ASTRONOMY & ASTROPHYSICS
SUPPLEMENT SERIES

Astron. Astrophys. Suppl. Ser. **114,** 367-371 (1995)

Atomic data from the IRON Project. XII. Electron excitation of forbidden transitions in V-like ions Mn III, Fe IV, Co V and Ni VI

K.A. Berrington and J.C. Pelan

Department of Applied Mathematics & Theoretical Physics, The Queen's University, Belfast, BT7 1NN, UK

Received April 4; accepted May 12, 1995

Abstract. — Electron excitation collision strengths for fine-structure transitions involving the four lowest $3d^5$ terms (^6S, ^4G, ^4P, ^4D) in vanadium-like ions Mn III, Fe IV, Co V and Ni VI are calculated using R-matrix techniques. All five sextet and quartet $3d^5$ target terms are included in the expansion of the total wavefunction. Fine-structure collision strengths are obtained from an algebraic transformation of the reactance matrices. These collision strengths are then averaged over a Maxwellian velocity distribution to obtain effective collision strengths as a function of electron temperature. To our knowledge, these are the first published data for these processes.

Key words: atomic data

1. Introduction

New astronomical observations are revealing the presence of trace metals in many types of astronomical objects. For example, high-dispersion IUE observations of the brightest of the hot stars showed absorption features from photospheric Fe and Ni (Holberg et al. 1994); identifications included V-like Fe IV, and Ni became the second iron group element to be positively identified in the photospheres of the hot DA white dwarfs. Adelman et al. (1993) have analysed the abundances of elements such as Cr, Mn, Fe, Co and Ni in early type stars from IUE high-dispersion spectrograms. Ruiz-Lapuente (1994) reviewed observations of Type Ia supernovae at late phases, which cover from the UV up to the infrared: calculations of spectra of different Type Ia models have shown the need for further computations of collision strengths for forbidden transitions of Fe I–V and Ci I–V ions. In SN 1992A, among the identified forbidden transitions giving rise to UV emission lines in the HST spectra are the following V-like ions (Ruiz-Lapuente et al. 1994):

Fe IV	$^6S-^4D$	λ 2567
Fe IV	$^6S-^4P$	λ 2836, 2829
Mn III	$^6S-^4D$	λ 3087, 3094

The only available collision strengths in the literature for V-like ions appear to be some unpublished results on Fe IV by one of the present authors (Berrington), and these are referred to by Ruiz-Lapuente (1994) and in the bibliography survey by Pradhan & Gallagher (1992). These earlier collision strengths were calculated as a by-product of an 'Opacity Project' calculation (Sawey & Berrington 1992), and are in LS-coupling. The purpose of the present paper is to extend these calculations to other V-like ions and to calculate also for fine-structure transitions.

This work is part of an international collaboration known as the IRON Project (Hummer et al. 1993, referred to as Paper I) to obtain accurate collision rates for fine-structure transitions. Other papers in the IRON project series include: the calculation of effective collision strengths for infrared transitions in C-like ions (Lennon & Burke 1994, Paper II), B-like ions (Zhang et al. 1994, Paper III), F-like ions (Saraph & Tully 1994, Paper IV), O-like ions (Butler & Zeippen 1994, Paper V), Fe II (Zhang & Pradhan 1994, Paper VI); radiative transition probabilities for Fe II (Nahar 1994, Paper VII); fine-structure electron excitation of Ti-like ions (Berrington 1995, Paper VIII), Cl-like ions (Pelan & Berrington 1995, Paper IX), Si-like and S-like ions (Galavis et al. 1995, Paper X), and some Al-like ions (Saraph & Storey 1995, Paper XI).

2. The calculation

The basic atomic theory, the approximations and the computer codes employed in the IRON Project are described in Paper I.

The calculation was carried out in LS coupling; collision strengths for fine-structure transitions were obtained

using an algebraic transformation to intermediate coupling, as described in Sect. 2.6 of Paper I; the so-called JAJOM approach (Saraph 1978). This procedure makes no allowance for the fine-structure splitting of the terms. However, the ^{6}S ground state is not split by fine-structure, so the approximation should give good results for excitation from the ground state.

In this calculation, all five LS sextet and quartet terms (^{6}S, ^{4}G, ^{4}P, ^{4}D and ^{4}F) associated with the $1s^2 2s^2 2p^6 3s^2 3p^6 3d^5$ configuration are included in the target expansion, (cf. the corresponding Opacity Project calculation (Sawey & Berrington 1992)). The target wavefunctions were constructed from 1s, 2s, 2p, 3s, 3p and 3d orbitals as given by Clementi & Roetti (1974).

A refinement on the Sawey and Berrington calculation is that the $3d^5$ target terms were represented by configuration-interaction (CI) wavefunctions which included correlation mixing from the 3p subshell, $3p^4 3d^7$, which improved the target term energy splitting relative to experiment: see Table 1 for details. The theoretical term energies thus obtained were used in the calculation without further adjustment, partly because of experimental uncertainties in in the energies for some of the states (see also discussion Sect. 4). To be consistent with the CI target term description, configurations of the type $3p^6 3d^6$ and $3p^4 3d^8$ were included in the collisional wavefunction.

Table 1. Term energies for the $3d^5$ states included in the R-matrix calculation for V-like ions, in Rydberg units. The first row for each ion contains theoretical energies for the single-configuration wavefunction; the second row contains energies for the CI wavefunction actually used in the collision calculation; the third row is from the following tabulations: (1) Corliss & Sugar (1975), (2) Corliss & Sugar (1977), (3) Kelly (1987), (4) Corliss & Sugar (1981)

	^{6}S	^{4}G	^{4}P	^{4}D	^{4}F
Mn III					
$3d^5$	.0	.297	.343	.370	.499
$+3p^4 3d^7$	.0	.303	.310	.359	.477
(1)	.0	.245	.266	.295	.398
Fe IV					
$3d^5$	.0	.346	.400	.430	.580
$+3p^4 3d^7$	.0	.352	.362	.417	.555
(2)	.0	.294	.322	.354	.481
Co V					
$3d^5$	.0	.391	.452	.486	.656
$+3p^4 3d^7$	.0	.397	.411	.472	.628
(3)	.0	.340	.373	.409	.557
Ni VI					
$3d^5$	.0	.434	.502	.539	.727
$+3p^4 3d^7$	.0	.440	.459	.524	.698
(4)	.0	.383	.420	.461	.626

3. Results

Collision strengths were computed for each ion for the required transitions over a sufficiently wide and fine energy mesh, in order to be able to integrate over a Maxwellian distribution to obtain the *effective collision strength*, from which the excitation and de-excitation rate coefficients can easily be obtained (Paper I).

Table 2 contains the effective collision strengths (Υ) for the excitation from the ^{6}S ground state to the ^{4}G, ^{4}P and ^{4}D terms. To a good approximation, collision strengths to the fine-structure levels in the final states are in statistical ratio, and may be obtained from the $\Upsilon(^6\mathrm{S}\rightarrow{}^4\mathrm{L})$ values in Table 1:

$$\Upsilon(^6\mathrm{S}_{5/2} \rightarrow {}^4\mathrm{L}_J) = \frac{2J+1}{4(2L+1)}\Upsilon(^6\mathrm{S} \rightarrow {}^4\mathrm{L}) \qquad (1)$$

where $L = 4$, 1 and 2 for the ^{4}G, ^{4}P and ^{4}D terms respectively. Note that collision strengths involving the ^{4}F term are not tabulated as this is the highest energy term included in the expansion of the total wavefunction and lies above some omitted doublet terms.

Tables 4 to 7 are tabulations of Υ for each fine-structure transition involving the ^{4}G, ^{4}P and ^{4}D of each ion. The range of temperatures chosen for each ion was $\pm$ 1.0 dex of the temperature of maximum ionic abundance given by Shull & Van Steenberg (1982).

Table 3. Key to the J level numbering scheme

LS term	J level ; Label			
^{6}S	$\frac{5}{2}$; 1			
^{4}G	$\frac{5}{2}$; 2	$\frac{7}{2}$; 3	$\frac{9}{2}$; 4	$\frac{11}{2}$; 5
^{4}P	$\frac{1}{2}$; 6	$\frac{3}{2}$; 7	$\frac{5}{2}$; 8	
^{4}D	$\frac{1}{2}$; 9	$\frac{3}{2}$; 10	$\frac{5}{2}$; 11	$\frac{7}{2}$; 12

4. Discussion

Collision strengths have been calculated using R-matrix techniques for excitation from the $3d^5$ ^{6}S ground state to the ^{4}G, ^{4}P and ^{4}D metastable terms, and for fine-structure transitions involving the $3d^5$ ^{4}G, ^{4}P and ^{4}D terms in V-like ions. These appear to be the first such data in the literature, so it is not possible to compare against other workers. However, it is known from other R-matrix calculations on other ions that the method should be reliable, particularly at low energies and temperatures. The most serious limitation of the present work is the omission of any effects due to doublet target states associated with the $3d^5$ configuration, and with states above the $3d^5$ manifold. States such as $3d^4$ 4s and $3d^4$ 4p will give resonance structures below their thresholds, and at higher energies channel coupling effects, particularly with the odd-parity 4p states, would

Table 2. Effective collision strengths for $3d^5\ ^6S \rightarrow\ ^4G$, ^4P, and ^4D transitions in V-like ions. The row containing the ion symbol indicates the values of log T (Kelvin) for that ion. The left-hand column indicates the initial and final terms

Mn III	3.4	3.6	3.8	4.0	4.2	4.4	4.6	4.8	5.0	5.2	5.4
$^6S-^4G$	3.26	3.29	3.26	3.18	3.08	2.99	2.93	2.89	2.87	2.83	2.73
$^6S-^4P$	1.14	1.17	1.15	1.10	1.04	0.98	0.94	0.91	0.89	0.89	0.87
$^6S-^4D$	1.49	1.51	1.51	1.51	1.50	1.49	1.50	1.51	1.53	1.55	1.54
Fe IV	3.6	3.8	4.0	4.2	4.4	4.6	4.8	5.0	5.2	5.4	5.6
$^6S-^4G$	3.22	3.10	2.94	2.76	2.60	2.48	2.39	2.32	2.26	2.17	2.03
$^6S-^4P$	0.91	0.92	0.90	0.86	0.81	0.77	0.75	0.73	0.73	0.73	0.71
$^6S-^4D$	1.30	1.29	1.28	1.26	1.25	1.25	1.25	1.25	1.26	1.26	1.24
Co V	3.8	4.0	4.2	4.4	4.6	4.8	5.0	5.2	5.4	5.6	5.8
$^6S-^4G$	2.71	2.53	2.36	2.21	2.09	1.99	1.92	1.85	1.77	1.66	1.50
$^6S-^4P$	0.81	0.80	0.77	0.74	0.70	0.68	0.66	0.65	0.64	0.63	0.59
$^6S-^4D$	1.12	1.12	1.11	1.10	1.10	1.09	1.10	1.10	1.09	1.07	1.01
Ni VI	4.0	4.2	4.4	4.6	4.8	5.0	5.2	5.4	5.6	5.8	6.0
$^6S-^4G$	1.93	1.85	1.76	1.69	1.62	1.57	1.52	1.46	1.37	1.26	1.11
$^6S-^4P$	0.76	0.72	0.67	0.64	0.61	0.60	0.59	0.58	0.57	0.53	0.48
$^6S-^4D$	1.00	1.00	0.99	0.98	0.98	0.98	0.98	0.97	0.95	0.90	0.82

Table 4. Effective collision strengths (Υ) for fine-structure transitions involving the ^4G, ^4P and ^4D terms in Mn III. The row containing the ion symbol denotes the values of log T (Kelvin) while the initial and final J levels are labelled as in Table 3. We use the notation $x \pm n$ to indicate the number $x \times 10^{\pm n}$

Mn III	3.4	4.4	5.4	Mn III	3.4	4.4	5.4	Mn III	3.4	4.4	5.4
2- 3	2.69+0	2.34+0	1.70+0	4- 5	3.56+0	2.92+0	2.28+0	6-11	2.34−1	2.15−1	3.48−1
2- 4	5.43−1	4.03−1	2.49−1	4- 6	3.36−1	2.45−1	2.15−1	6-12	1.90−1	1.53−1	9.82−2
2- 5	7.40−2	4.66−2	2.66−2	4- 7	2.82−1	1.81−1	9.35−2	7- 8	9.38−1	8.04−1	5.76−1
2- 6	1.71−1	1.05−1	4.88−2	4- 8	7.95−1	5.51−1	5.19−1	7- 9	1.72−1	1.56−1	2.47−1
2- 7	4.87−1	3.35−1	2.47−1	4- 9	2.77−1	2.76−1	2.14−1	7-10	2.92−1	2.63−1	3.21−1
2- 8	1.89−1	1.15−1	8.77−2	4-10	4.76−1	4.44−1	3.30−1	7-11	3.63−1	3.07−1	2.21−1
2- 9	2.98−1	2.81−1	2.09−1	4-11	7.87−1	7.52−1	5.75−1	7-12	5.05−1	4.51−1	6.23−1
2-10	4.84−1	4.72−1	3.52−1	4-12	1.11+0	1.08+0	8.71−1	8- 9	1.50−1	1.17−1	9.21−2
2-11	5.50−1	5.49−1	4.19−1	5- 6	3.74−2	1.74−2	6.56−3	8-10	3.43−1	2.81−1	3.13−1
2-12	2.58−1	2.55−1	2.00−1	5- 7	5.53−1	4.07−1	4.07−1	8-11	6.01−1	5.22−1	7.26−1
3- 4	3.37+0	2.94+0	2.20+0	5- 8	1.11+0	7.98−1	7.88−1	8-12	9.03−1	8.64−1	1.30+0
3- 5	5.26−1	3.73−1	2.50−1	5- 9	8.56−2	8.31−2	6.54−2	9-10	6.95−1	6.62−1	5.42−1
3- 6	3.03−1	2.12−1	1.53−1	5-10	3.51−1	3.35−1	2.63−1	9-11	1.57−1	1.41−1	9.98−2
3- 7	3.72−1	2.45−1	1.62−1	5-11	8.91−1	8.22−1	6.39−1	9-12	1.18−1	1.02−1	6.96−2
3- 8	4.54−1	3.01−1	2.61−1	5-12	1.85+0	1.77+0	1.49+0	10-11	1.09+0	1.03+0	8.27−1
3- 9	2.93−1	2.79−1	2.06−1	6- 7	5.14−1	4.58−1	3.48−1	10-12	2.88−1	2.44−1	1.68−1
3-10	5.96−1	5.77−1	4.39−1	6- 8	2.99−1	2.35−1	1.47−1	11-12	1.20+0	1.08+0	8.40−1
3-11	6.33−1	6.17−1	4.66−1	6- 9	7.78−2	7.60−2	6.04−2				
3-12	5.97−1	5.90−1	4.69−1	6-10	1.65−1	1.47−1	1.79−1				

Table 5. Effective collision strengths (Υ) for fine-structure transitions involving the ^{4}G, ^{4}P and ^{4}D terms in Fe IV. The row containing the ion symbol denotes the values of log T (Kelvin) while the initial and final J levels are labelled as in Table 3. We use the notation $x \pm n$ to indicate the number $x \times 10^{\pm n}$

Fe IV	3.6	4.6	5.6	Fe IV	3.6	4.6	5.6	Fe IV	3.6	4.6	5.6
2- 3	1.40+3	2.80+2	3.10+1	4- 5	6.56+2	1.33+2	1.58+1	6-11	1.82−1	1.60−1	3.68−1
2- 4	7.67+2	1.53+2	1.66+1	4- 6	1.32+2	1.83+1	2.05+0	6-12	1.17−1	8.19−2	5.42−2
2- 5	1.62+2	3.23+1	3.47+0	4- 7	7.18+1	9.98+0	1.07+0	7- 8	1.80+1	2.89+0	6.37−1
2- 6	4.70+1	6.53+0	6.95−1	4- 8	2.44+2	3.40+1	3.91+0	7- 9	1.36−1	1.16−1	2.59−1
2- 7	1.98+2	2.74+1	3.00+0	4- 9	1.87−1	1.72−1	1.30−1	7-10	2.10−1	1.76−1	3.01−1
2- 8	1.59+2	2.20+1	2.34+0	4-10	3.19−1	2.67−1	2.00−1	7-11	2.34−1	1.72−1	1.45−1
2- 9	2.11−1	1.74−1	1.26−1	4-11	5.57−1	4.69−1	3.58−1	7-12	3.63−1	3.06−1	6.33−1
2-10	3.31−1	2.84−1	2.10−1	4-12	7.52−1	6.68−1	5.85−1	8- 9	9.58−2	6.69−2	6.92−2
2-11	3.71−1	3.33−1	2.47−1	5- 6	3.30+1	4.55+0	4.72−1	8-10	2.34−1	1.76−1	2.87−1
2-12	1.76−1	1.62−1	1.24−1	5- 7	1.51+1	2.27+0	5.45−1	8-11	4.33−1	3.47−1	6.97−1
3- 4	2.61+3	5.23+2	5.74+1	5- 8	6.04+1	8.70+0	1.51+0	8-12	6.56−1	6.00−1	1.36+0
3- 5	6.42+2	1.28+2	1.39+1	5- 9	5.88−2	5.34−2	4.06−2	9-10	4.75−1	4.26−1	3.77−1
3- 6	1.47+2	2.04+1	2.21+0	5-10	2.38−1	2.12−1	1.66−1	9-11	1.10−1	8.39−2	5.85−2
3- 7	1.49+2	2.06+1	2.23+0	5-11	6.00−1	5.05−1	4.17−1	9-12	8.68−2	6.19−2	4.20−2
3- 8	3.00+2	4.15+1	4.49+0	5-12	1.28+0	1.10+0	1.05+0	10-11	7.57−1	6.59−1	5.62−1
3- 9	1.96−1	1.67−1	1.24−1	6- 7	6.64+0	1.16+0	3.32−1	10-12	2.14−1	1.52−1	1.04−1
3-10	4.18−1	3.60−1	2.64−1	6- 8	2.64+1	3.74+0	4.68−1	11-12	8.62−1	6.93−1	5.64−1
3-11	4.33−1	3.73−1	2.82−1	6- 9	5.18−2	4.83−2	4.31−2				
3-12	4.04−1	3.69−1	3.02−1	6-10	1.21−1	9.83−2	1.66−1				

Table 6. Effective collision strengths (Υ) for fine-structure transitions involving the ^{4}G, ^{4}P and ^{4}D terms in Co V. The row containing the ion symbol denotes the values of log T (Kelvin) while the initial and final J levels are labelled as in Table 3. We use the notation $x \pm n$ to indicate the number $x \times 10^{\pm n}$

Co V	3.8	4.8	5.8	Co V	3.8	4.8	5.8	Co V	3.8	4.8	5.8
2- 3	1.38+0	1.06+0	8.66−1	4- 5	1.90+0	1.52+0	1.43+0	6-11	1.48−1	1.40−1	4.19−1
2- 4	2.75−1	1.68−1	1.12−1	4- 6	1.35−1	8.41−2	1.65−1	6-12	7.25−2	5.22−2	3.55−2
2- 5	3.97−2	2.09−2	1.15−2	4- 7	1.14−1	6.00−2	3.63−2	7- 8	5.08−1	3.74−1	3.04−1
2- 6	6.84−2	3.30−2	1.79−2	4- 8	3.21−1	1.93−1	4.30−1	7- 9	1.12−1	1.00−1	2.85−1
2- 7	1.96−1	1.17−1	1.76−1	4- 9	1.33−1	1.20−1	8.75−2	7-10	1.60−1	1.44−1	3.14−1
2- 8	7.76−2	4.80−2	8.07−2	4-10	2.22−1	1.84−1	1.38−1	7-11	1.57−1	1.19−1	1.19−1
2- 9	1.52−1	1.21−1	8.55−2	4-11	4.01−1	3.25−1	2.56−1	7-12	2.73−1	2.50−1	7.22−1
2-10	2.32−1	1.95−1	1.44−1	4-12	5.32−1	4.70−1	4.75−1	8- 9	6.23−2	4.67−2	6.43−2
2-11	2.61−1	2.26−1	1.65−1	5- 6	1.62−2	5.47−3	1.83−3	8-10	1.66−1	1.34−1	2.97−1
2-12	1.26−1	1.14−1	8.59−2	5- 7	2.24−1	1.42−1	3.34−1	8-11	3.25−1	2.73−1	7.15−1
3- 4	1.76+0	1.38+0	1.18+0	5- 8	4.45−1	2.80−1	6.48−1	8-12	4.99−1	5.07−1	1.57+0
3- 5	2.76−1	1.81−1	1.44−1	5- 9	4.26−2	3.76−2	2.76−2	9-10	3.64−1	3.34−1	2.99−1
3- 6	1.22−1	7.14−2	1.01−1	5-10	1.70−1	1.49−1	1.17−1	9-11	7.75−2	5.75−2	3.95−2
3- 7	1.50−1	8.43−2	1.04−1	5-11	4.20−1	3.50−1	3.17−1	9-12	6.07−2	4.27−2	2.84−2
3- 8	1.84−1	1.09−1	2.24−1	5-12	9.18−1	7.78−1	8.79−1	10-11	5.69−1	5.01−1	4.34−1
3- 9	1.36−1	1.15−1	8.55−2	6- 7	2.76−1	2.23−1	1.94−1	10-12	1.46−1	1.04−1	7.33−2
3-10	3.01−1	2.48−1	1.77−1	6- 8	1.64−1	9.97−2	7.14−2	11-12	6.19−1	5.10−1	4.29−1
3-11	3.06−1	2.56−1	1.99−1	6- 9	3.71−2	3.99−2	3.69−2				
3-12	2.87−1	2.60−1	2.27−1	6-10	9.39−2	7.82−2	1.69−1				

Table 7. Effective collision strengths (Υ) for fine-structure transitions involving the ^{4}G, ^{4}P and ^{4}D terms in Ni VI. The row containing the ion symbol denotes the values of log T (Kelvin) while the initial and final J levels are labelled as in Table 3. We use the notation $x \pm n$ to indicate the number $x \times 10^{\pm n}$

Ni VI	4.0	5.0	6.0	Ni VI	4.0	5.0	6.0	Ni VI	4.0	5.0	6.0
2- 3	1.12+0	8.81−1	6.85−1	4- 5	1.77+0	1.41+0	1.20+0	6-11	1.26−1	1.30−1	5.23−1
2- 4	2.30−1	1.28−1	8.32−2	4- 6	8.70−2	5.53−2	2.04−1	6-12	4.95−2	3.79−2	2.52−2
2- 5	3.60−2	1.50−2	8.23−3	4- 7	8.86−2	4.47−2	2.99−2	7- 8	4.22−1	3.19−1	2.46−1
2- 6	5.14−2	2.39−2	1.33−2	4- 8	2.17−1	1.37−1	5.03−1	7- 9	9.53−2	8.94−2	3.41−1
2- 7	1.29−1	7.99−2	2.14−1	4- 9	1.02−1	9.02−2	6.28−2	7-10	1.33−1	1.29−1	3.54−1
2- 8	5.60−2	4.00−2	9.94−2	4-10	1.71−1	1.39−1	1.02−1	7-11	1.20−1	9.50−2	1.15−1
2- 9	1.11−1	8.95−2	6.10−2	4-11	2.92−1	2.39−1	2.04−1	7-12	2.22−1	2.25−1	9.16−1
2-10	1.76−1	1.45−1	1.07−1	4-12	4.09−1	3.62−1	4.50−1	8- 9	4.48−2	3.75−2	7.14−2
2-11	2.00−1	1.64−1	1.21−1	5- 6	1.46−2	3.78−3	1.43−3	8-10	1.28−1	1.13−1	3.44−1
2-12	9.61−2	8.57−2	6.41−2	5- 7	1.47−1	9.50−2	4.14−1	8-11	2.61−1	2.33−1	7.78−1
3- 4	1.47+0	1.18+0	9.53−1	5- 8	3.11−1	2.04−1	7.44−1	8-12	4.24−1	4.83−1	1.93+0
3- 5	2.64−1	1.57−1	1.17−1	5- 9	3.20−2	2.80−2	1.98−2	9-10	2.96−1	2.89−1	2.44−1
3- 6	8.19−2	4.81−2	1.20−1	5-10	1.29−1	1.11−1	9.12−2	9-11	5.44−2	4.20−2	2.80−2
3- 7	1.07−1	6.15−2	1.16−1	5-11	3.22−1	2.63−1	2.71−1	9-12	4.05−2	3.05−2	2.01−2
3- 8	1.25−1	7.96−2	2.71−1	5-12	6.86−1	6.01−1	8.25−1	10-11	4.51−1	4.21−1	3.43−1
3- 9	1.06−1	8.80−2	6.26−2	6- 7	2.27−1	1.95−1	1.60−1	10-12	9.96−2	7.75−2	5.46−2
3-10	2.21−1	1.80−1	1.28−1	6- 8	1.38−1	8.01−2	5.59−2	11-12	4.73−1	4.17−1	3.38−1
3-11	2.31−1	1.90−1	1.58−1	6- 9	3.29−2	3.92−2	3.35−2				
3-12	2.21−1	1.98−1	1.95−1	6-10	7.83−2	6.60−2	1.88−1				

be important. For this reason, V-like Cr II was omitted from consideration in this paper, as the 4s and 4p states lie close to the 3d states for that ion. However, these effects should diminish as we ascend the isoelectronic sequence.

A check was also made on the target term separations used, which, as shown in Table 1, differered significantly from observed separations. The calculation for Fe IV was repeated with term energies adjusted to match observed thresholds. The biggest effect was on the ^{6}S−^{4}P transition, where the effective collision strength differed by 4% at 4000 K. From this check, and from work on other ions by the IRON Project, the accuracy of the effective collision strengths given in Tables 2 and 4 to 7 is estimated to be better than 10%, with a greater uncertainty for the fine-structure transitions involving the metastable states given in Table 3.

Acknowledgements. This work was done with the support of a SERC grant GR/H93576, and an EC network contract ERB CHRX CT920013.

References

Adelman S.J., Cowley C.R., Leckrone D.S., Roby S.W., Wahlgren G.M., 1993, ApJ 419, 276
Berrington K.A., 1995, A&AS 109, 193 (Paper VIII)
Butler K., Zeippen C.J., 1994, A&AS 108, 1 (Paper V)
Clementi E., Roetti C., 1974, Atom. Data Nucl. Data Tables 14, 177
Corliss C., Sugar J., 1977, J. Phys. Chem. Ref. Data 4, 397
Corliss C., Sugar J., 1977, J. Phys. Chem. Ref. Data 6, 1253
Corliss C., Sugar J., 1981, J. Phys. Chem. Ref. Data 10, 250
Galavis M.E., Mendoza C., Zeippen C.J., 1995, A&AS (Paper X, in press)
Holberg J.B., Hubeny I., Barstow M.A., Lanz T., Sion E.M., Tweedy R.W., 1994, ApJ 425, L105
Hummer D.G., Berrington K.A., Eissner W., Pradhan A.K., Saraph H.E., Tully J.A., A&A 279, 298 (Paper I)
Kelly R.L., 1987, J. Phys. Chem. Ref. Data. 16, Supp. 1
Lennon D.J., Burke V.M., 1994, A&AS 103, 273 (Paper II)
Nahar S.N., 1994, A&A 293, 967 (Paper VII)
Pelan J., Berrington K.A., 1995, A&AS 110, 209 (Paper IX)
Pradhan A.K., Gallagher J.W., 1992, Atom. Data Nucl. Data Tables 52, 227
Ruiz-Lapuente P., 1994, In: van Woerden H. (ed.) 22nd IAU Astronomy Posters Abstracts. Tari Press, ISBN 90-5598-001-8/CIP, p. 240
Ruiz-Lapuente P., Kirshner R.P., Phillips M.M., et al., 1994, ApJ (in press)
Saraph H.E., 1978, Comp. Phys. Commun. 15, 247
Saraph H.E., Tully J.A., 1994, A&AS 107, 29 (Paper IV)
Saraph H.E., Storey P.J., 1995, A&AS (Paper XI, in press)
Sawey P.M.J., Berrington K.A., 1992, J. Phys. B 25, 1451
Shull J.M., Van Steenberg M., 1982, ApJS 48, 95
Zhang H.L., Graziani M., Pradhan A.K., 1994, A&A 283, 319 (Paper III)
Zhang H.L., Pradhan A.K., 1994, A&A 293, 953 (Paper VI)