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PROTON EXCITATION RATE COEFFICIENTS AND CROSS SECTIONS AMONG THE FINE-STRUCTURE LEVELS OF THE $(2s2p)^3P$ STATE IN BE-LIKE IONS

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Proton excitation cross sections and rate coefficients are given for the fine-structure transitions in the $(2s2p)^3P$ state in the Be-like ions C III, N IV, O V, F VI, Ne VII, Mg IX, Si XI, S XIII, Ar XV, Ca XVII, and Fe XXIII. In the low-energy region we used the semiclassical Coulomb excitation method, while for the intermediate-energy range, we used a close-coupling impact parameter method. For the temperatures tabulated here, the rate coefficients for all the transitions are better than 5%.

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INTRODUCTION

The importance of collisional excitation by protons within the fine-structure levels of a term in a positive ion was first discussed by Seaton.[1] Since then, several authors have presented such calculations (Reid and Schwartz,[2] Bely and Faucher,[3] Masnou-Seeuws and McCarroll,[4] Faucher and Landman,[5] Kastner,[6] Landman and Brown,[7] and Doyle et al.,[8] and references therein). Further references and a review of the various methods of calculating proton impact excitation cross sections can be found in Dalgarno.[9] Interest in calculating proton excitation cross sections stems from the fact that several important solar diagnostic lines arise from these levels; for example the $(2s2p)^3P_1$–$(1s^2)^1S_0$ and the $(2s2p)^3P_J$–$(2p^2)^3P_J$ transitions in Be-like ions have been used to derive information on the electron densities and temperature structures of different solar features (Dupree et al.,[10] Doyle et al.[8,11]). For this, an accurate determination of the various atomic processes involved is required.

Here, the cross sections between the $(2s2p)^3P_J$ levels of C III, N IV, O V, F VI, Ne VII, Mg IX, Si XI, S XIII, Ar XV, Ca XVII, and Fe XXIII are calculated using the close-coupling impact parameter method employed by Reid and Schwartz[2] and Doyle et al.[8] Rate coefficients are calculated assuming a Maxwell–Boltzmann distribution of proton velocities for a range of temperatures of astrophysical interest.

Method of Calculation and Accuracy

The calculations were split into two energy ranges, which we call a low-energy and an intermediate-energy range. For both energy ranges, the perturbing proton follows a classical Coulomb trajectory. An adequate approximation at low energies is given by the expression of Alder et al.[12] and Kastner.[6] The energy cutoff point where this expression becomes inaccurate is given by a dimensionless parameter ξ (the definition is given later). As the incident energy increases and ξ decreases, this approximation gives cross sections which are too large. In C III this occurs at 1 eV, while for Mg IX it is at $\sim$50 eV. These energies correspond to $\xi \sim 1$ (see Kastner[6] for figures showing the low-energy/intermediate-energy cross sections for several ions). Below, the two methods are discussed in more detail.

(a) Low-Energy Range

For the electric quadrupole case the semiclassical Coulomb excitation cross section (in units of a_0^2, where a_0 is the Bohr radius) is given by

$$Q_{E_2} = 134.97K(x-1)B(E_2)f_{E_2}(\xi), \tag{1}$$

where $x = E/\Delta E$, $K = \Delta E/Z^2$, $B(E_2)$ is the reduced radiative quadrupole transition probability from the initial state of spin J_i to the final state of spin J_f given by

$$B(E_2) = 104.1\Delta E^{-5}A_q(2J_f+1)/(2J_i+1), \tag{2}$$

and $f_{E_2}(\xi)$ is the classical orbital function for collisions in a Coulomb potential given by

$$f_{E_2}(\xi) = \text{antilog}[-0.046959 + 0.10104\xi - 3.31043\xi^2 + 2.7471\xi^3 - 1.3405\xi^4 + 0.33718\xi^5 - 0.03277\xi^6]. \tag{3}$$

In the above, $B(E_2)$ is in atomic units of $e^2a_0^4$, A_q is the quadrupole transition probability, E is the projectile energy in the center of mass in eV, and ΔE is the energy difference of the levels involved in the transition in eV (taken from Bashkin and Stoner[13] for the present calculation). The dimensionless parameter ξ is given by

$$\xi = \frac{Ze^2}{\hbar}\left(\frac{1}{v_f} - \frac{1}{v_i}\right) = 158.0K^{-1/2}[(x-1)^{-1/2} - x^{-1/2}], \quad (4)$$

where Z is the ion charge; e is the electron charge; and v_i and v_f are the initial and final proton velocities, respectively. The expressions above are used to derive the cross sections for the J = 0–2 and 1–2 quadrupole transitions. The cross section for the J = 0–1 transition is set equal to zero in the low-energy range. Further details on this approximation can be found in Alder et al.[12] or Kastner.[6]

(b) Intermediate-Energy Range

For this energy range (that is where $\xi < 1$), we use a close-coupling impact parameter formulation. According to this method the interaction matrix elements are proportional to $\Psi(R) = \langle r^2\rangle_{2p}R^{-3}$, where R is the distance between the proton and the ion and $\langle r^2\rangle_{2p}$ is the expectation value of r^2 for the p electron. Values for $\langle r^2\rangle_{2p}$ used in the present work were from Hartree–Fock wave functions of Tatewaki et al.[14] For C III, N IV, O V, F VI, Ne VII, Mg IX, Si XI, S XIII, Ar XV, Ca XVII, and Fe XXIII we derive values for $\langle r^2\rangle_{2p}$ of 2.158, 1.363, 0.912, 0.662, 0.500, 0.317, 0.218, 0.157, 0.121, 0.095, and 0.053, respectively. A full description of the method of calculation and the evaluation of the matrix elements is given in Doyle.[15] Details concerning the matrix elements are also found in Doyle et al.[8] The proton excitation cross sections for the fine-structure transitions among the $(2s2p)^3P$ triplet levels of C III to Fe XXIII are given in Table I.

For most uses, the excitation rate coefficient is required, as opposed to the cross sections. These rates were calculated with an assumed Maxwell–Boltzmann distribution of proton velocities. For the cross sections given in Table I, rate coefficients were calculated in steps of 0.1 in $\log_{10}T$ for those temperatures for which the ionization fractions (taken from Arnaud and Rothenflug[16]) were greater than 0.1 of their peak value. The upper integration limit was taken to be the last calculated cross-section energy point. To check that this upper limit was sufficient for convergence, we varied it and recalculated the rate coefficient for the highest-temperature point tabulated here for each ion; in all cases the limit was found sufficient. At the low-energy end the cross sections were set to zero. A check on the accuracy of this was provided by extending the cross sections for one ion down to energies lower than those tabulated in Table I and recalculating the rate coefficients. A tabulation of the rate coefficients can be found in Table II.

Regarding the accuracy of the calculated cross sections, we have estimated by various numerical tests that errors arising from numerical solutions of the coupled equations and their subsequent integration over all impact parameters are less than 1%. To calculate the errors arising from the penetration by the proton of the ion's electron cloud, we recalculated the cross sections with a different short-range form of $\Psi(R)$ (see Doyle[15]). At temperatures close to that expected for an ion in ionization equilibrium, the error estimate for all transitions is less than 1%, although at temperatures substantially above this, larger errors are expected (see Doyle et al.[8]). Landman and Brown[7] presented proton cross-section data and rate coefficients for several Be-like ions, derived from semiclassical Coulomb excitation theory. For lower-Z ions such as C III the difference between their rates and those given here is ~3% for the 0–1 transition, while for the 0–2 and 1–2 transitions the differences are ~10%–15%. For O V to Ca XVII the differences between the two calculations are less than ~5% for the 0–2 and 1–2 transitions and 5%–10% for the 0–1 transition. We estimate an overall error of ~5% for all transitions in all ions.

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EXPLANATION OF TABLES

TABLE I. Proton Collisional Excitation Cross Sections versus Incident Energy for the Three Fine-Structure Transitions in the $(2s2p)^3P$ State of the Be-like Ions C III to Fe XXIII

In the table, the fine-structure transitions within the $(2s2p)^3P$ state are designated by their J values 0–1, 0–2, and 1–2. Below each J–J' transition the energy difference ΔE of the levels[13] is given in eV, followed by the cross sections in units of a_0^2, where a_0 is the Bohr radius. 3.40E-2 means 3.40×10^{-2}.

E(e.V)   Projectile energy in the center of mass in eV

TABLE II. Proton Collisional Excitation Rate Coefficients versus Temperature for the Three Fine-Structure Transitions in the $(2s2p)^3P$ State of the Be-like Ions C III to Fe XXIII

In the table, the proton excitation collision rates in $cm^3\ s^{-1}$ are listed below each J–J' transition within the $(2s2p)^3P$ state.

$\log_{10}$ T   Logarithm to the base 10 of the proton temperature

TABLE I. Proton Collisional Excitation Cross Sections versus Incident Energy for the Three Fine-Structure Transitions in the $(2s2p)^3P$ State of the Be-like Ions C III to Fe XXIII

See page 445 for Explanation of Tables

	C III		
E(e.V)	0 - 1	0 - 2	1 - 2
	(.0029)	(.0099)	(.0070)
1	---	3.40E-2	3.06E-1
2	1.09E-2	9.22	9.97
3	1.45E-1	33.10	27.54
4	6.29E-1	58.07	44.48
5	1.72	78.28	58.31
6	3.63	92.14	68.32
7	6.44	99.26	74.25
8	10.07	100.22	76.41
9	14.18	96.55	75.70
10	18.26	91.08	73.41
12	24.48	80.10	69.16
13	26.07	77.77	68.36
15	27.11	76.05	67.75
20	27.61	69.23	63.25
25	26.63	64.70	59.60
30	25.34	61.09	56.42
40	22.86	55.60	51.33
50	20.80	51.52	47.43
60	19.14	48.18	44.23
70	17.75	45.45	41.59
80	16.58	43.24	39.44
90	15.63	41.30	37.58
100	14.87	39.52	35.92
120	13.52	36.62	33.17
150	11.94	33.46	30.13
200	10.35	29.38	26.40
250	9.15	26.64	23.83
350	7.78	22.75	20.33
500	6.45	19.21	17.10

	N IV		
E(e.V)	0 - 1	0 - 2	1 - 2
	(.0078)	(.0256)	(.0178)
2	---	4.79E-4	1.39E-2
4	1.51E-3	1.52	2.86
6	2.62E-2	9.78	9.81
8	1.28E-1	20.15	16.70
10	3.74E-1	29.21	22.49
12	8.32E-1	36.20	27.08
15	2.03	42.53	31.57
18	3.85	44.14	33.31
19	4.54	43.79	33.36
20	5.28	43.11	33.21
22	6.80	41.06	32.46
25	8.86	37.47	30.97
30	10.92	33.83	29.51
35	11.40	32.83	29.08
40	11.54	31.25	28.05
50	11.46	29.14	26.57
60	11.07	27.31	25.10
70	10.58	26.09	24.00
80	10.10	24.92	22.94
90	9.66	23.91	22.00
100	9.25	23.04	21.19
120	8.52	21.61	19.80
150	7.69	19.89	18.16
200	6.72	17.66	16.08
250	5.91	16.20	14.64
300	5.38	15.03	13.53
500	4.18	12.92	10.68
750	3.20	10.17	8.97

TABLE I. Proton Collisional Excitation Cross Sections versus Incident Energy for the Three Fine-Structure Transitions in the $(2s2p)^3P$ State of the Be-like Ions C III to Fe XXIII

See page 445 for Explanation of Tables

		O V	
E(e.V)	0 - 1	0 - 2	1 - 2
	(.0169)	(.0549)	(.0380)
5	---	8.42E-3	8.01E-2
8	7.26E-4	8.09E-1	1.54
10	4.23E-3	2.58	3.39
20	2.10E-1	15.24	11.87
25	5.58E-1	19.37	14.49
30	1.14	21.55	16.02
35	1.94	21.95	16.55
40	2.89	21.05	16.31
45	3.83	19.52	15.69
50	4.62	18.04	15.06
55	5.15	17.05	14.66
60	5.43	16.58	14.49
70	5.57	16.02	14.18
80	5.64	15.12	13.60
90	5.64	14.53	13.19
100	5.55	14.12	12.87
120	5.31	13.26	12.15
150	4.96	12.25	11.27
200	4.41	11.10	10.19
250	3.96	10.28	9.39
300	3.64	9.59	8.74
400	3.22	8.47	7.72
500	2.85	7.73	6.99
750	2.16	6.69	5.93

		F VI	
E(e.V)	0 - 1	0 - 2	1 - 2
	(.0330)	(.1036)	(.0706)
10	---	2.29E-2	1.35E-1
15	8.81E-4	7.19E-1	1.20
18	3.43E-3	1.71	2.17
20	6.92E-3	2.54	2.86
22	1.25E-2	3.45	3.53
25	2.61E-2	4.85	4.49
30	6.82E-2	7.07	5.89
35	1.43E-1	8.97	7.06
40	2.59E-1	10.47	7.98
45	4.23E-1	11.55	8.66
50	6.37E-1	12.22	9.12
60	1.20	12.46	9.43
70	1.85	11.68	9.15
80	2.45	10.61	8.70
90	2.88	9.82	8.36
100	3.08	9.45	8.22
110	3.15	9.27	8.13
120	3.17	9.03	7.98
150	3.20	8.23	7.45
200	3.03	7.54	6.90
250	2.82	6.99	6.42
300	2.64	6.54	6.01
400	2.35	5.85	5.37
500	2.08	5.40	4.93
1000	1.27	4.31	3.76

TABLE I. Proton Collisional Excitation Cross Sections versus Incident Energy for the Three Fine-Structure Transitions in the $(2s2p)^3P$ State of the Be-like Ions C III to Fe XXIII

See page 445 for Explanation of Tables

	Ne VII				Mg IX		
E(e.V)	0 - 1 (.0564)	0 - 2 (.1796)	1 - 2 (.1232)	E(e.V)	0 - 1 (.1800)	0 - 2 (.4505)	1 - 2 (.2705)
15	---	5.31E-3	4.50E-2	35	---	4.99E-3	5.50E-2
20	1.17E-4	1.21E-1	3.28E-1	40	2.89E-5	2.50E-2	9.05E-2
25	8.06E-4	5.16E-1	8.58E-1	45	9.38E-5	6.78E-2	1.75E-1
30	3.07E-3	1.21	1.51	50	2.44E-4	1.42E-1	2.87E-1
35	8.32E-3	2.08	2.18	55	5.36E-4	2.51E-1	4.18E-1
40	1.82E-2	3.01	2.81	60	1.04E-3	3.91E-1	5.61E-1
45	3.43E-2	3.91	3.38	65	1.85E-3	5.57E-1	7.12E-1
50	5.85E-2	4.74	3.90	70	3.05E-3	7.44E-1	8.64E-1
55	9.24E-2	5.47	4.35	75	4.75E-3	9.44E-1	1.02
60	1.38E-1	6.10	4.73	80	7.05E-3	1.15	1.16
65	1.95E-1	6.62	5.05	90	1.39E-2	1.57	1.44
70	2.65E-1	7.03	5.31	100	2.44E-2	1.97	1.69
80	4.44E-1	7.52	5.65	110	3.93E-2	2.33	1.91
90	6.69E-1	7.63	5.77	120	5.94E-2	2.64	2.09
100	9.25E-1	7.44	5.72	130	8.52E-2	2.91	2.25
110	1.19	7.06	5.57	140	1.17E-1	3.12	2.38
120	1.43	6.63	5.39	150	1.51E-1	3.27	2.47
130	1.63	6.25	5.22	160	1.99E-1	3.38	2.54
150	1.87	5.82	5.05	180	3.03E-1	3.48	2.61
160	1.91	5.74	5.02	200	4.21E-1	3.38	2.58
200	1.95	5.38	4.78	250	7.02E-1	2.92	2.40
250	1.94	4.91	4.46	275	7.98E-1	2.73	2.33
300	1.88	4.61	4.23	300	8.58E-1	2.63	2.29
350	1.80	4.37	4.02	350	9.01E-1	2.52	2.24
400	1.71	4.18	3.85	400	9.05E-1	2.44	2.18
450	1.62	4.03	3.70	450	8.92E-1	2.35	2.12
500	1.54	3.90	3.57	500	8.75E-1	2.27	2.06
550	1.45	3.80	3.46	600	8.33E-1	2.15	1.95
750	1.19	3.47	3.10	1000	6.66E-1	1.83	1.65
1000	9.77E-1	3.15	2.78	1500	4.80E-1	1.58	1.39
1500	6.61E-1	2.69	2.30	2000	3.32E-1	1.40	1.20

TABLE I. Proton Collisional Excitation Cross Sections versus Incident Energy for the Three Fine-Structure Transitions in the $(2s2p)^3P$ State of the Be-like Ions C III to Fe XXIII

See page 445 for Explanation of Tables

	Si XI				S XIII		
E(e.V)	0 - 1 (.2976)	0 - 2 (.9510)	1 - 2 (.6534)	E(e.V)	0 - 1 (.5345)	0 - 2 (1.738)	1 - 2 (1.204)
60	---	7.31E-4	7.86E-3	90	---	5.61E-5	1.17E-3
70	---	5.07E-3	2.83E-2	100	8.01E-7	3.08E-4	3.64E-3
80	3.71E-5	2.26E-2	6.90E-2	110	2.59E-6	1.48E-3	9.07E-3
90	1.15E-4	5.66E-2	1.28E-1	120	7.07E-6	3.99E-3	1.78E-2
100	2.86E-4	1.12E-1	2.01E-1	150	6.99E-5	2.91E-2	6.81E-2
120	1.16E-3	2.84E-1	3.74E-1	180	3.35E-4	9.29E-2	1.48E-1
130	2.01E-3	3.94E-1	4.65E-1	200	7.45E-4	1.57E-1	2.11E-1
140	3.26E-3	5.13E-1	5.56E-1	250	3.29E-3	3.64E-1	3.72E-1
150	4.98E-3	6.37E-1	6.44E-1	300	9.34E-3	5.83E-1	5.14E-1
180	1.40E-2	1.01	8.83E-1	350	2.04E-2	7.71E-1	6.27E-1
200	2.39E-2	1.23	1.02	450	6.12E-2	9.91E-1	7.53E-1
250	6.66E-2	1.63	1.25	500	9.02E-2	1.02	7.73E-1
300	1.36E-1	1.79	1.35	550	1.23E-1	1.01	7.73E-1
350	2.25E-1	1.76	1.35	600	1.56E-1	9.74E-1	7.59E-1
400	3.16E-1	1.63	1.30	700	2.16E-1	8.84E-1	7.24E-1
450	3.92E-1	1.50	1.25	750	2.39E-1	8.44E-1	7.08E-1
500	4.44E-1	1.41	1.21	850	2.71E-1	7.84E-1	6.84E-1
550	4.76E-1	1.35	1.18	1000	2.95E-1	7.26E-1	6.57E-1
600	4.94E-1	1.30	1.16	1100	3.01E-1	6.99E-1	6.42E-1
700	5.05E-1	1.24	1.13	1200	3.01E-1	6.77E-1	6.28E-1
800	5.02E-1	1.19	1.09	1500	2.83E-1	6.28E-1	5.89E-1
850	4.97E-1	1.17	1.08	1800	2.51E-1	5.94E-1	5.53E-1
900	4.91E-1	1.15	1.06	2000	2.26E-1	5.75E-1	5.31E-1
950	4.85E-1	1.13	1.04	2250	1.97E-1	5.53E-1	5.03E-1
1000	4.78E-1	1.11	1.03	2500	1.70E-1	5.32E-1	4.77E-1
1100	4.61E-1	1.07	9.99E-1	2800	1.41E-1	5.08E-1	4.47E-1
1200	4.43E-1	1.04	9.70E-1	3000	1.25E-1	4.92E-1	4.29E-1
1500	3.80E-1	9.73E-1	8.94E-1	3250	1.08E-1	4.73E-1	4.07E-1
2000	2.75E-1	8.82E-1	7.85E-1	3500	9.35E-2	4.55E-1	3.87E-1
2500	1.96E-1	8.02E-1	6.92E-1	4000	7.13E-2	4.21E-1	3.52E-1
				4500	5.56E-2	3.90E-1	3.21E-1

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TABLE I. Proton Collisional Excitation Cross Sections versus Incident Energy for the Three Fine-Structure Transitions in the $(2s2p)^3P$ State of the Be-like Ions C III to Fe XXIII

See page 445 for Explanation of Tables

	ArXV				Ca XVII		
E(e.V)	0 - 1	0 - 2	1 - 2	E(e.V)	0 - 1	0 - 2	1 - 2
	(.9248)	(2.998)	(2.074)		(1.364)	(4.802)	(3.438)
150	---	8.15E-5	1.35E-2	300	---	2.57E-3	1.13E-2
200	---	3.54E-3	1.65E-2	350	---	1.02E-2	2.89E-2
250	9.53E-5	2.39E-2	5.83E-2	400	---	2.66E-2	5.50E-2
300	4.30E-4	8.19E-2	1.20E-1	450	3.78E-4	5.94E-2	8.35E-2
350	1.30E-3	1.62E-1	1.90E-1	500	8.15E-4	9.60E-2	1.16E-1
400	3.05E-3	2.55E-1	2.58E-1	550	1.54E-3	1.38E-1	1.48E-1
450	6.04E-3	3.50E-1	3.19E-1	600	2.65E-3	1.82E-1	1.79E-1
500	1.06E-2	4.37E-1	3.72E-1	650	4.24E-3	2.26E-1	2.08E-1
550	1.70E-2	5.11E-1	4.15E-1	700	6.37E-3	2.68E-1	2.34E-1
600	2.53E-2	5.69E-1	4.47E-1	750	9.11E-3	3.06E-1	2.56E-1
650	3.53E-2	6.10E-1	4.70E-1	800	1.25E-2	3.40E-1	2.76E-1
700	4.75E-2	6.34E-1	4.84E-1	850	1.66E-2	3.67E-1	2.90E-1
750	6.09E-2	6.44E-1	4.91E-1	900	2.13E-2	3.89E-1	3.03E-1
800	7.50E-2	6.42E-1	4.91E-1	950	2.66E-2	4.05E-1	3.12E-1
850	8.94E-2	6.32E-1	4.88E-1	1000	3.30E-2	4.16E-1	3.18E-1
900	1.03E-1	6.17E-1	4.83E-1	1100	4.50E-2	4.24E-1	3.24E-1
1000	1.28E-1	5.83E-1	4.70E-1	1200	5.79E-2	4.19E-1	3.23E-1
1100	1.49E-1	5.50E-1	4.57E-1	1300	7.02E-2	4.08E-1	3.20E-1
1150	1.58E-1	5.35E-1	4.51E-1	1400	8.11E-2	3.94E-1	3.15E-1
1200	1.64E-1	5.22E-1	4.46E-1	1500	9.03E-2	3.80E-1	3.09E-1
1300	1.75E-1	4.99E-1	4.36E-1	1600	9.77E-2	3.67E-1	3.04E-1
1400	1.82E-1	4.81E-1	4.27E-1	1700	1.03E-1	3.55E-1	2.99E-1
1500	1.85E-1	4.65E-1	4.19E-1	1800	1.07E-1	3.44E-1	2.94E-1
1600	1.86E-1	4.52E-1	4.12E-1	2000	1.12E-1	3.26E-1	2.85E-1
1700	1.85E-1	4.41E-1	4.04E-1	2200	1.12E-1	3.11E-1	2.76E-1
1800	1.83E-1	4.32E-1	3.97E-1	2500	1.07E-1	2.94E-1	2.63E-1
2000	1.74E-1	4.15E-1	3.84E-1	3000	9.14E-2	2.71E-1	2.43E-1
3000	1.12E-1	3.57E-1	3.20E-1	4000	6.02E-2	2.36E-1	2.06E-1
4000	6.67E-2	3.11E-1	2.67E-1	5000	3.88E-2	2.07E-1	1.76E-1
5000	4.14E-2	2.71E-1	2.25E-1	7500	1.52E-2	1.55E-1	1.26E-1

TABLE I. Proton Collisional Excitation Cross Sections versus Incident Energy for the Three Fine-Structure Transitions in the $(2s2p)^3P$ State of the Be-like Ions C III to Fe XXIII

See page 445 for Explanation of Tables

Fe XXIII

E(e.V)	0 - 1	0 - 2	1 - 2
	(3.908)	(15.14)	(11.24)
600	---	2.64E-5	2.68E-4
700	---	2.48E-4	1.33E-3
800	---	1.14E-3	3.97E-3
900	---	3.39E-3	8.72E-3
1000	5.92E-5	7.64E-3	1.56E-2
1250	3.63E-4	3.22E-2	3.77E-2
1500	1.26E-3	6.51E-2	6.24E-2
1750	3.09E-3	9.81E-2	8.38E-2
2000	5.99E-3	1.24E-1	9.92E-2
2250	9.69E-3	1.40E-1	1.09E-1
2500	1.37E-2	1.48E-1	1.14E-1
2750	1.74E-2	1.50E-1	1.15E-1
3000	2.05E-2	1.48E-1	1.15E-1
3250	2.29E-2	1.45E-1	1.14E-1
3500	2.46E-2	1.41E-1	1.12E-1
4000	2.58E-2	1.33E-1	1.07E-1
4250	2.57E-2	1.28E-1	1.04E-1
4500	2.52E-2	1.24E-1	1.02E-1
4750	2.44E-2	1.20E-1	9.86E-2
5000	2.34E-2	1.16E-1	9.57E-2
5250	2.23E-2	1.12E-1	9.28E-2
5500	2.12E-2	1.08E-1	9.01E-2
5750	2.00E-2	1.05E-1	8.75E-2
6000	1.89E-2	1.02E-1	8.48E-2
8000	1.11E-2	8.13E-2	6.72E-2
10000	6.66E-3	6.73E-2	5.48E-2

TABLE II. Proton Collisional Excitation Rate Coefficients versus Temperature for the Three Fine-Structure Transitions in the $(2s2p)^3P$ State of the Be-like Ions C III to Fe XXIII

See page 445 for Explanation of Tables

C III

$\log_{10}$ T	0 - 1	0 - 2	1 - 2
4.5	4.12E-10	4.33E-9	3.42E-9
4.6	6.90E-10	5.45E-9	4.34E-9
4.7	1.06E-9	6.57E-9	5.31E-9
4.8	1.51E-9	7.63E-9	6.27E-9
4.9	2.02E-9	8.60E-9	7.22E-9
5.0	2.55E-9	9.53E-9	8.11E-9
5.1	3.08E-9	1.04E-8	8.87E-9

N IV

$\log_{10}$ T	0 - 1	0 - 2	1 - 2
4.9	3.17E-10	3.15E-9	2.51E-9
5.0	5.14E-10	3.89E-9	3.13E-9
5.1	7.68E-10	4.61E-9	3.75E-9
5.2	1.07E-9	5.28E-9	4.37E-9
5.3	1.40E-9	5.90E-9	4.96E-9
5.4	1.73E-9	6.45E-9	5.51E-9

O V

$\log_{10}$ T	0 - 1	0 - 2	1 - 2
5.1	1.34E-10	1.71E-9	1.38E-9
5.2	2.34E-10	2.22E-9	1.78E-9
5.3	3.73E-10	2.72E-9	2.20E-9
5.4	5.50E-10	3.21E-9	2.63E-9
5.5	7.55E-10	3.66E-9	3.04E-9
5.6	9.78E-10	4.07E-9	3.43E-9

F VI

$\log_{10}$ T	0 - 1	0 - 2	1 - 2
5.2	4.14E-11	8.19E-10	6.86E-10
5.3	8.31E-11	1.15E-9	9.45E-10
5.4	1.50E-10	1.52E-9	1.23E-9
5.5	2.46E-10	1.89E-9	1.54E-9
5.6	3.69E-10	2.26E-9	1.85E-9
5.7	5.15E-10	2.60E-9	2.15E-9

Ne VII

$\log_{10}$ T	0 - 1	0 - 2	1 - 2
5.5	6.76E-11	8.82E-10	7.31E-10
5.6	1.21E-10	1.16E-9	9.53E-10
5.7	1.96E-10	1.45E-9	1.19E-9
5.8	2.92E-10	1.73E-9	1.42E-9
5.9	4.05E-10	1.98E-9	1.65E-9

Mg IX

$\log_{10}$ T	0 - 1	0 - 2	1 - 2
5.8	4.27E-11	5.32E-10	4.47E-10
5.9	7.67E-11	7.11E-10	5.89E-10
6.0	1.25E-10	8.96E-10	7.41E-10
6.1	1.87E-10	1.08E-9	8.95E-10
6.2	2.58E-10	1.25E-9	1.05E-9

TABLE II. Proton Collisional Excitation Rate Coefficients versus Temperature for the Three Fine-Structure Transitions in the $(2s2p)^3P$ State of the Be-like Ions C III to Fe XXIII

See page 445 for Explanation of Tables

Si XI

$\log_{10}$ T	0 - 1	0 - 2	1 - 2
6.0	2.27E-11	3.00E-10	2.58E-10
6.1	4.30E-11	4.17E-10	3.52E-10
6.2	7.33E-11	5.44E-10	4.55E-10
6.3	1.14E-10	6.70E-10	5.61E-10
6.4	1.64E-10	7.91E-10	6.67E-10

S XIII

$\log_{10}$ T	0 - 1	0 - 2	1 - 2
6.2	1.60E-11	2.03E-10	1.77E-10
6.3	3.05E-11	3.22E-10	2.44E-10
6.4	5.24E-11	3.78E-10	3.18E-10
6.5	8.19E-11	4.69E-10	3.95E-10
6.6	1.17E-10	5.56E-10	4.72E-10

Ar XV

$\log_{10}$ T	0 - 1	0 - 2	1 - 2
6.4	1.49E-11	1.67E-10	1.48E-10
6.5	2.76E-11	2.34E-10	2.01E-10
6.6	4.58E-11	3.05E-10	2.60E-10
6.7	6.90E-11	3.77E-10	3.20E-10
6.8	9.54E-11	4.43E-10	3.78E-10

Ca XVII

$\log_{10}$ T	0 - 1	0 - 2	1 - 2
6.5	7.98E-12	1.02E-10	9.12E-11
6.6	1.55E-11	1.51E-10	1.31E-10
6.7	2.68E-11	2.07E-10	1.76E-10
6.8	4.18E-11	2.64E-10	2.23E-10
6.9	5.92E-11	3.21E-10	2.70E-10

Fe XXIII

$\log_{10}$ T	0 - 1	0 - 2	1 - 2
6.9	4.49E-12	5.76E-11	5.02E-11
7.0	7.98E-12	8.52E-11	7.23E-11
7.1	1.26E-11	1.16E-10	9.67E-11
7.2	1.80E-11	1.48E-10	1.22E-10
7.3	2.33E-11	1.76E-10	1.44E-10