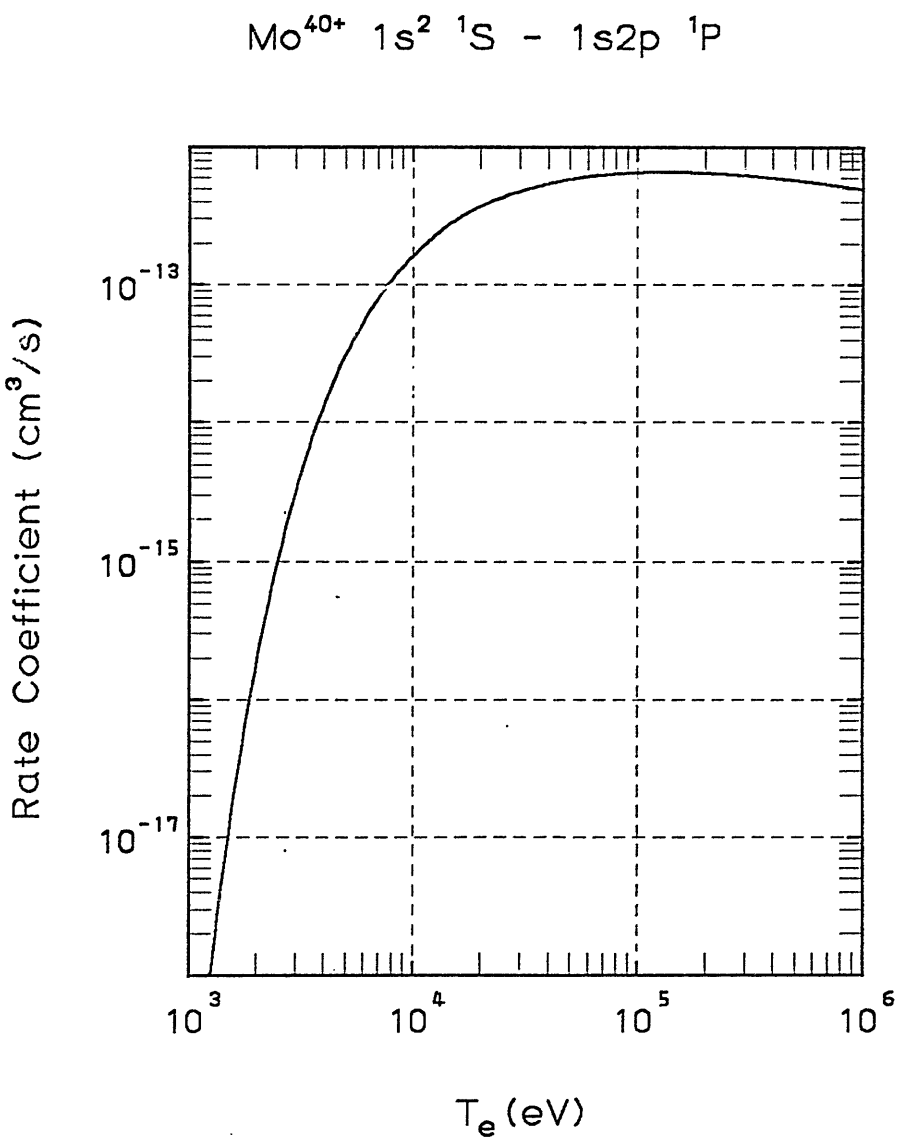
Rate Coefficient (cm3/s)
10-14
10-16
10-18
10 3
10 4
10 5
10 6
Te (eV)


Mo40+ 1s2 1S - 1s2s 1S
Rate Coefficient (cm3/s)
10-13
10-15
10-17
10 3
10 4
10 5
10 6
Te (eV)


Mo40+ 1s2 1S - 1s2p 1P
Rate Coefficient (cm3/s)
10-13
10-15
10-17
10 3
10 4
10 5
10 6
Te (eV)

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