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Theoretical atomic structure and electron scattering data for ions in the nitrogen isoelectronic sequence: Mg VI, Si VIII, S X, A XII and Ca XIV

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Summary. Intermediate coupling energy levels, oscillator strengths and electron collision strengths have been computed for the configurations $2s^2\,2p^3$, $2s\,2p^4$ of Mg VI, Si VIII, S X, A XII and Ca XIV. The electron scattering problem was solved using the 'distorted wave' approximation. The statistical equilibrium equations for level populations were solved including all relevant excitation and de-excitation mechanisms. The level populations for the ground configuration and theoretical intensity ratios for the UV spectral lines are tabulated for conditions appropriate to the solar atmosphere.

1 Introduction

In previous papers we have tabulated new atomic data for ions in the boron and carbon iso-electronic sequences (Mg VII, Si IX and S XI – Mason & Bhatia 1978; A XIII, Ca XV, A XIV, Ca XVI – Dere *et al.* 1979). In this paper we report calculations for several ions in the nitrogen iso-electronic sequence. All these atomic data have been obtained using a computer package developed at University College, London. In Section 2 we tabulate the atomic data for Mg VI, Si VIII, S X, A XII, Ca XIV and compare our results with publications by other authors.

These calculations are useful in the analysis of solar spectra. We have discussed the theoretical and observed intensity ratios for transitions in the ground configuration in a separate paper (Feldman *et al.* 1978). Using available EUV observations from the quiet Sun and active regions, we found that the ion S X is most useful for electron density diagnostics.

Transitions between configurations $2s^2\,2p^3$ and $2s\,2p^4$ give rise to lines in the wavelength region 100–500 Å. Identifications of these lines has been made in laboratory spectra and solar spectra. We discuss the theoretical intensity ratios and line identifications in Section 3.

2 Atomic data

The configurations included in the solution of the atomic structure and electron scattering codes were $2s^2\,2p^3$, $2s\,2p^4$ and $2p^5$. Atomic data for all transitions between terms in these configurations was computed but we tabulate only the radiative and electron collisional

data within the $2s^2\,2p^3$ configuration and between the $2s^2\,2p^3$ and $2s\,2p^4$ configurations. The data connected with $2p^5$ and within $2s\,2p^4$ is available on request. The configuration interaction effects between $2s^2\,2p^3$ and $2p^5$ are fully allowed for.

2.1 ATOMIC STRUCTURE

The energy levels (Table 1) and radiative data (Tables 2(a)–(e)) were computed in intermediate coupling, allowing for spin–orbit and other relativistic effects. The Slater state expansion method was used and interaction between configurations was allowed for. The radial wavefunctions for the one electron orbitals were obtained using a Thomas–Fermi statistical model potential. The scaling parameters (λ_l) for the potential were determined by minimizing the sum of the energies of the terms in $2s^2\,2p^3$ and $2s\,2p^4$. The computer code is called SSTRUCT. The theoretical methods used are discussed in Eissner, Jones & Nussbaumer (1974). Tables 1–4 are on *Microfiche* MN 190/2.

Previous atomic structure calculations for the ions considered have been carried out by Kastner (1967), Froese (1967), Nicolaides & Beck (1973). Kastner and Froese used the Hartree–Fock program of Froese (1963). They did not allow for configuration interaction between $2s^2\,2p^3$ and $2p^5$. Froese (1967) lists multiplet oscillator strengths for only three transitions of Si VIII. Her values for $2s^2\,2p^3\,{}^2D$–$2s\,2p^4\,{}^2D$ (1.28) and $2s^2\,2p^3\,{}^2D$–$2s\,2p^4\,{}^2P$ (1.63) agree well with ours (1.27 and 1.65 respectively) but her value for $2s^2\,2p^3\,{}^4S$–$2s\,2p^4\,{}^4P$ (1.32) is very different from ours (0.86). To facilitate comparison with Kastner, we ran SSTRUCT including only the configurations $2s^2\,2p^3$ and $2s\,2p^4$. The agreement between our results and his is better than 25 per cent for all large oscillator strengths (>0.1), including the transitions $2s^2\,2p^3\,{}^4S_{3/2}$–$2s\,2p^4\,{}^4P_J$. Our wavelengths are substantially closer to the experimental values than are Kastner's. Nicolaides & Beck have also calculated oscillator strengths for Si VIII. They use wavefunctions containing all the important non-dynamical correlation effects in the non-closed shell many electron theory. Their Hartree–Fock results are in excellent agreement with our structure results, including only two configurations. Their high accuracy calculations agree to within 25 per cent with our three configuration calculations. Their wavelengths are in better agreement with the experimental values than ours. We consider our results to be adequate for calculating the theoretical intensity ratios but emphasize that more accurate results could be obtained using the atomic structure code by including a more elaborate set of correlation configurations. Forbidden transition probabilities are very sensitive to errors in energy separations. Zeippen (1977) computed the transition probabilities $A(^2D_{5/2}$–$^4S_{3/2})$ and $A(^2D_{3/2}$–$^4S_{3/2})$ in the ground configuration of O II. Using a modified form of SSTRUCT, he carried out sophisticated calculations involving configuration interaction, semi-empirical term energy corrections and optimized wavefunctions. His transition probabilities are about 15 per cent different from previous calculations. He also considered the effect of higher order terms in the magnetic dipole operator, which are usually neglected, and could be important for higher members of the nitrogen isoelectronic sequence. Kastner, Bhatia & Cohen (1977) published results for the ground configuration (and $2s^2\,2p^2\,3s$, $2s^2\,2p^2\,3d$) of Mg VI, Si VIII and S X. They used the same computer program as ourselves but for expediency they used a scaling parameter of value one for the Thomas–Fermi potential. We optimized the scaling parameter as indicated above, consequently our results are more accurate.

2.2 ELECTRON SCATTERING

The electron scattering program uses the same target wavefunctions as the atomic structure code, including configurations $2s^2\,2p^3$, $2s\,2p^4$ and $2p^5$. For low partial wave values of the incoming electron ($l \leqslant 7$) we used the program COLLDW based on the 'distorted wave'

approximation (theoretical methods discussed in Eissner & Seaton 1972). The R matrices, computed in the L–S coupling scheme, are transformed into pair coupling using algebraic re-coupling coefficients which allow for spin–orbit interaction and other relativistic effects in the target system. The program used is called JJOM (Saraph 1972). For large angular momentum values ($l > 7$) a 'Bethe' approximation code, developed by Burgess & Shoerey (1975, private communication) was used. Convergence between the 'distorted wave' and 'Bethe' results was checked by plotting the collision strengths in L–S coupling as a function of partial wave value. The final collision strengths (Ω_{ij}) are given in Tables 2(a)–(e) for three values of the energy of the incident electron appropriate to each ion. Previous calculations of electron-scattering from these ions have been published by Blaha (1969) and Davis, Kepple & Blaha (1976). Blaha only tabulated results for the transition between $2s^2\,2p^3(^2P_{1/2}$–$^2P_{3/2})$. He used a weak coupling approximation, with exchange and quotes an accuracy of a factor 2 for low z and up to 50 per cent for highly ionized atoms. His results and ours agree to 25 per cent for Mg VI and agreement for the more highly ionized atoms is even better. Davis *et al.* used a 'distorted wave' approximation to compute electron excitation rates in L–S coupling. They tabulate results for a couple of transitions in Mg VI and Si VIII and agreement with our L–S coupled results is better than 5 per cent.

3 Level populations and line intensities

The statistical equilibrium equations were solved including all relevant processes (see Mason 1975), electron excitation and de-excitation and radiative transitions. For these ions, proton excitations were found to be negligible in comparison to electron excitations (see Feldman *et al.* 1978). The level populations

$$N_i/N, \quad N = \sum_{i=1}^{5} N_i$$

for the ground configuration are given in Table 3 for each ion as a function of electron density. These values correspond to the temperature of maximum abundance ($T_{\max}$) for each ion (Jordan (1969), Mg VI – 5×10^5 K, Si VIII – 8×10^5 K, S X – 1.3×10^6 K; Storey (1975, private communication), A XII – 2.5×10^6 K, Ca XIV – 3×10^6 K). The dilution factor [$D(h)$] for the radiation field is taken as 0.5. For low electron densities the population of the ion is primarily in the ground level, but as the electron density increases, the excited levels become populated and eventually Boltzmann equilibrium is reached between all the levels in the ground configuration. The wavelength and intensity ratios of transitions within the ground configuration were discussed in Feldman *et al.* (1978) so we will discuss only the transitions between levels in configurations $2s^2\,2p^3$–$2s\,2p^4$. We note, however, that the observed EUV wavelengths for Mg VI correspond to a different energy ordering than that listed in Table 1. In particular, the positions of the $2s^2\,2p^3\,^2D_{5/2}$ and $^2D_{3/2}$ are observed to be 55 350 and 55 370 cm^{-1} respectively, above the $2s^2\,2p^3\,^4S_{3/2}$ level. These levels are very close together in both the experimental and theoretical results. The splitting of the $2s^2\,2p^3\,^2D_J$ levels for Si VIII and more highly ionized ions has a consistent energy ordering for the observed and theoretical values.

Theoretical intensity ratios for the strongest UV lines from the ions Mg VI, Si VIII, S X, A XII, Ca XIV are given in Table 4. The wavelengths are taken from Kelly & Palumbo (1973). We comment below on uncertain or new wavelengths. From Table 4 we see that the Mg VI transition $2s^2\,2p^3\,^2D_{3/2}$–$2s\,2p^4\,^2D_{3/2}$ has a strong intensity. A line is listed (by Kelly & Palumbo) at 387.787 Å as transition $2s^2\,2p^3\,^2P_{1/2}$–$2s\,2p^4\,^2D_{3/2}$, but the theoretical intensity for this transition is relatively weak. Assuming Kelly & Palumbo's identification to be correct, the predicted wavelength for the transition $2s^2\,2p^3\,^2D_{3/2}$–$2s\,2p^4\,^2D_{3/2}$ is

349.14 Å. For Si VIII, Table 4, Kelly & Palumbo list a predicted wavelength 308.26 Å for the transition $2s^2\,2p^3\,^2P_{3/2}$–$2s\,2p^4\,^2D_{5/2}$. From this we predict a wavelength of 277.11 Å for the strong transition at $2s^2\,2p^3\,^2D_{5/2}$–$2s\,2p^4\,^2D_{5/2}$. For A XII and Ca XIV, Table 4, only the six strongest transitions are listed. For A XII, Kelly & Palumbo do not list the wavelengths for transitions $2s^2\,2p^3\,^2D_{3/2}$–$2s\,2p^4\,^2D_{3/2}$ or $2s^2\,2p^3\,^2D_{5/2}$–$2s\,2p^4\,^2D_{5/2}$. Using other wavelengths listed by Kelly & Palumbo and the EUV wavelengths listed in Feldman *et al.* (1978), we predict these lines to lie at 192.44 and 193.91 Å respectively.

Some of these lines are listed in Behring *et al.* (1976). This was a full Sun rocket spectrum (160–770 Å) with a spectral resolution of 0.06 Å. With this data we expect only to observe lines which are intense for electron densities less than $10^{10}\,cm^{-3}$. For Mg VI, the only line listed is at 403.299 Å but it is blended with a Ne VI line. For Si VIII, lines are listed at 319.830 Å (22, wide line), 316.216 Å (10), 314.350 Å (6), 276.850 Å (8), 216.90 Å (5, blended) and 214.76 Å (–). The numbers in parentheses indicate the intensities as listed by Behring *et al.* We see that they are reasonably consistent with our theoretical values. The intensity of the 276.85 Å line relative to the 314.35 Å line indicates an electron density just above $10^{10}\,cm^{-3}$. For S X, Behring *et al.* list lines at 264.233 Å (20, blended), 259.494 Å (17), 257.136 Å (5), 228.167 Å (11) and 177.593 Å (–, wide line). Again the intensities are reasonably consistent with the theoretical values and the intensity of the line 228.167 Å relative to the rest indicates an electron density just above $10^{10}\,cm^{-3}$. No A XIII lines are identified by Behring *et al.*, but two Ca XIV lines are listed, 193.872 Å (–) and 185.605 Å (5). Malinovsky & Heroux (1973) also obtained a full Sun rocket spectrum (150–300 Å, spectral resolution of 0.25 Å). They observed only a few Si VIII lines at 216.9, 214.75, 235.55 Å and S X lines at 264.27 and 259.50 Å. A compilation of lines from solar flare spectra in the wavelength region 171–630 Å has recently been published by Dere (1978). These data were obtained using the Naval Research Laboratory's (NRL) spectroheliograph aboard *Skylab*. The wavelength resolution was limited by the spatial extent of the emitting region, the highest resolution being about 0.1 Å. Several of the UV lines from ions in the nitrogen isoelectronic sequence were recorded. Mg VI lines were identified at 403.32 Å (blended with Ne VI), 400.68, 399.27, 349.13, 270.34 and 269.00 Å. Most of these lines in the nitrogen isoelectronic sequence are relatively weak (compared to lines from iron ions), however, it has been possible to measure the intensity of a few of the lines for a compact intense flare – 1973 August 9, in the data from the NRL spectroheliograph. Details of these intensity measurements are given in Dere *et al.* (1979). The Mg VI intensity ratio for line 349.16 relative to 400.68 Å was measured as 4.3. This is twice as high as that predicted for the high density limit which would indicate that there is some unaccounted for blend. Several Si VIII lines are listed in Dere (1978), they are 319.84, 316.19, 314.31, 276.85, 277.04 Å (blended with Mg VII), 216.88 Å (blended with Fe XIII) and 214.77 Å. The intensity ratio for Si VIII of 277.10 relative to 316.20 Å was measured as 1.4 for the August 9 flare (Dere *et al.* 1978). This indicates an electron density of $3 \times 10^{10}\,cm^{-3}$. The S X lines identified by Dere lie at 264.24, 259.49, 228.16 and 228.70 Å. Although the intensities for these lines cannot be reliably measured, the presence of the lines at 228.16 and 228.70 Å is indicative of a high electron density. The instrument sensitivity falls very rapidly below 200 Å and we therefore do not expect to see the Ca XIV lines. If one could measure the intensity of these lines, they could be very useful for determining the electron density in solar flare conditions, where the electron density can reach values in excess of $10^{11}\,cm^{-3}$.

4 Conclusion

Our atomic structure results are in good agreement with previous publications. The amount of electron scattering data available in the literature for these systems is very sparse. In

this paper we have tabulated a comprehensive set of electron collision strengths for several ions in the nitrogen isoelectronic sequence. We used these data to compute theoretical intensity ratios for the EUV (see Feldman *et al.* 1978) and UV lines for conditions appropriate to the solar corona. We have commented on the available line identifications both in laboratory and solar spectra. Although these lines are relatively weak in the solar spectrum, some of them are potentially very useful for electron density diagnostics in different solar phenomena – coronal holes, quiet Sun, active regions and solar flares.

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Table 1

Index	Configurations	Term	J	E(cm^{-1}) MgVI	SiVIII	SX	AXII	CaXIV
1	$2s^2 2p^3$	^4S	1.5	0	0	0	0	0
2		^2D	1.5	58192	72029	85285	97597	108642
3			2.5	58196	72351	86613	101272	116780
4		^2P	0.5	82514	103847	125416	147556	170748
5			1.5	82592	104374	127280	152547	181879
6	$2s2p^4$	^4P	2.5	246690	311146	376762	444085	513787
7			1.5	248257	314588	383415	455831	533168
8			0.5	249167	316533	387030	461887	542478
9		^2D	1.5	351770	440103	530170	622911	719373
10			2.5	351800	440220	530537	623886	721656
11		^2S	0.5	409970	512310	616130	722250	831587
12		^2P	1.5	443017	548033	654192	762566	874454
13			0.5	444934	552325	662704	778054	900767

Table 2a

Transition	$\omega_i f_{ij}$	A_{ji}	Ω_{ij}		
			10 Ryd	15 Ryd	20 Ryd
1 - 2		1.45-1 †	0.1897	0.1300	0.0936
3		3.11-3	0.2188	0.1526	0.1118
4		4.92+0	0.0582	0.0371	0.0249
5		1.20+1	0.101[illegible]	0.0649	0.0439
6	0.520	3.52+9	3.0794	3.3999	3.6508
7	0.349	3.58+9	2.0408	2.2538	2.4217
8	0.175	3.62+9	1.0594	1.1556	1.2336
9		2.12+4	0.0016	0.0008	0.0005
10		2.91+3	0.0020	0.0010	0.0006
11		3.14+6	0.0003	0.0002	0.0002
12		5.62+6	0.0538	0.0394	0.0297
13		1.66+6	0.0338	0.0236	0.0173
2 - 3			0.2777	0.1944	0.1432
4		1.85+0	0.1531	0.1520	0.1521
5		2.99+0	0.1933	0.1765	0.1674
6		6.53+4	0.0136	0.0102	0.0077
7		4.29+4	0.0476	0.0337	0.0248
8		3.95+4	0.0338	0.0238	0.0175
9	0.578	8.31+9	2.6621	2.9365	3.1630
10	0.045	4.28+8	0.2477	0.2711	0.2783
11	0.007	3.09+8	0.0267	0.0304	0.0327
12	0.167	4.13+9	0.4937	0.5551	0.6042
13	0.630	3.14+10	1.8377	2.0771	2.2644

Transition	$\omega_i f_{ij}$	A_{ji}	Ω_{ij}		
			10 Ryd	15 Ryd	20 Ryd
3 - 4		7.67-2	0.1423	0.1278	0.1197
5		1.69+0	0.3746	0.3640	0.3588
6		3.47+5	0.0801	0.0601	0.0463
7		1.83+4	0.0314	0.0223	0.0166
8			0.0050	0.0034	0.0024
9	0.056	8.00+8	0.3107	0.3330	0.3423
10	0.866	8.30+9	3.8703	4.3040	4.6553
11			0.0019	0.0016	0.0013
12	1.224	3.02+10	3.6444	4.0903	4.4408
13			0.0113	0.0077	0.0057
4 - 5		4.36-6	0.1524	0.1053	0.0765
6			0.0129	0.0092	0.0069
7		1.57+3	0.0293	0.0205	0.0151
8		1.16+5	0.0204	0.0147	0.0109
9	0.091	1.10+9	0.5103	0.5467	0.5818
10			0.0201	0.0210	0.0160
11	0.199	7.10+9	0.8016	0.8891	0.9539
12	0.077	1.67+9	0.2625	0.2937	0.3167
13	0.134	5.89+9	0.4451	0.4987	0.5415
5 - 6		2.26+5	0.0530	0.0396	0.0304
7		3.57+5	0.0373	0.0269	0.0201
5 - 8		1.34+4	0.0172	0.0116	0.0085
9		8.01+7	0.0607	0.0649	0.0614
10	0.182	1.47+9	0.9751	1.0628	1.1388
11	0.350	1.25+10	1.4250	1.5569	1.6667
12	0.331	7.17+9	1.0745	1.2147	1.3214
13	0.135	5.91+9	0.4404	0.4992	0.5407

Table 2b

Transition	$\omega_i f_{ij}$	A_{ji}	Ω_{ij} 10 Ryd	15 Ryd	20 Ryd
1 - 2		1.96+0	0.1505	0.1142	0.0890
3		3.75-2	0.1759	0.1351	0.1066
4		2.99+1	0.0483	0.0347	0.0258
5		7.12+1	0.0845	0.0612	0.0456
6	0.436	4.70+9	2.0657	2.2444	2.3893
7	0.294	4.85+9	1.3647	1.4829	1.5795
8	0.148	4.95+9	0.7100	0.7628	0.8070
9		1.77+5	0.0011	0.0007	0.0005
10		2.73+4	0.0013	0.0008	0.0005
11		1.12+7	0.0006	0.0005	0.0005
12		2.22+7	0.0403	0.0325	0.0265
13		6.18+6	0.0247	0.0192	0.0152
2 - 3		3.54-4	0.2191	0.1691	0.1343
4		1.14+1	0.1044	0.1023	0.1016
5		1.90+1	0.1331	0.1214	0.1142
6		3.99+5	0.0131	0.0105	0.0086
7		1.07+5	0.0351	0.0273	0.0217
8		2.16+5	0.0242	0.0187	0.0149
9	0.493	1.11+10	1.8387	2.0011	2.1324
10	0.029	4.30+8	0.1504	0.1515	0.1526
11	0.019	1.21+9	0.0549	0.0596	0.0634
12	0.155	5.84+9	0.3833	0.4224	0.4537
13	0.484	3.72+10	1.1888	1.3085	1.4053

Transition	$\omega_i f_{ij}$	A_{ji}	Ω_{ij} 10 Ryd	15 Ryd	20 Ryd
3 - 4		1.19-1	0.1017	0.0921	0.0860
5		1.05+1	0.2573	0.2482	0.2432
6		1.49+6	0.0596	0.0489	0.0405
7		8.65+4	0.0235	0.0185	0.0149
8			0.0037	0.0028	0.0022
9	0.042	9.55+8	0.2085	0.2118	0.2155
10	0.722	1.09+10	2.6137	2.8609	3.0615
11			0.0010	0.0008	0.0007
12	1.013	3.82+10	2.5565	2.7948	2.9905
13			0.0079	0.0061	0.0048
4 - 5		1.29-3	0.1196	0.0915	0.0720
6			0.0090	0.0072	0.0058
7		7.05+3	0.0217	0.0168	0.0133
8		5.15+5	0.0161	0.0125	0.0100
9	0.076	1.43+9	0.3438	0.3688	0.3888
10			0.0207	0.0167	0.0136
11	0.175	9.72+9	0.5864	0.6352	0.6737
12	0.067	2.19+9	0.1935	0.2110	0.2248
13	0.102	6.86+9	0.2828	0.3120	0.3346
5 - 6		8.34+5	0.0370	0.0302	0.0249
7		1.48+6	0.0298	0.0236	0.0191
8		3.47+4	0.0139	0.0108	0.0086
5 - 9	0.002	3.50+7	0.0343	0.0298	0.0265
10	0.162	2.03+9	0.6995	0.7582	0.8054
11	0.267	1.48+10	0.9037	0.9711	1.0265
12	0.255	8.38+9	0.7031	0.7751	0.8318
13	0.157	1.05+10	0.4367	0.4781	0.5114

Table 2c

Transition	$\omega_i f_{ij}$	A_{ji}	Ω_{ij} 15 Ryd	20 Ryd	30 Ryd
1 - 2		1.78+1	0.0946	0.0781	0.0555
3		3.44-1	0.1137	0.0947	0.0685
4		1.35+2	0.0303	0.0241	0.0159
5		3.06+2	0.0536	0.0428	0.0286
6	0.376	5.93+9	1.5942	1.6837	1.8339
7	0.255	6.26+9	1.0500	1.1096	1.2101
8	0.129	6.46+9	0.5417	0.5688	0.6157
9		1.27+6	0.0007	0.0005	0.0003
10		1.44+5	0.0006	0.0004	0.0002
11		3.18+7	0.0010	0.0009	0.0007
12		7.13+7	0.0268	0.0230	0.0174
13		1.78+7	0.0148	0.0124	0.0090
2 - 3		2.42-2	0.1403	0.1179	0.0870
4		5.10+1	0.0745	0.0733	0.0724
5		9.13+1	0.0865	0.0810	0.0742
6		1.96+6	0.0110	0.0095	0.0073
7		1.18+5	0.0212	0.0178	0.0129
8		9.62+5	0.0138	0.0116	0.0084
9	0.435	1.44+10	1.4668	1.5484	1.6859
10	0.016	3.59+8	0.0833	0.0825	0.0818
11	0.038	3.55+9	0.1002	0.1056	0.1147
12	0.149	8.02+9	0.3457	0.3669	0.4021
13	0.366	4.07+10	0.8390	0.8894	0.9743

Transition	$\omega_i f_{ij}$	A_{ji}	Ω_{ij} 15 Ryd	20 Ryd	30 Ryd
3 - 4		1.67-1	0.0696	0.0653	0.0600
5		4.81+1	0.1810	0.1764	0.1713
6		4.93+6	0.0395	0.0344	0.0264
7		3.21+5	0.0149	0.0126	0.0093
8			0.0022	0.0018	0.0013
9	0.0031	1.03+9	0.1378	0.1390	0.1424
10	0.621	1.36+10	2.0449	2.1671	2.3719
11			0.0005	0.0005	0.0004
12	0.869	4.67+10	2.0514	2.1685	2.3682
13			0.0046	0.0038	0.0028
4 - 5		5.55-2	0.0750	0.0626	0.0455
6			0.0054	0.0046	0.0034
7		2.52+4	0.0133	0.0111	0.0080
8		1.84+6	0.0105	0.0088	0.0064
9	0.065	1.77+9	0.2633	0.2754	0.2961
10			0.0131	0.0112	0.0084
11	0.161	1.29+10	0.4957	0.5206	0.5625
12	0.060	2.79+9	0.1632	0.1718	0.1862
13	0.076	7.32+9	0.1972	0.2090	0.2283
5 - 6		2.36+6	0.0221	0.0192	0.0147
7		4.84+6	0.0207	0.0177	0.0132
8		5.69+4	0.0099	0.0084	0.0061
9		3.14+5	0.0166	0.0142	0.0106
5 - 10	0.149	2.68+9	0.5801	0.6114	0.6637
11	0.197	1.57+10	0.6106	0.6387	0.6874
12	0.196	9.08+9	0.5127	0.5435	0.5947
13	0.191	1.83+10	0.4955	0.5240	0.5718

Table 2d

Transition	$\omega_i f_{ij}$	A_{ji}	Ω_{ij} 15 Ryd	30 Ryd	45 Ryd
1 - 2		1.13+2	0.0774	0.0507	0.0355
3		2.49+0	0.0944	0.0631	0.0450
4		4.94+2	0.0260	0.0156	0.0101
5		1.04+3	0.0453	0.0275	0.0180
6	0.331	7.25+9	1.1893	1.3500	1.4689
7	0.227	7.85+9	0.7808	0.8879	0.9679
8	0.116	8.22+9	0.4040	0.4536	0.4915
9		7.46+6	0.0009	0.0005	0.0004
10		5.56+5	0.0004	0.0002	0.0001
11		7.81+7	0.0018	0.0013	0.0010
12	0.002	1.98+8	0.0230	0.0166	0.0125
13		4.17+7	0.0112	0.0076	0.0054
2 - 3		4.92-1	0.1149	0.0796	0.0594
4		1.81+2	0.0572	0.0545	0.0535
5		3.70+2	0.0630	0.0531	0.0480
6		8.10+6	0.0122	0.0089	0.0068
7		3.07+3	0.0164	0.0111	0.0079
8		3.69+6	0.0100	0.0068	0.0049
9	0.392	1.80+10	1.1251	1.2727	1.3847
10	0.008	2.41+8	0.0444	0.0414	0.0396
11	0.062	8.11+9	0.1419	0.1604	0.1743
12	0.143	1.06+10	0.2896	0.3306	0.3615
13	0.266	4.11+10	0.5267	0.5987	0.6538

Transition	$\omega_i f_{ij}$	A_{ij}	Ω_{ij} 15 Ryd	30 Ryd	45 Ryd
3 - 4		2.23-1	0.0543	0.0473	0.0438
5		1.79+2	0.1379	0.1289	0.1247
6		1.37+7	0.0327	0.0241	0.0183
7		1.02+6	0.0120	0.0084	0.0060
8			0.0018	0.0012	0.0008
9	0.022	1.01+9	0.0885	0.0894	0.0913
10	0.547	1.66+10	1.5353	1.7516	1.9151
11			0.0004	0.0003	0.0002
12	0.764	5.57+10	1.5789	1.7866	1.9485
13			0.0035	0.0023	0.0016
4 - 5		1.02+0	0.0601	0.0410	0.0301
6			0.0040	0.0028	0.0020
7		7.75+4	0.0104	0.0070	0.0050
8		5.69+6	0.0090	0.0062	0.0045
9	0.056	2.10+9	0.1942	0.2156	0.2321
10			0.0104	0.0073	0.0054
11	0.153	1.69+10	0.4079	0.4558	0.4919
12	0.056	3.53+9	0.1335	0.1498	0.1621
13	0.055	7.24+9	0.1223	0.1392	0.1515
5 - 6		5.32+6	0.0162	0.0118	0.0090
7		1.31+7	0.0188	0.0133	0.0100
8		4.18+4	0.0091	0.0062	0.0044
9		4.30+7	0.0170	0.0139	0.0118
5 - 10	0.138	3.40+9	0.4623	0.5219	0.5665
11	0.135	1.47+10	0.3686	0.4069	0.4375
12	0.150	9.32+9	0.3462	0.3936	0.4293
13	0.230	2.99+10	0.5173	0.5859	0.6382

Table 2e

Transition	$\omega_i f_{ij}$	A_{ij}	Ω_{ij} 15 Ryd	30 Ryd	45 Ryd
1 - 2		5.28+2	0.0643	0.0457	0.0340
3		1.47+1	0.0785	0.0568	0.0430
4		1.57+3	0.0224	0.0148	0.0103
5		2.91+3	0.0372	0.0250	0.0176
6	0.295	8.65+9	0.9188	1.0289	1.1140
7	0.205	9.72+9	0.6020	0.6753	0.7327
8	0.106	1.04+10	0.3130	0.3470	0.3743
9		3.67+7	0.0015	0.0011	0.0009
10		1.72+6	0.0003	0.0002	0.0001
11		1.78+8	0.0026	0.0021	0.0017
12	0.004	4.93+8	0.0217	0.0185	0.0162
13		7.95+7	0.0082	0.0060	0.0046
2 - 3		5.07+0	0.0943	0.0708	0.0561
4		5.33+2	0.0456	0.0427	0.0414
5		1.35+3	0.0476	0.0396	0.0349
6		2.87+7	0.0143	0.0113	0.0092
7		6.71+5	0.0131	0.0096	0.0073
8		1.27+7	0.0075	0.0055	0.0042
9	0.361	2.25+10	0.8940	0.9966	1.0780
10	0.003	1.20+8	0.0223	0.0175	0.0141
11	0.087	1.51+10	0.1731	0.1915	0.2065
12	0.134	1.31+10	0.2359	0.2682	0.2913
13	0.186	3.88+10	0.3209	0.3576	0.3871

Transition	$\omega_i f_{ij}$	A_{ji}	Ω_{ij} 15 Ryd	30 Ryd	45 Ryd
3 - 4		2.87-1	0.0434	0.0383	0.0355
5		5.73+2	0.1084	0.1004	0.0962
6		3.30+7	0.0285	0.0225	0.0181
7		2.91+6	0.0099	0.0074	0.0057
8			0.0014	0.0010	0.0008
9	0.014	8.73+8	0.0551	0.0543	0.0545
10	0.490	1.99+10	1.1946	1.3416	1.4580
11			0.0005	0.0003	0.0002
12	0.687	6.58+10	1.2597	1.4010	1.5163
13			0.0026	0.0019	0.0014
4 - 5		1.07+1	0.0480	0.0357	0.0280
6			0.0029	0.0022	0.0017
7		2.16+5	0.0082	0.0060	0.0045
8		1.59+7	0.0081	0.0061	0.0047
9	0.048	2.42+9	0.1461	0.1604	0.1717
10			0.0084	0.0064	0.0049
11	0.148	2.15+10	0.3459	0.3812	0.4088
12	0.054	4.45+9	0.1142	0.1302	0.1357
13	0.038	6.75+9	0.0741	0.0829	0.0898
5 - 6		9.92+6	0.0121	0.0095	0.0076
7		3.03+7	0.0177	0.0136	0.0108
8		3.47+2	0.0080	0.0059	0.0045
9	0.004	2.01+8	0.0197	0.0157	0.0129
5 - 10	0.128	4.13+9	0.3773	0.4204	0.4539
11	0.085	1.19+10	0.2091	0.2265	0.2412
12	0.116	9.28+9	0.2409	0.2692	0.2913
13	0.261	4.51+10	0.5212	0.5802	0.6272

Table 3

Ion	i	N_i/N for N_e (cm^{-3}) = 10^8	10^9	10^{10}	10^{11}	10^{12}
MgVI	1	0.62	0.50	0.35	0.29	0.29
	2	0.15	0.19	0.20	0.20	0.20
	3	0.22	0.24	0.28	0.29	0.29
	4	0.50-2	0.31-1	0.65-1	0.75-1	0.76-1
	5	0.42-2	0.36-1	0.12	0.15	0.15
SiVIII	1	0.84	0.70	0.54	0.35	0.29
	2	0.22-1	0.10	0.17	0.19	0.20
	3	0.14	0.19	0.23	0.27	0.29
	4	0.32-3	0.41-2	0.29-1	0.64-1	0.75-1
	5	0.30-3	0.37-2	0.34-1	0.12	0.15
SX	1	0.96	0.87	0.75	0.55	0.34
	2	0.13-2	0.13-1	0.78-1	0.16	0.19
	3	0.43-1	0.17	0.16	0.22	0.28
	4	0.31-4	0.37-3	0.48-2	0.32-1	0.66-1
	5	0.27-4	0.38-3	0.48-2	0.43-1	0.12
AXII	1	0.99	0.96	0.88	0.74	0.50
	2	0.14-3	0.14-2	0.14-1	0.78-1	0.16
	3	0.44-2	0.34-1	0.11	0.16	0.23
	4	0.51-5	0.55-4	0.66-3	0.79-2	0.42-1
	5	0.41-5	0.48-4	0.66-3	0.85-2	0.65-1
CaXIV	1	1.0	1.0	0.96	0.86	0.68
	2	0.24-4	0.24-3	0.24-2	0.21-1	0.10
	3	0.53-3	0.51-2	0.39-1	0.12	0.19
	4	0.12-5	0.13-4	0.14-3	0.16-2	0.17-1
	5	0.96-6	0.99-5	0.12-3	0.17-2	0.20-1

Table 4

Ion	Transition i	Transition j	Theoretical intensity ratios relative to transition 1-6 for $N_e(cm^{-3})$ = 10^8	10^9	10^{10}	10^{11}	10^{12}	λ(A) Kelly and Palumbo (1973)
MgVI	1	6	1.0	1.0	1.0	1.0	1.0	403.315
	1	7	0.67	0.67	0.67	0.67	0.67	400.676
	1	8	0.35	0.35	0.35	0.35	0.35	399.289
	2	9	0.19	0.32	0.50	0.60	0.62	349.14 *
	3	9	0.02	0.03	0.05	0.06	0.06	
	4	9	0.02	0.04	0.06	0.07	0.08	387.787
	2	10	0.01	0.02	0.04	0.04	0.05	
	3	10	0.26	0.39	0.68	0.85	0.88	349.155
	5	10	0.04	0.06	0.11	0.14	0.14	388.020
	4	11	0.00	0.03	0.11	0.14	0.14	314.554
	5	11	0.01	0.05	0.17	0.24	0.25	314.676
	2	12	0.03	0.05	0.09	0.11	0.11	
	3	12	0.25	0.36	0.64	0.80	0.83	270.394
	4	12	0.01	0.02	0.03	0.04	0.04	293.026
	5	12	0.05	0.08	0.14	0.18	0.18	293.124
	2	13	0.12	0.20	0.34	0.42	0.43	268.986
	4	13	0.02	0.04	0.06	0.07	0.08	291.348
	5	13	0.02	0.04	0.06	0.07	0.08	291.458
SiVIII	1	6	1.0	1.0	1.0	1.0	1.0	319.829
	1	7	0.66	0.66	0.66	0.67	0.67	316.202
	1	8	0.34	0.34	0.34	0.34	0.34	314.31
	2	9	0.02	0.08	0.19	0.42	0.58	276.839
	3	10	0.12	0.18	0.29	0.60	0.84	277.10 *
	5	10	0.02	0.03	0.05	0.10	0.14	308.26P
	4	11	0.00	0.00	0.02	0.09	0.14	250.45
	5	11	0.00	0.00	0.03	0.14	0.22	250.79
	2	12	0.02	0.03	0.05	0.10	0.13	216.80
	3	12	0.13	0.18	0.29	0.61	0.85	216.918
	5	12	0.03	0.04	0.06	0.13	0.17	235.563
	2	13	0.01	0.04	0.12	0.28	0.40	214.756
	5	13	0.00	0.01	0.03	0.07	0.10	233.159

Ion	Transition i	Transition j	Theoretical intensity ratios relative to transition 1-6 for $N_e(cm^{-3})$ = 10^8	10^9	10^{10}	10^{11}	10^{12}	λ(A) Kelly and Palumbo (1973)
SX	1	6	1.0	1.0	1.0	1.0	1.0	264.24
	1	7	0.66	0.66	0.67	0.67	0.67	259.52
	1	8	0.35	0.35	0.35	0.35	0.35	257.16
	2	9	0.00	0.02	0.11	0.31	0.60	228.18
	3	10	0.04	0.11	0.20	0.38	0.79	228.70
	5	10	0.01	0.02	0.04	0.07	0.14	255.08
	4	11	0.00	0.00	0.01	0.04	0.14	207.53
	5	11	0.00	0.00	0.01	0.05	0.17	208.33
	2	12	0.01	0.02	0.04	0.08	0.15	180.36
	3	12	0.05	0.13	0.22	0.44	0.88	180.72
	5	12	0.01	0.02	0.04	0.08	0.16	196.83
	2	13	0.01	0.01	0.06	0.17	0.37	177.55
AXII	1	6	1.0	1.0	1.0	1.0	1.0	224.25
	1	7	0.67	0.67	0.67	0.67	0.67	218.29
	1	8	0.35	0.35	0.35	0.35	0.35	215.49
	2	9	0.00	0.00	0.02	0.11	0.34	192.44 *
	3	10	0.00	0.03	0.10	0.18	0.43	193.91 *
	3	12	0.02	0.04	0.12	0.23	0.52	154.43
CaXIV	1	6	1.0	1.0	1.0	1.0	1.0	193.88
	1	7	0.68	0.68	0.68	0.68	0.68	186.02
	1	8	0.36	0.36	0.36	0.36	0.36	183.46
	2	9	0.00	0.00	0.00	0.03	0.16	165.36
	3	10	0.00	0.00	0.03	0.11	0.24	167.00
	3	12	0.02	0.02	0.05	0.14	0.30	134.30