FORBIDDEN TRANSITION PROBABILITIES FOR GROUND TERMS OF IONS WITH p OR p^5 CONFIGURATIONS

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Abstract. Forbidden transition probabilities are listed for ground term transitions of ions in the B I, F I, Al I and Cl I sequences. Some of these transitions remain to be observed in flares.

The isoelectronic sequences with outer configurations $2s^22p$, $2p^5$, $3s^23p$, $3p^5$ give rise to several well known coronal forbidden transitions associated with their ground term intervals. For these particular transitions the magnetic dipole transition probabilities A_m have been given but for other ions in the same sequences values of A_m are not available, nor generally are electric quadrupole transition probabilities A_q. The latter, though smaller in value than A_m, are needed for obtaining proton excitation rates from the ground level-important at higher temperatures – by the the semi-classical Coulomb excitation formula (see Landman (1973) for references) which involves the "reduced transition probability" $B(E2)$ $B(E2)=(104.1)\ (\Delta E)^{-5}\ A_q(2J_i+1)/(2J_f+1)$, where ΔE is the transition energy in electron volts and i, f refer to upper and lower levels respectively.

The quadrupole radial integral $s_q=\int R(n,l)\ R(n',l')\ r^2\,\mathrm{d}r$ required to give $A_q(i\to f)=C(l)(2J_i+1)^{-1}\ (\Delta E)^5\ s_q^2$, where $C(l=1)=0.004\,587$, was obtained by use of the Coulomb approximation tables of Oertel and Shomo (1968) as described elsewhere (Kastner and Wade, 1974).

The tables give, for each ion, the interval ΔE in electron volts, the associated wavelength λ(Å), s_q, A_q, A_m and also the ionization potential of the previous stage which is a measure of the temperature required to produce the given ion.

In Table I, for five-electron ions, it is seen that coronal lines due to five of the ions have now been observed. The most recent observation, that of Fe XXII in a flare, shows that under similar conditions the EUV lines due to Cr XX, Mn XXI and Ni XXIV are also likely to be observable. Wavelengths for these lines are taken from Kastner (1971) where an accurate value of the wavelength for Fe XXII was originally predicted. At the other extreme in Table 1, the infrared transition in Mg VIII has been observed as a coronal line. This suggests that other solar-abundant ions with low values of A_m may be observable.

The transition in S XII has been observed at 7611 Å according to Edlen (1969) so that the present value of $A_m=20.4$ differs slightly from the value 21.0 tabulated by Wiese *et al.* (1969) who used a wavelength of 7536 Å. For Si X Wiese *et al.* adopt a somewhat lower value $s_q=0.20$ than the present value 0.231,

TABLE I

B I sequence: $2p\left(\frac{3}{2}\rightarrow\frac{1}{2}\right)$

Ion	ΔE(eV)	λ(Å)	s_q	A_q (sec^{-1})	A_m (sec^{-1})	Ionization potential (eV) of previous stage
Mg VIII	0.4096	30275[a]	0.342	1.54×10^{-6}	0.324[b]	225
Si X	0.8667	14305[a]	0.231	3.00×10^{-5}	3.07[b]	351
S XII	1.6285	7611[a]	0.167	3.67×10^{-4}	20.4[b]	505
Ar XIV	2.8101	4412[a]	0.127	3.23×10^{-3}	105[b]	686
Ca XVI	(4.545)[d]	(2728)[d]	0.0994	0.0220	443	895
Ti XVIII	(6.985)[d]	(1775)[d]	0.0780	0.122	1.61×10^{3}	1131
Cr XX	(10.315)[d]	(1202)[d]	0.0658	0.579	5.18×10^{3}	1396
Mn XXI	(12.34)[d]	(1005)[d]	0.0600	1.18	8.86×10^{3}	1539
Fe XXII	14.666[c]	845.4[c]	0.0550	2.35	1.49×10^{4}	1689
Ni XXIV	(20.33)[d]	(610)[d]	0.0467	8.67	3.96×10^{4}	2010

[a] Observed; see Edlén (1969)
[b] Given earlier (Wiese *et al.*, 1969)
[c] Noyes (1973)
[d] Kastner (1971)

leading to a lower A_q. An independent calculation of s_q using Clementi wave functions verifies that the former value is too low.

In Table II, for the $2p^5$ ground configuration of the nine-electron ions, the EUV transitions in Cr XVI, Mn XVII, Fe XVIII and Ni XX are likely to be observable as coronal lines under flare conditions, especially Fe XVIII at 974.2 A.

Tables III and IV give A_m and A_q for thirteen and seventeen electron ions respectively. Because of theoretical interest in the simple one-outer-electron

TABLE II

F I sequence: $2p^5\left(\frac{1}{2}\rightarrow\frac{3}{2}\right)$

Ion	ΔE(eV)	λ(Å)	s_q	A_q (sec^{-1})	A_m (sec^{-1})	Ionization potential (eV) of previous stage
Si VI	0.6319	19620	0.276	1.77×10^{-5}	2.38[b]	167
S VIII	1.2292	10087[a]	0.196	2.77×10^{-4}	18.7[b]	280
Ar X	2.2407	5533[a]	0.146	2.76×10^{-3}	106[b]	423
Ca XII	3.7261	3327[a]	0.113	0.0210	488[b]	592
Ti XIV	5.805	2136	0.0893	0.121	1.85×10^{3}	788
Cr XVI	8.748	1417	0.0727	0.621	6.32×10^{3}	1011
Mn XVII	10.601	1170	0.0662	1.35	1.12×10^{4}	1136
Fe XVIII	12.727[c]	974.2[c]	0.0605	2.80	1.94×10^{4}	1266
Ni XX	(17.73)[d]	(699)[d]	0.0510	10.4	5.26×10^{4}	1546

[a] Observed; see Edlén (1969)
[b] Given earlier (Wiese *et al.*, 1969)
[c] Feldman *et al.* (1973)
[d] Extrapolated from data of Feldman *et al.* (1973) on F I sequence

TABLE III

Al I sequence: $3p\left(\frac{3}{2}\rightarrow\frac{1}{2}\right)$

Ion	ΔE(eV)	λ(Å)	s_q	A_q (sec^{-1})	A_m (sec^{-1})	Ionization potential (eV) of previous stage
Ca VIII	0.5339	23220	1.459	1.06×10^{-4}	0.717[b]	128
Ti X	0.9351	13260	1.030	8.70×10^{-4}	3.86	193
Cr XII	1.5205	8154[a]	0.769	5.84×10^{-3}	16.6[b]	271
Mn XIII	1.8969	6536[a]	0.675	0.0128	32.2[b]	314
Fe XIV	2.3380	5303[a]	0.598	0.0286	60.2[b]	361
Ni XVI	3.4532	3601[a]	0.479	0.129	194[b]	464
Zn XVIII	(4.8957)[c]	(2533)[c]	0.393	0.497	553	579
Ga XIX	(5.7742)[c]	(2147)[c]	0.358	0.943	908	632[d]
Ge XX	(6.766)[c]	(1830)[c]	0.328	1.74	1.46×10^{3}	696[d]

[a] Observed; see Edlén (1969)
[b] Given earlier (Wiese *et al.*, 1969)
[c] Extrapolated; see text
[d] Kastner (1969)

ions and the possibility of observing them in high temperature laboratory plasmas, it was thought useful to include elements up to germanium. Values of the ground interval were not available for elements beyond nickel; the fitted cubic formulas of Edlén (1964) for $3s^23p$ and $3p^5$ were used to obtain such values. The corresponding wavelengths should be fairly accurate. It may be noted that the temperatures required to produce such ions, even Ge XX, are no higher than the coronal temperatures that produce the observed line of Ar XIV, according to the

TABLE IV

Cl I sequence: $3p^5\left(\frac{1}{2}\rightarrow\frac{3}{2}\right)$

Ion	ΔE(eV)	λ(Å)	s_q	A_q (sec^{-1})	A_m (sec^{-1})	Ionization potential (eV) of previous stage
Ca IV	0.3862	32100	2.335	1.07×10^{-4}	0.543[c]	50.9
Ti VI	0.7222	17170	1.411	9.09×10^{-4}	3.58	99.4
Cr VIII	1.2275	10100	0.982	6.16×10^{-3}	17.5	161
Mn IX	1.5559[a]	7969[a]	0.840	0.0148	35.5	197
Fe X	1.9445	6374[b]	0.732	0.0342	69.4[c]	235
Ni XII	2.9293	4232[b]	0.568	0.160	237[c]	321
Zn XIV	(4.2397)[d]	(2924)[d]	0.458	0.658	719	412
Ga XV	(5.0371)[d]	(2461)[d]	0.414	1.27	1.21×10^{3}	—
Ge XVI	(5.941)[d]	(2087)[d]	0.375	2.39	1.98×10^{3}	532[e]

[a] Predicted by Edlén (1969)
[b] Observed
[c] Given earlier (Wiese *et al.*, 1969)
[d] Extrapolated; see text
[e] Finkelnburg and Humbach (1955)

column giving ionization potentials. The production of these ions is thus within the capability of the high power pulsed laser method, though resulting plasma densities may be too high to observe the forbidden transitions directly. The ground splittings predicted here should be of aid in analyzing the allowed spectra.

To judge the reliability of the s_q values given in Table III, the tabulated value 0.598 for Fe XIV may be compared with an accurate value of 0.551 obtained by both Froese (1957) and Steele and Trefftz (1966). (A misprint in Table XIX of Krueger and Czyzak (1964) gives s_q as 0.693 for Fe XIV; the correct value appears however in their Table XVI.) The given values of A_q may be corrected accordingly, if desired, by multiplying them by the factor 0.85. In the case of the s_q values of Table IV, independent calculations using Clementi wave functions show that they are somewhat high for Ca IV (by a factor of about 1.4) but become more accurate as Z increases, as expected with the Coulomb approximation method.

Note added in proof: In connection with the note on 'Forbidden Transition Probabilities for Ground Terms of Ions with p or p^5 Configurations', the author brings to the reader's attention an article by B. Warner in *Zeitschrift f. Astrophysik* **69** (1968), 399–402, which contains overlapping material. Warner's values for the quadrupole radial integral $I(p) \equiv s_q$ are generally somewhat lower than accurate values obtained from Clementi wave functions, while the values in the present note are somewhat higher. The term intervals given explicitly in the present note are based on more recent results than were available to Warner.

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