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Atomic data from the IRON Project. XIX. Radiative transition probabilities for forbidden lines in Fe II*

P. Quinet[1], M. Le Dourneuf[1] and C.J. Zeippen[2]

[1] Laboratoire SIMPA (EP 99 du CNRS), Université de Rennes 1, Campus de Beaulieu, F-35042 Rennes, France
[2] URA 173 (associée au CNRS et à l'Université Paris 7) et DAEC, Observatoire de Paris, F-92195 Meudon, France

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Abstract. — Radiative transition probabilities have been calculated for the magnetic dipole (M1) and electric quadrupole (E2) transitions connecting the 63 metastable levels in the $3d^64s$, $3d^7$ and $3d^54s^2$ configurations in Fe II. The most important configuration interaction (CI) and relativistic effects have been taken into account in the computations carried out with the help of two independent computer programs, SUPERSTRUCTURE (SST) and RELATIVISTIC HARTREE-FOCK (HFR). The results obtained in the present work are compared with previous theoretical studies and with some astrophysical observations. The new data presented here are probably the most reliable to date.

Key words: atomic data — Fe II — transition probabilities

1. Introduction

Singly ionized iron is one of the most important atomic ions in astrophysics because of its high relative abundance in many sources, its comparatively low ionization potential and the sheer density of its energy structure. Hence, the calculation of oscillator strengths for lines in Fe II is of considerable practical interest (see, for example, Viotti et al. 1988). The most extensive studies were performed by Kurucz (1981, 1990), Fawcett (1987, 1988) and Nahar & Pradhan (1994). Critical compilations of oscillator strengths for Fe II lines were published by Fuhr et al. (1988) and by Giridhar & Ferro (1995). However, most of previous work concerns only allowed electric dipole (E1) radiation without consideration of forbidden transitions.

The present calculations were performed within the framework of the IRON Project (IP), an international collaboration whose aim is to produce accurate collisional and radiative atomic data for ions of astrophysical interest, with a particular attention to members of the Fe group. The goals and methods of the Project are presented in Paper I of this series (Hummer et al. 1993). A considerable amount of IP work has already been devoted to Fe II: collision strengths and rate coefficients can be found in Paper VI (Zhang & Pradhan 1995), E1 transition probabilities are reported in Paper VII (Nahar 1995) while electron excitation rates and emissivity ratios for forbidden lines are presented in Paper XIII (Bautista & Pradhan 1996).

Forbidden lines of Fe II were first identified by Merril (1928) in the spectrum of η Carinae and they have since been observed in many other astrophysical objects like novae, nebulae and peculiar stars. To mention but recent studies in which IP collisional atomic data were used, Bautista et al. (1994), Bautista & Pradhan (1995) and Bautista et al. (1995) have considered [Fe II] lines in the Orion Nebula and in Supernova 1987A.

In this context, it must be noted that a very limited number of transition probability calculations have been performed for [Fe II] lines. Smith & Wiese (1973) and Fuhr et al. (1988) have published compilations of forbidden lines in iron group elements. The transition probabilities reported in these tabulations for [Fe II] lines are essentially taken from the extensive work of Garstang (1962) who used an intermediate coupling method. Radiative data for a small number of forbidden lines in Fe II were also published by Nussbaumer & Swings (1970), Johansson (1977) and Nussbaumer & Storey (1980). However, CI effects were considered to a very limited extent in all these computations. More recently, Nussbaumer & Storey (1988) used a twelve-configuration basis set in the program SUPERSTRUCTURE (SST) of Eissner et al. (1974) as modified by Nussbaumer & Storey (1978) for calculating transition probabilities for forbidden lines

Send offprint requests to: P. Quinet
*Table 4 is also available in electronic form from the CDS via anonymous ftp 130.79.128.5 or on www at http://cdsweb.u-strasbg.fr/abstract.html

connecting the lowest four terms of Fe II. The results of Garstang and Nussbaumer & Storey were used by Bautista and his colleagues in their work on the Orion Nebula and SN 1987A.

The aim of the present attempt is to describe Fe II with a more elaborate physical model in order to provide a firmer basis to astrophysical studies. Together, the three low even configurations $3d^6 4s$, $3d^7$ and $3d^5 4s^2$ in Fe II have 63 metastable levels. In this paper, radiative transition probabilities for forbidden lines between these metastable levels are reported. The new data were calculated using the SST and RELATIVISTIC HARTREE-FOCK (HFR) codes. Indeed, it was felt that thorough comparisons between sets of radiative data obtained with two independent methods would help to assess more clearly the reliability of the present transition probabilities. The most important CI and relativistic effects were included in the calculations. This study can be seen as an extension of the recent investigations of forbidden transitions in iron group elements carried out in the cases of Fe III (Quinet 1996), Ni I and Ni II (Quinet & Le Dourneuf 1996).

2. Methods and physical models

2.1. *SUPERSTRUCTURE (SST)*

First, the calculations were performed using the SST code due to Eissner et al. (1974) as modified by Nussbaumer & Storey (1978). In this formalism, the wavefunctions are expressed as linear combinations of the type

of the wavefunctions can be improved by means of semi-empirical term energy corrections (TECs) following the procedure described by Zeippen et al. (1977). In practice, the TEC for a given term is simply taken to be the difference between the measured and calculated energy of the lowest level in the multiplet. Experience has shown that this type of "fine-tuning" is both justified and efficient when the corrections are sufficiently small as compared to observed energies (see, for example, Biémont et al. 1992, 1994).

The TECs used in the present calculations are reported in Table 1 together with the calculated fine-structure splittings (FS). Observed energies taken from the compilation of Sugar & Corliss (1985) are also given for comparison. It appears that most of the TECs are small (5−15%) as compared to the observed energies, that is taking into account the complexity of the ion treated here. One can see also that the fine-structure splittings are in very good agreement with experiment for all multiplets, which gives some confidence in the quality of the present wavefunctions.

Finally, it is important to note that the radiative transition probabilities were calculated with experimental level energies.

2.2. *Relativistic Hartree-Fock (HFR)*

An independent set of calculations was carried out with the relativistic Hartree-Fock method (HFR) originally introduced by Cowan & Griffin (1976). The computer codes written by Cowan (1981) were used. The same set of con-

Table 1. Observed energy levels, E_{obs}, and fine-structure splittings, FS_{obs}, for the 24 lowest terms of Fe II. The present fine-structure splittings, FS_{calc}, obtained with SST and the semi-empirical corrections to calculated non-relativistic ener-

as

$$s = \sqrt{\sum_k \frac{(E_k - T_k)^2}{N_k - N_\mathrm{p}}} \qquad (2)$$

where N_k is the number of levels involved in the fit, N_p

It can be seen from Table 4 that there is general agreement between our SST and HFR transition probabilities. In particular, for the strongest lines ($A_{ki} > 0.01$ s^{-1}), both

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sets of results are in very good agreement (within 15%) if we except the a^{6}D$_{7/2}$–a^{2}D$_{5/2}$, a^{4}F$_{7/2,9/2}$–b^{2}H$_{11/2}$, a^{4}F$_{5/2}$–b^{2}H$_{9/2}$, a^{4}F$_{5/2}$–a^{2}F$_{7/2}$, a^{4}F$_{3/2}$–a^{2}F$_{5/2}$, a^{4}F$_{3/2}$–b^{2}D$_{3/2}$, a^{4}P$_{3/2}$–a^{2}S$_{1/2}$, a^{4}P$_{3/2}$–c^{2}D$_{3/2,5/2}$ and a^{2}D$_{5/2}$–b^{2}F$_{7/2}$ transitions for which the discrepancies reach 20, 27, 28, 37, 32, 30, 32, 22, 28, 28 and 22% respectively. Exceptions occur also for a^{4}D$_{7/2}$–b^{2}F$_{7/2}$ and a^{4}P$_{5/2}$–c^{2}D$_{5/2}$ where cancellation effects are present in the HFR calculations and where consequently the SST results are probably more reliable. For weaker lines, our SST and HFR A-values generally agree to within 15–40% except for some very weak transitions and again for some transitions affected by cancellation effects.

The transition probabilities published for [Fe II] lines by Garstang (1962), Nussbaumer & Swings (1970), Johansson (1977) and Nussbaumer & Storey (1980) were obtained with the help of configuration basis sets including only the 3d^{6}4s, 3d^7 and, occasionally, 3d^{5}4s^2 configurations. In general, for the magnetic dipole transitions within a configuration, the results obtained by Garstang agree well with the SST and HFR transition probabilities reported in the present work. For the E2 contributions and for the M1 transitions arising through CI effects, large discrepancies are observed for a number of

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The magnitudes of the coefficients due to spin-orbit and CI depend on the a^{6}D–b^{4}P and a^{4}P–b^{4}P term separations. These term separations calculated in our work us-

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ing two methods, SST (21020 and 7826 cm^{-1}) and HFR (21105 and 7886 cm^{-1}), are in very good agreement with the observations (21005 and 7809 cm^{-1}) while the values obtained by Nussbaumer & Storey (1988), i.e. 27122 and 13158 cm^{-1}, are too large.

Preliminary values of HFR transition probabilities for some forbidden lines in Fe II have already been published (Quinet et al. 1996). These A-coefficients differ slightly from the present HFR results due to the fact that the set of configurations included explicitly in the model has been extended in the present calculation.

Some limited comparisons between our calculated transition probabilities and astrophysical observations can be made. For example, intensity ratios for some [Fe II] lines have been measured in supernova remnants by Dennefeld (1982, 1986), in two LMC supernova remnants by Oliva (1987) and in the Orion Nebula by Bautista et al. (1994). The ratios of intensities deduced from the transition probabilities calculated in the present work, $R_1 = I$(a^{4}F$_{9/2}$–a^{4}P$_{5/2}$)/ I(a^{4}F$_{7/2}$–a^{4}P$_{5/2}$) = 4.47 (SST) and 4.55 (HFR) and $R_2 = I$(a^{4}F$_{7/2}$–a^{4}P$_{3/2}$)/ I(a^{4}F$_{5/2}$–a^{4}P$_{3/2}$) = 1.78 (SST) and 1.81 (HFR) are in good agreement with the observations of Dennefeld (1982) for the Kepler supernova remnant ($R_1 = 4.1$ and $R_2 =$ 2.2 respectively) while larger discrepancies are observed

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low-lying even-parity levels in Fe II. The analysis of the

factory. Thus a more extended and reliable physical basis has been provided for astrophysical studies where Fe II plays an important rôle. Of course, the quality of our results is likely to increase with even better optimization of the codes and mainly with further developments of modern computers. At this stage however the new SST data presented in this paper are probably the best available.

Note added in proof: The effect of some configurations not included explicitly in our physical models due to computer memory limitations was estimated in separate ab initio HFR calculations. More precisely, the configurations $3d^54d^2$ and $3d^54f^2$ were investigated separately. By comparing a three-configuration calculation (including $3d^64s$, $3d^7$ and $3d^54s^2$) with a four-configuration calculation (adding $3d^54d^2$), the effect of the latter configuration on A-values was estimated for the transitions reported in Table 4. In general, both calculations agree within a few percent if we except some transitions affected by cancellation effects and the a^4F-a^4P, a^4F-a^2P, a^2D-a^2S, b^4P-b^2P, b^4P-b^4D, b^4P-c^2D, b^2P-b^4D, b^2P-a^2S M1 transitions and a^4P-b^4D, a^2G-a^2F, a^2G-b^2G, a^2G-a^2I, a^2D-b^2D and a^2D-a^2S E2 transitions for which the A-values were about 25−30% larger when calculated with the four-configuration expansion. Exceptions occur also for the a^4F-a^4D and a^2P-b^2P E2 lines for which the transition probabilities were reduced by 30% when adding the $3d^54d^2$ configuration. The inclusion of $3d^54f^2$ was found to affect the A-values for all the transitions by less than 1%.

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Table 3. Calculated HFR energy levels (in cm^{-1}) and comparison with experiment for the $3d^64s$, $3d^7$ and $3d^54s^2$ configurations of Fe II

Configuration	Term	J	E_{obs} [a]	E_{calc}	ΔE [b]
$3d^6(^5D)4s$	a^6D	9/2	0.	0.	0.
		7/2	385.	379.	6.
		5/2	668.	661.	7.
		3/2	863.	857.	6.
		1/2	977.	972.	5.
$3d^7$	a^4F	9/2	1873.	1898.	-25.
		7/2	2430.	2460.	-30.
		5/2	2838.	2876.	-38.
		3/2	3117.	3163.	-46.
$3d^6(^5D)4s$	a^4D	7/2	7955.	7961.	-6.
		5/2	8392.	8402.	-10.
		3/2	8680.	8697.	-17.
		1/2	8847.	8869.	-22.
		3/2	13673.	13705.	-32.
		1/2	13905.	13963.	-58.
$3d^7$	a^2G	9/2	15845.	15871.	-26.
		7/2	16369.	16404.	-35.
$3d^7$	a^2P	3/2	18361.	18380.	-19.
		1/2	18887.	18911.	-24.
$3d^7$	a^2H	11/2	20340.	20367.	-27.
		9/2	20806.	20835.	-29.
$3d^7$	a^2D	5/2	20517.	20588.	-71.
		3/2	21308.	21356.	-48.
		1/2	22410.	22490.	-80.
$3d^6(^3H)4s$	a^4H	13/2	21252.	21332.	-80.
		11/2	21430.	21479.	-49.
		9/2	21582.	21606.	-24.
		7/2	21712.	21718.	-6.
$3d^6(^3F)4s$	b^4F	9/2	22637.	22687.	-50.
		7/2	22810.	22849.	-39.
		5/2	22939.	22974.	-35.
		3/2	23031.	23067.	-36.
$3d^54s^2$	a^6S	5/2	23318.	23246.	72.
$3d^6(^3G)4s$	a^4G	11/2	25429.	25424.	5.
		9/2	25805.	25777.	28.
		7/2	25982.	25934.	48.
		5/2	26055.	25991.	64.

Table 3. continued

Configuration	Term	J	E_{obs} [a]	E_{calc}	ΔE [b]
$3d^6(^3P)4s$	c^2P	1/2	54063.	54163.	-100.
		3/2	54902.	54992.	-90.
$3d^54s^2$	b^4G	11/2	54232.	54350.	-118.
		9/2	54274.	54358.	-84.
		5/2	54276.	54308.	-32.
		7/2	54283.	54339.	-56.
$3d^6(^3F)4s$	c^2F	5/2	54870.	54842.	28.
		7/2	54904.	54855.	49.
$3d^54s^2$	d^4P	5/2	57411.	57445.	-34.
		3/2	57493.	57522.	-29.
		1/2	57578.	57612.	-34.
$3d^6(^1G)4s$	d^2G	9/2	58631.	58557.	74.
		7/2	58666.	58568.	98.
$3d^54s^2$	c^4D	7/2	60270.	60327.	-57.
		1/2	60384.	60415.	-31.
		5/2	60445.	60503.	-58.
$3d^54s^2$	^2I	11/2		68664.	
		13/2		68742.	
$3d^54s^2$	^2D	5/2		71166.	
		3/2		71630.	
$3d^54s^2$	^4F	9/2	73394.	73448.	-54.
		5/2	73396.	73415.	-19.
		7/2	73492.	73534.	-42.
		3/2	73637.	73686.	-49.
$3d^54s^2$	^2F	7/2		72967.	
		5/2		77019.	
$3d^54s^2$	^2H	9/2	77231.	77195.	36.
		11/2		77608.	
$3d^54s^2$	^2G	7/2	78185.	78208.	-23.
		9/2	78577.	78564.	13.
$3d^54s^2$	^2F	5/2	81639.	81628.	11.
		7/2	81735.	81779.	-44.
$3d^54s^2$	^2S	1/2		86661.	
$3d^54s^2$	^2D	3/2		93882.	
		5/2		93954.	
$3d^6(^1S)4s$	^2S	1/2		97723.	
$3d^54s^2$	^2G	9/2		101928.	
		7/2		101964.	
$3d^54s^2$	^2P	3/2		117646.	

Table 4. Radiative transition probabilities, A_{ki} in s^{-1}, as obtained with SST and HFR for forbidden lines of Fe II. $A(B)$ stands for $A.10^{B}$

Multiplet	2J–2J'	λ(Å)[a]	Type	A_{ki}(SST)	A_{ki}(HFR)
a^{6}D–a^{6}D	9–7	259811.18	M1	2.13(-3)	2.05(-3)
	7–5	353397.94	M1	1.57(-3)	1.56(-3)
a^{6}D–a^{4}D	9–7	12566.80	M1	4.74(-3)	5.18(-3)
	7–7	13205.54	M1	1.31(-3)	1.44(-3)
	5–5	12942.68	M1	1.98(-3)	2.23(-3)*
	3–5	13277.76	M1	1.17(-3)	1.30(-3)
	3–3	12787.76	M1	2.45(-3)	2.80(-3)
	1–3	12977.73	M1	1.08(-3)	1.23(-3)
	1–1	12703.46	M1	3.32(-3)	3.82(-3)
a^{6}D–a^{4}P	7–5	7637.54	M1	6.64(-3)	7.30(-3)
	5–3	7686.93	M1	6.81(-3)	7.53(-3)
	3–1	7665.30	M1	6.23(-3)	6.95(-3)
	1–1	7733.16	M1	1.93(-3)	2.14(-3)
a^{6}D–a^{2}D	7–5	4965.79	M1	1.16(-2)	1.42(-2)
a^{6}D–b^{4}P	7–5	4889.62	M1	3.41(-1)	3.47(-1)
	5–5	4958.22	M1	5.00(-3)	5.13(-3)*
	5–3	4728.07	M1	4.53(-1)	4.78(-1)
	3–5	5006.62	M1	2.70(-2)	2.60(-2)
	3–3	4772.06	M1	2.30(-2)	2.41(-2)*
	3–1	4639.67	M1	4.67(-1)	4.99(-1)
	1–3	4798.27	M1	6.75(-2)	6.85(-2)
	1–1	4664.44	M1	1.47(-1)	1.56(-1)
a^{6}D–a^{4}H	9–9	4632.27	M1	2.01(-3)	2.14(-3)*
a^{6}D–b^{4}F	9–9	4416.27	M1	4.19(-1)	4.54(-1)*
	9–7	4382.74	M1	5.14(-2)	5.43(-2)
	7–9	4492.63	M1	5.61(-2)	5.97(-2)
	7–7	4457.94	M1	2.55(-1)	2.79(-1)
	7–5	4432.45	M1	4.88(-2)	5.27(-2)
	5–7	4514.90	M1	6.00(-2)	6.51(-2)

Table 4. continued

Multiplet	2J–2J'	λ(Å)[a]	Type	A_{ki}(SST)	A_{ki}(HFR)
	3–3	9470.93	E2	3.65(-3)	3.18(-3)
	3–1	9267.57	E2	2.13(-2)	1.91(-2)
a^{4}F–a^{2}G	9–9	7155.16	M1	1.46(-1)	1.53(-1)*
	9–7	6896.18	M1	5.31(-3)	5.28(-3)
	7–9	7452.54	M1	4.77(-2)	4.92(-2)
	7–7	7172.00	M1	5.51(-2)	5.88(-2)
	5–7	7388.18	M1	4.21(-2)	4.48(-2)
a^{4}F–a^{2}P	7–3	6275.51	E2	3.16(-3)	2.60(-3)
	5–3	6440.40	M1,E2	2.33(-2)	2.13(-2)
	5–1	6229.26	E2	1.74(-3)	1.47(-3)
	3–3	6558.49	M1	1.61(-2)	1.42(-2)
a^{4}F–a^{2}H	9–9	5280.26	M1,E2	1.19(-3)	1.38(-3)*
a^{4}F–a^{2}D	9–5	5362.05	E2	9.06(-3)	1.40(-2)
	7–5	5527.34	M1	2.78(-1)	2.73(-1)
	5–5	5654.86	M1,E2	3.14(-2)	3.11(-2)*
	5–3	5412.65	M1	2.74(-1)	2.83(-1)
	3–5	5745.70	M1	1.40(-2)	1.29(-2)
	3–3	5495.82	M1	1.47(-1)	1.51(-1)
a^{4}F–b^{4}P	9–5	5273.35	E2	4.80(-1)	5.50(-1)
	7–5	5433.13	M1,E2	1.51(-1)	1.74(-1)
	7–3	5158.00	E2	3.84(-1)	4.40(-1)
	5–5	5556.29	M1,E2	3.01(-2)	3.45(-2)*
	5–3	5268.87	E2	2.50(-1)	2.88(-1)
	5–1	5107.94	E2	3.13(-1)	3.60(-1)
	3–5	5643.97	M1,E2	3.42(-3)	3.91(-3)
	3–3	5347.65	E2	7.57(-2)	8.70(-2)
	3–1	5181.95	E2	4.37(-1)	5.00(-1)
a^{4}F–a^{4}H	9–13	5158.78	E2	5.56(-1)	6.05(-1)
	9–11	5111.63	E2	1.20(-1)	1.31(-1)
	9–9	5072.39	E2	2.53(-2)	2.80(-2)
	9–7	5039.08	E2	1.86(-3)	2.04(-3)
	7–11	5261.62	E2	4.01(-1)	4.29(-1)
	7–9	5220.06	E2	1.34(-1)	1.44(-1)

Table 4. continued

Multiplet	$2J-2J'$	$\lambda(Å)^a$	Type	A_{ki}(SST)	A_{ki}(HFR)
a^4F-b^2G	9–9	3505.80	M1,E2	4.56(-3)	5.79(-3)
	7–9	3575.72	M1,E2	2.67(-3)	3.19(-3)
	7–7	3528.27	M1,E2	2.67(-3)	3.15(-3)*
	5–9	3628.65	E2	1.30(-3)	1.62(-3)
	5–7	3579.80	E2	1.51(-3)	1.94(-3)
a^4F-b^4D	9–7	3376.20	E2	8.46(-1)	9.81(-1)
	9–5	3387.09	E2	2.49(-1)	2.82(-1)
	7–7	3440.99	E2	2.89(-1)	3.26(-1)
	7–5	3452.31	E2	4.24(-1)	4.97(-1)
	7–3	3455.11	E2	4.38(-1)	5.00(-1)
	5–7	3489.98	E2	4.23(-2)	4.71(-2)
	5–5	3501.63	E2	3.97(-1)	4.52(-1)
	5–3	3504.51	E2	2.31(-1)	2.73(-1)
	5–1	3504.02	E2	6.35(-1)	7.20(-1)
	3–7	3524.37	E2	1.94(-3)	2.14(-3)
	3–5	3536.25	E2	7.67(-2)	8.57(-2)
	3–3	3539.19	E2	4.54(-1)	5.15(-1)
	3–1	3538.69	E2	4.73(-1)	5.40(-1)

Table 4. continued

Multiplet	$2J-2J'$	$\lambda(Å)^a$	Type	A_{ki}(SST)	A_{ki}(HFR)
	5–5	5199.17	M1	1.13(-1)	1.18(-1)
	3–5	5278.37	M1	6.48(-2)	6.75(-2)
a^4D-b^2G	7–7	4382.97	M1	2.44(-3)	2.21(-3)*
	5–7	4468.51	M1,E2	1.07(-3)	9.99(-4)
a^4D-b^4D	7–7	4249.08	M1,E2	4.00(-3)	4.50(-4)*
	7–5	4266.35	M1,E2	2.04(-2)	1.98(-2)
	5–7	4329.43	M1,E2	1.63(-2)	1.51(-2)
	5–3	4351.81	M1,E2	1.56(-2)	1.38(-2)
	5–1	4351.05	E2	1.39(-3)	3.63(-6)*
	3–5	4402.59	M1,E2	1.47(-2)	1.35(-2)
	3–1	4406.38	M1,E2	6.10(-3)	2.76(-3)*
	1–3	4439.71	M1,E2	7.85(-3)	6.58(-3)*
a^4D-b^2F	7–7	4157.91	M1,E2	1.65(-2)	2.65(-2)*
	5–7	4234.82	M1	4.03(-3)	6.96(-3)
	5–5	4268.68	M1	7.25(-3)	1.20(-2)
	3–5	4321.92	M1	3.77(-3)	6.37(-3)
a^4D-c^2G	7–7	3913.41	M1	2.02(-3)	3.43(-3)*

Table 4. continued

Multiplet	$2J$–$2J'$	λ(Å)^a	Type	A_{ki}(SST)	A_{ki}(HFR)
a^{2}G–a^{2}G	9–7	190529.52	M1	2.14(-3)	2.26(-3)
a^{2}G–a^{2}H	9–11	22237.65	M1	1.48(-2)	1.58(-2)
	9–9	20151.24	M1	4.37(-2)	4.65(-2)
	7–9	22534.60	M1	1.39(-2)	1.48(-2)
a^{2}G–a^{4}G	7–5	10321.29	M1,E2	1.62(-3)	1.87(-3)
a^{2}G–b^{2}H	9–11	9682.08	M1,E2	2.07(-2)	2.16(-2)
	9–9	9513.84	M1,E2	1.40(-2)	1.52(-2)
	7–11	10200.43	E2	1.18(-3)	1.24(-3)
	7–9	10013.87	M1,E2	1.74(-2)	1.80(-2)
a^{2}G–a^{2}F	9–7	8715.80	M1,E2	7.47(-2)	6.97(-2)
	9–5	8489.69	E2	6.92(-3)	6.10(-3)
	7–7	9133.62	M1,E2	1.00(-2)	9.74(-3)*
	7–5	8885.62	M1,E2	6.70(-2)	6.02(-2)
a^{2}G–b^{2}G	9–9	6873.84	E2	1.40(-1)	1.51(-1)
	9–7	6700.63	E2	1.26(-2)	1.07(-2)
	7–9	7131.12	M1,E2	1.50(-2)	1.61(-2)
	7–7	6944.88	E2	1.26(-1)	1.35(-1)
a^{2}G–b^{2}F	9–7	6188.55	M1,E2	1.94(-1)	2.19(-1)
	9–5	6261.12	E2	3.52(-2)	3.97(-2)
	7–7	6396.31	M1,E2	4.86(-2)	4.63(-2)*
	7–5	6473.86	M1,E2	1.65(-1)	1.83(-1)
a^{2}G–a^{2}I	9–13	5870.02	E2	1.95(-1)	2.14(-1)
	9–11	5858.23	E2	1.61(-3)	1.43(-3)
	7–11	6044.07	E2	1.51(-1)	1.63(-1)
a^{2}G–c^{2}G	9–9	5673.21	E2	3.77(-1)	4.02(-1)
	9–7	5662.03	M1,E2	9.93(-3)	9.31(-3)*
	7–9	5847.32	E2	4.07(-2)	4.44(-2)
	7–7	5835.45	E2	4.07(-1)	4.38(-1)
a^{2}G–b^{2}D	9–5	4898.61	E2	1.22(+0)	1.33(+0)
	7–5	5027.88	E2	8.89(-2)	9.72(-2)
	7–3	5060.08	E2	8.23(-1)	8.85(-1)
a^{2}G–c^{2}D	9–5	4479.12	E2	1.75(-1)	1.55(-1)
	7–5	4586.96	E2	2.96(-2)	2.90(-2)
	7–3	4576.39	E2	6.69(-1)	6.90(-1)
a^{2}P–a^{2}P	3–1	190015.29	M1	2.46(-3)	2.54(-3)
a^{2}P–a^{2}D	3–5	46362.88	M1	7.17(-3)	7.30(-3)
	3–3	33919.07	M1	5.10(-2)	5.08(-2)
	1–3	41289.55	M1	9.29(-3)	9.20(-3)
a^{2}P–b^{2}P	3–3	13460.80	M1,E2	6.80(-3)	7.42(-3)*
	3–1	11662.56	M1,E2	1.20(-2)	1.27(-2)*
	1–3	14487.07	M1,E2	3.90(-3)	4.04(-3)*
a^{2}P–a^{2}F	3–7	11164.80	E2	1.06(-2)	9.94(-3)
	3–5	10796.46	E2	7.64(-3)	7.03(-3)
	1–5	11446.86	E2	8.25(-3)	7.57(-3)
a^{2}P–b^{4}D	3–1	7685.58	M1,E2	2.18(-3)	2.29(-3)
a^{2}P–b^{2}F	3–7	7330.22	E2	1.21(-3)	1.15(-3)
	3–5	7432.25	M1,E2	3.03(-3)	2.28(-3)
	1–5	7734.79	E2	1.07(-3)	8.53(-4)
a^{2}P–c^{2}G	3–7	6602.93	E2	1.45(-3)	1.56(-3)
a^{2}P–b^{2}D	3–5	5587.45	E2	3.84(-2)	3.55(-2)
	3–3	5627.25	E2	2.21(-1)	2.30(-1)
	1–5	5756.74	E2	2.74(-2)	2.78(-2)
	1–3	5798.99	E2	1.32(-1)	1.38(-1)
a^{2}P–a^{2}S	3–1	5298.88	M1,E2	2.32(-2)	2.63(-2)
	1–1	5450.88	M1	5.20(-3)	6.35(-3)
a^{2}P–c^{2}D	3–5	5048.19	E2	5.20(-1)	5.77(-1)
	3–3	5035.40	E2	1.15(-1)	1.27(-1)

Table 4. continued

Multiplet	$2J$–$2J'$	λ(Å)^a	Type	A_{ki}(SST)	A_{ki}(HFR)
a^{2}D–b^{2}P	5–3	18967.85	M1,E2	1.70(-3)	1.96(-3)
	5–1	15582.29	E2	2.70(-3)	2.94(-3)
	3–1	17773.84	M1,E2	3.83(-3)	4.08(-3)
a^{2}D–a^{2}F	5–7	14706.28	E2	2.49(-3)	2.20(-3)
a^{2}D–b^{2}G	5–9	10127.31	E2	1.16(-2)	1.14(-2)
	3–7	10571.90	E2	1.04(-2)	1.04(-2)
a^{2}D–b^{4}D	5–7	9116.41	M1	2.52(-3)	2.98(-3)
a^{2}D–b^{2}F	5–7	8706.82	M1,E2	1.06(-2)	8.46(-3)
	5–5	8851.15	M1,E2	9.92(-3)	9.18(-3)*
	3–5	9517.77	M1,E2	6.03(-3)	5.19(-3)
a^{2}D–c^{2}G	5–9	7720.18	E2	3.67(-2)	3.97(-2)
	5–7	7699.50	M1,E2	2.45(-3)	2.59(-3)
	3–7	8199.03	E2	2.42(-2)	2.59(-2)
a^{2}D–b^{2}D	5–5	6353.11	E2	2.34(-1)	2.45(-1)
	5–3	6404.61	M1,E2	8.33(-2)	8.64(-2)*
	3–5	6689.41	M1,E2	6.70(-2)	6.47(-2)*
	3–3	6746.53	E2	7.03(-2)	7.45(-2)
a^{2}D–a^{2}S	5–1	5982.65	E2	3.01(-1)	3.32(-1)
	3–1	6279.95	M1,E2	2.05(-1)	2.31(-1)
a^{2}D–c^{2}D	5–5	5665.04	M1,E2	2.69(-2)	2.69(-2)*
	5–3	5648.93	M1,E2	4.20(-2)	4.42(-2)*
	3–5	5930.91	M1,E2	1.05(-2)	1.12(-2)*
	3–3	5913.26	E2	1.32(-1)	1.39(-1)
b^{4}P–b^{4}P	5–3	101859.17	M1	2.22(-2)	2.03(-2)
	3–1	167237.23	M1	9.49(-3)	9.50(-3)
b^{4}P–b^{2}P	5–3	20167.90	M1	4.20(-2)	4.35(-2)
	3–3	25146.95	M1	1.42(-2)	1.51(-2)
	3–1	19523.29	M1	4.17(-3)	3.99(-3)
	1–3	29597.43	M1	6.15(-3)	6.45(-3)
	1–1	22103.68	M1	2.20(-2)	2.47(-2)
b^{4}P–b^{4}D	5–7	9384.80	M1,E2	3.98(-2)	3.97(-2)
	5–5	9469.46	M1,E2	2.40(-2)	2.43(-2)*
	5–3	9490.59	M1,E2	1.58(-2)	1.57(-2)
	3–5	10440.03	M1	5.77(-3)	5.92(-3)
	3–3	10465.73	M1	3.25(-2)	3.25(-2)
	3–1	10461.34	M1,E2	2.90(-2)	2.89(-2)
	1–1	11159.40	M1	4.24(-2)	4.22(-2)
b^{4}P–b^{2}D	5–5	6482.31	M1,E2	4.29(-2)	4.61(-2)*
	5–3	6535.93	M1,E2	2.07(-3)	2.45(-3)*
	3–5	6922.89	M1	9.35(-3)	9.50(-3)
	3–3	6984.08	M1,E2	2.19(-3)	2.28(-3)
b^{4}P–a^{2}S	5–1	6097.08	E2	5.24(-3)	6.80(-3)
	3–1	6485.28	M1	5.54(-1)	5.70(-1)
	1–1	6746.92	M1	1.45(-1)	1.52(-1)
b^{4}P–c^{2}D	5–5	5767.54	M1,E2	6.42(-2)	6.92(-2)*
	5–3	5750.84	M1,E2	1.22(-2)	1.42(-2)
	3–5	6113.72	M1,E2	1.00(-2)	1.10(-2)
	3–3	6094.96	M1	3.97(-2)	4.35(-2)
	1–3	6325.50	M1	9.50(-3)	1.04(-2)
a^{4}H–a^{4}G	13–11	23933.12	M1	2.11(-2)	2.10(-2)
	11–11	25003.06	M1	1.14(-2)	1.17(-2)*
	11–9	22851.06	M1,E2	2.50(-3)	2.57(-3)
	9–9	23669.52	M1	1.73(-2)	1.79(-2)*
	9–7	22721.12	M1,E2	2.78(-3)	2.69(-3)
	7–7	23414.40	M1	1.86(-2)	1.96(-2)
	7–5	23016.63	M1	3.04(-2)	3.12(-2)
a^{4}H–b^{2}H	13–11	20325.56	M1	1.01(-2)	1.18(-2)
	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]

Table 4. continued

Multiplet	2J–2J'	λ(Å)[a]	Type	A_{ki}(SST)	A_{ki}(HFR)
	9–9	31555.85	M1	1.41(-2)	1.42(-2)*
	9–7	29892.40	M1	1.68(-3)	1.50(-3)
	7–9	33380.21	M1	1.45(-3)	1.46(-3)
	7–7	31524.51	M1	2.02(-2)	2.00(-2)
	7–5	30807.67	M1	1.89(-3)	1.70(-3)
	5–7	32861.23	M1	1.79(-3)	1.75(-3)
	5–5	32083.06	M1	1.81(-2)	1.78(-2)
	3–5	33058.45	M1	1.50(-2)	1.49(-2)
b⁴F–b²H	9–11	28297.08	M1	1.43(-3)	1.97(-3)
	9–9	26906.50	M1	1.30(-3)	1.24(-3)
	7–9	28221.67	M1	1.36(-3)	1.68(-3)
b⁴F–a²F	9–7	21372.15	M1	1.95(-3)	2.43(-3)
	5–5	21356.90	M1	1.15(-3)	1.28(-3)
b⁴F–b²G	9–9	12897.48	M1	1.64(-2)	1.84(-2)
	7–9	13192.17	M1	5.85(-3)	6.55(-3)
	7–7	12568.65	M1	5.34(-3)	5.85(-3)
	5–7	12775.85	M1	4.77(-3)	5.21(-3)
b⁴F–b⁴D	9–7	11301.49	M1,E2	7.90(-3)	7.53(-3)
	7–7	11527.12	M1,E2	2.77(-3)	2.15(-3)*
	5–7	11701.16	M1,E2	1.26(-3)	1.11(-3)
	5–5	11833.06	M1,E2	3.29(-3)	3.25(-3)*
	5–3	11866.08	M1,E2	1.52(-3)	1.50(-3)
	5–1	11860.43	E2	1.22(-3)	1.84(-3)
	3–3	11996.99	M1,E2	2.75(-3)	2.81(-3)
	3–1	11991.22	M1,E2	4.33(-3)	4.25(-3)
b⁴F–b²F	7–7	10879.96	M1	1.10(-3)	1.28(-3)*
	5–7	11034.88	M1	1.31(-3)	1.68(-3)
b⁴F–c²G	9–9	9231.72	M1	1.75(-1)	1.84(-1)*
	9–7	9202.15	M1	1.08(-2)	1.15(-2)
	7–9	9381.72	M1	5.84(-2)	6.15(-2)
	7–7	9351.19	M1	8.15(-2)	8.68(-2)
	5–7	9465.41	M1	5.75(-2)	6.13(-2)
b⁴F–b²D	7–5	7437.01	M1	1.20(-2)	1.23(-2)
	5–5	7509.07	M1	1.61(-3)	1.64(-3)*
	3–5	7561.29	M1	1.37(-3)	1.36(-3)
b⁴F–c²D	7–5	6511.23	M1	1.57(-1)	1.56(-1)
	5–5	6566.40	M1	2.00(-2)	1.93(-2)*
	5–3	6544.77	M1	1.94(-1)	1.95(-1)
	3–5	6606.30	M1	7.72(-3)	7.55(-3)
	3–3	6584.40	M1	1.13(-1)	1.13(-1)
a⁴G–a⁴G	11–9	265496.60	M1	1.75(-3)	1.44(-3)
a⁴G–b²H	11–11	134843.19	M1	1.04(-3)	2.04(-3)*
a⁴G–a²F	9–7	66225.09	M1	3.60(-3)	3.74(-3)
	7–5	61004.37	M1	3.04(-3)	2.87(-3)
	5–5	63880.75	M1	2.30(-3)	2.32(-3)
a⁴G–b²G	9–9	21812.81	M1	2.87(-3)	3.81(-3)*
	7–7	20902.29	M1	2.73(-3)	3.36(-3)
	5–7	21229.82	M1	4.89(-3)	5.78(-3)
a⁴G–b²F	7–5	17147.42	M1	1.02(-3)	1.72(-3)
a⁴G–a²I	11–11	13363.31	M1	4.00(-3)	5.10(-3)*
a⁴G–c²G	11–9	12438.00	M1	8.07(-3)	1.02(-2)
	9–9	13049.34	M1	3.14(-3)	4.01(-3)*
	7–7	13294.91	M1	2.34(-3)	3.38(-3)*
	5–7	13426.66	M1	3.75(-3)	4.99(-3)
a⁴G–c²D	7–5	8206.20	M1	5.48(-3)	6.48(-3)
	5–5	8256.21	M1	4.99(-3)	6.23(-3)
b²P–b²P	3–1	87301.00	M1	2.70(-2)	2.68(-2)
b²P–b⁴D	3–5	17851.15	M1	6.61(-3)	6.83(-3)
	1–3	22558.60	M1	6.42(-3)	6.65(-3)
	1–1	22538.20	M1	2.35(-3)	2.41(-3)
b²P–b²D	3–5	9552.75	M1,E2	1.68(-2)	1.61(-2)
	3–3	9669.66	M1,E2	6.16(-2)	6.26(-2)
	1–3	10874.11	M1,E2	1.36(-2)	1.39(-2)
b²P–a²S	3–1	8739.06	M1	1.56(-1)	1.62(-1)
	1–1	9711.19	M1	1.55(-1)	1.60(-1)
b²P–c²D	3–5	8077.55	M1,E2	2.25(-2)	2.67(-2)
	3–3	8044.84	M1,E2	2.09(-2)	2.46(-2)
	1–3	8861.43	M1,E2	9.16(-3)	1.08(-2)
b²H–b²G	11–9	23699.43	M1	1.50(-2)	1.53(-2)
	9–9	24771.66	M1	2.00(-2)	2.01(-2)*
	9–7	22660.71	M1	1.44(-2)	1.44(-2)
b²H–a²I	11–13	14909.12	M1	1.35(-2)	1.44(-2)
	11–11	14833.34	M1	2.66(-2)	2.79(-2)*
	9–11	15246.38	M1	1.16(-2)	1.23(-2)
b²H–c²G	11–9	13701.87	M1	2.64(-2)	2.57(-2)
	9–9	14053.56	M1	5.27(-2)	5.28(-2)*
	9–7	13985.16	M1	2.93(-2)	2.94(-2)

Table 4. continued

Multiplet	2J–2J'	λ(Å)[a]	Type	A_{ki}(SST)	A_{ki}(HFR)
a²F–b²G	7–9	32526.05	M1	6.37(-3)	7.19(-3)
	7–7	28981.21	M1	1.88(-2)	2.01(-2)
	5–7	31797.13	M1	5.67(-3)	6.31(-3)
a²F–b⁴D	7–7	23984.28	M1	1.21(-3)	1.12(-3)*
a²F–b²F	7–5	22231.47	M1,E2	1.11(-3)	1.86(-3)*
a²F–c²G	7–9	16251.65	M1	2.75(-2)	3.03(-2)
	7–7	16160.26	M1	5.63(-2)	6.01(-2)*
	5–7	16999.73	M1	1.85(-2)	1.93(-2)
a²F–b²D	7–5	11185.12	M1,E2	1.76(-3)	1.08(-3)
	5–5	11580.95	M1,E2	1.40(-3)	7.82(-4)*
	5–3	11753.22	M1,E2	5.25(-3)	4.66(-3)*
a²F–c²D	7–5	9214.68	M1,E2	4.17(-2)	4.26(-2)
	5–5	9481.66	M1	7.28(-2)	7.32(-2)
	5–3	9436.63	M1,E2	3.81(-2)	3.90(-2)
b⁴D–b²D	7–5	20959.78	M1	1.44(-3)	1.44(-3)
b⁴D–c²D	7–5	14963.71	M1	4.22(-2)	3.98(-2)
	5–5	14753.41	M1	8.88(-3)	8.83(-3)*
	5–3	14644.66	M1	4.86(-3)	4.68(-3)
	3–5	14702.40	M1	1.75(-2)	1.70(-2)
	3–3	14594.40	M1	1.40(-2)	1.38(-2)
	1–3	14602.95	M1	3.61(-2)	3.53(-2)
b²D–c²D	5–3	50965.15	M1	1.07(-2)	1.01(-2)
	3–5	49059.15	M1	7.85(-3)	7.45(-3)

[a] The wavelengths, given in air, are deduced from the observed energy levels compiled by Sugar & Corliss (1985).
* Cancellation effects (see text).

Table 5. Comparison of the transition probabilities, A_{ki} in s^{-1}, calculated in the present work using SST and HFR with those obtained by Nussbaumer & Storey (1988) (NS) for the [illegible]

Multiplet	2J–2J'	Type	NS	SST	HFR
a^6D–a^6D	9–7	M1	2.13(-3)	2.13(-3)	2.05(-3)
	7–5	M1	1.57(-3)	1.57(-3)	1.56(-3)
	5–3	M1	7.18(-4)	7.18(-4)	7.28(-4)
	3–1	M1	1.88(-4)	1.89(-4)	1.94(-4)
a^6D–a^4F	9–9	M1	4.17(-5)	9.15(-5)	5.35(-5)
	7–9	M1	2.72(-6)	8.36(-6)	4.77(-6)
	9–7	M1	8.89(-6)	3.04(-5)	1.66(-5)
	7–7	M1	3.71(-5)	6.39(-5)	3.93(-5)
	5–7	M1	5.80(-6)	1.14(-5)	6.93(-6)
	7–5	M1	1.10(-5)	2.31(-5)	1.36(-5)
	5–5	M1	2.47(-5)	3.69(-5)	2.37(-5)
	3–5	M1	5.73(-6)	8.89(-6)	5.67(-6)
	5–3	M1	6.14(-6)	9.87(-6)	6.18(-6)
	3–3	M1	1.09(-5)	1.51(-5)	9.90(-6)
	1–3	M1	2.71(-6)	3.74(-6)	2.46(-6)
a^4F–a^4F	9–7	M1	5.84(-3)	5.84(-3)	6.01(-3)
	7–5	M1	3.92(-3)	3.92(-3)	4.17(-3)
	5–3	M1	1.41(-3)	1.41(-3)	1.53(-3)
a^6D–a^4D	9–7	M1	4.83(-3)	4.74(-3)	5.18(-3)
	7–7	M1	1.33(-3)	1.31(-3)	1.44(-3)
	5–7	M1	9.03(-4)	8.42(-4)	8.93(-4)
	9–5	E2	2.67(-6)	5.84(-6)	3.50(-6)
	7–5	M1	3.19(-4)	3.78(-4)	4.62(-4)
	5–5	M1	1.94(-3)	1.98(-3)	2.23(-3)
	3–5	M1	1.21(-3)	1.17(-3)	1.30(-3)
	7–3	E2	1.14(-6)	2.62(-6)	1.44(-6)
	5–3	M1	8.51(-5)	4.64(-5)	4.70(-5)
	3–3	M1	2.25(-3)	2.45(-3)	2.80(-3)
	1–3	M1	1.00(-3)	1.08(-3)	1.23(-3)
	3–1	M1	6.48(-4)	6.46(-4)	7.30(-4)
	1–1	M1	2.91(-3)	3.32(-3)	3.82(-3)

Table 5. continued

Multiplet	2J–2J'	Type	NS	SST	HFR
a^4D–a^4P	7–5	M1,E2	1.84(-3)	2.23(-3)	2.30(-3)
	1–5	E2	2.89(-5)	3.36(-5)	3.22(-5)
	7–3	E2	1.92(-3)	2.25(-3)	2.23(-3)
	5–3	M1,E2	3.56(-5)	6.28(-5)	4.86(-5)
	3–3	M1,E2	5.79(-4)	6.35(-4)	6.74(-4)
	1–3	M1,E2	5.12(-4)	5.77(-4)	5.93(-4)
	5–1	E2	2.34(-3)	2.76(-3)	2.79(-3)
	3–1	E2	7.81(-4)	9.09(-4)	9.20(-4)
	1–1	M1	1.13(-4)	4.04(-5)	9.90(-5)
a^4P–a^4P	5–3	M1	1.91(-4)	1.86(-4)	3.05(-4)
	3–1	M1	5.59(-4)	5.51(-4)	7.65(-4)