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Calculated oscillator strengths of singly ionized cobalt*

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Abstract. Transition probabilities of the spectrum of Co II are calculated using the orthogonal operator description for both the odd and the even energy levels.

Key words: atomic data — ISM: abundances — stars: chemically peculiar — supernovae

1. Introduction

The results from the Goddard High Resolution Spectrograph (GHRS) onboard the Hubble Space Telescope (HST) supersede the recordings of the International Ultraviolet Explorer (IUE) both in range and resolution, as expected. At the same time, however, this illustrates the increased necessity for accurate atomic parameters for spectrum synthesis and diagnostics.

In this work, we present atomic data on Co II, i.e. calculated $\log(gf)$ values of the ultraviolet transitions. Stellar spectra in the ultraviolet region show a wealth of lines from second spectra of transition elements: Fe-group, Pd-group and Pt-group elements occur predominantly in their "singly ionized" stage in the stellar atmospheres (specifically the photospheres) of B- to G-type stars. Moreover, the class of chemically peculiar (CP) stars is known to display enhanced abundances for these heavy elements, in serious deviation from the solar abundance pattern. Being an odd-Z element, cobalt is not as abundant as chromium, iron or nickel; on the other hand, its appearance in specific astrophysical objects like Co-stars and supernovae certainly makes a study worthwhile.

The present work is part of a series of transition probability calculations in the Fe-group transition elements using orthogonal operators (Raassen & Uylings 1997; Uylings & Raassen 1997). Computational details of the method can be found in the above references.

The spectrum of Co II has been recorded using the Imperial College Fourier transform spectrometer (Thorne et al. 1987), which is operational down to 1400 Å. Experimental details and results will be published in another paper (Pickering et al. 1997).

With its appreciable nuclear dipole moment, ^{59}Co (similar to ^{55}Mn in the Fe-group) displays a sizeable hyperfine structure. To some degree, this has already been studied in Co I (Dembczyński et al. 1993; Dembczyński 1996; Pickering 1996). As it obviously affects abundance determinations (the line profiles will appear "too broad", Biémont 1978), we plan to give A and B hyperfine structure constants in the near future; this work will include both the FTS obtained experimental values as the calculated eigenvector composition.

1.1. Astrophysical applications

Cobalt stars constitute a subgroup of CP stars for which the cobalt abundance justifies the special peculiarity label "Co"; they are mostly Ap-type, sometimes Bp-type. Co-stars often have strong magnetic fields (5 kG or more) which, in combination with the hyperfine structure, makes abundance determination a challenging task (Matthys 1995) in which accurate atomic data like transition probabilities are indispensable. Given the scarcity of large scale hfs measurements, hfs calculations are particularly important in this. Examples of Co-stars are the Bp star HR 1094 (Sadakane 1992), the Ap stars HD 200311 (Adelman 1974) and HD 203932 (Gelbmann et al. 1997) and possibly HD 208217 (Adelman et al. 1993) and HR 4059.

Stellar iron, nickel and cobalt are products of nuclear burning in a supernova event. Strong absorption lines can be found in supernovae of types Ia and II (Jaschek & Jaschek 1995) as a result of explosive nucleosynthesis. The strong Co II emission in late-type SN II may at early epochs be due to radioactive ^{56}Co which is, like ^{26}Fe, a

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* The full Table 7 is only available in electronic form at the CDS via anonymous ftp to cdsarc.u-strasbg.fr (130.79.128.5) or via http://cdsweb.u-strasbg.fr/Abstract.html

Table 1. Values for the electric dipole transition integrals in Co II calculated by means of MCDF including core polarization

	$3d^8$	$3d^74s$	$3d^64s^2$	$3d^74d$	$3d^75s$	$3d^75d$	$3d^76s$
$3d^74p$	.79	−2.65	-	−3.20	2.13	−0.79	0.57
$3d^64s4p$	-	0.65	−2.44	-	-	-	-
$3d^54s^24p$	-	-	0.55	-	-	-	-
$3d^75p$	0.22	0.03	-	4.88	−6.41	−6.00	4.89
$3d^74f$	0.19	-	-	−5.56	-	7.32	-

beta-decay product of ^{56}Ni (Rank et al. 1998); at later times, ^{57}Co and the stable isotope ^{59}Co become more important. Especially the supernova SN 1987 A has been studied in this respect. Transition probabilities of forbidden lines in the infra-red (like the features at 10.52 μm, 1.547 μm and 18.8 μm) have been calculated (Nussbaumer & Storey 1988) and observed (Jennings et al. 1993), but many M1 and E2 transitions are uncertain though needed (Li et al. 1993).

Absorption resonance lines of Co II are seen in the Interstellar Medium (ISM). The advantage of Co II (compared to Fe II e.g.) is that its lines are weaker which is more apt for ISM studies of abundances and depletions.

Widths of Co II lines have apparently been used to determine the chromospheric turbulent velocity of the supergiant α Orionis (M2 Iab) (Carpenter & Robinson 1997).

1.2. Orthogonal operators

Transition probability calculations of such complex systems as transition metals with their many closely lying energy levels, require highly accurate eigenvectors. A semi-empirical approach, in which parameters of a model Hamiltonian are adjusted to yield eigenvalues as closely as possible to the experimental energies, is an obvious tool for this purpose.

Orthogonal operators (Hansen et al. 1988), have the marked advantage that the parameters are stabilized in the fit. As a result, several smaller (higher order or relativistic) effects can meaningfully be added to raise the accuracy of both eigenvalues and eigenvectors.

First, the angular coefficients of the transition matrix in pure LS coupling are found from straightforward Racah algebra. They are multiplied with the transition integrals (given in Table 1) obtained from a relativistic Hartree-Fock program (MCDF from Parpia et al. 1996) and corrected for core polarization (Hameed 1972; Laughlin 1992). The result of core polarization is a decrease of $5-10\%$ of the absolute values of the transition integrals from Parpia et al.

Second, the pure but unphysical LS transition matrix is transformed into the actual intermediate coupling by the eigenvectors obtained from the orthogonal operator approach. The squared matrix elements of this final transition matrix yield the line strengths and thereby the log(gf) or the A-values.

For details on the method and parameter values, we refer to our overview article on $d^{N-1}p$ configurations (Uylings & Raassen 1996). Those interested in orthogonal operators are invited to contact the authors or to visit our Internet address ftp://nucleus.phys.uva.nl in the directory pub/orth.

2. Transition probabilities

To calculate the ($3d^8$+$3d^74s$) → $3d^74p$ transitions in Co II properly, it is necessary to take several neighbouring configurations into account: we used ($3d^8$+$3d^74s$+$3d^64s^2$+$3d^74d$+$3d^75s$) for the even and ($3d^74p$+$3d^64s4p$+$3d^54s^24p$+$3d^75p$+$3d^74f$) for the odd system. Interactions with other (far-lying) configurations are taken into account by means of so-called effective operators. The overall mean deviations are 39 cm^{-1} for the even system and 19 cm^{-1} for the odd system. The mean deviations for the individual lower configurations are 1.4, 7.1 and 15 cm^{-1} for $3d^8$, $3d^74s$ and $3d^74p$, respectively.

2.1. E1 results

In Table 2 the log(gf) values for the ($3d^8$+$3d^74s$) → $3d^74p$ electric dipole (E1) transitions are given. This system is selected by cutting off energy values higher than 120 000 cm^{-1} of both the even and the odd system in the final printing procedure; only log(gf) values larger than −3 are included. In this paper a sample focusing on the resonance lines is given, as these UV lines are of most interest in ISM absorption observations; as explained in a footnote to the abstract, the complete table can be obtained at CDS.

The first column of this table shows the wavelength obtained from the energy differences between the experimental level values. Wavelengths below 2000 Å are given as vacuum wavelengths and above 2000 Å as air wavelengths. The second column gives the log(gf) values followed by the J-value, energy value and the name of the lower (even) level. The first character of the level name designates the configuration number: for the even levels "1" refers to $3d^8$ and "2" to $3d^74s$; for the odd levels "1" refers to $3d^74p$. An "*" after the energy value indicates that the level is known, in which case the experimental

Table 2. Calculated $\log(gf)$ values for the $(3d^8+3d^7 4s) - 3d^7 4p$ transition array of Co II

λ(Å)	$\log(gf)$	J_f	$E_\mathrm{f}(\mathrm{cm}^{-1})$	even	J_i	$E_\mathrm{i}(\mathrm{cm}^{-1})$	odd
2845.666	−2.680	2.0	11321.86*	$2\vert{}^4_3\mathrm{F})^3\mathrm{F}$	2.0	46452.70*	$1\vert{}^4_3\mathrm{F})^5\mathrm{F}$
2834.943	−2.190	3.0	10708.33*	$2\vert{}^4_3\mathrm{F})^3\mathrm{F}$	3.0	45972.03*	$1\vert{}^4_3\mathrm{F})^5\mathrm{F}$
2825.237	−1.731	4.0	9812.86*	$2\vert{}^4_3\mathrm{F})^3\mathrm{F}$	5.0	45197.71*	$1\vert{}^4_3\mathrm{F})^5\mathrm{F}$
2818.888	−2.543	2.0	11321.86*	$2\vert{}^4_3\mathrm{F})^3\mathrm{F}$	1.0	46786.41*	$1\vert{}^4_3\mathrm{F})^5\mathrm{F}$
2810.855	−1.809	4.0	9812.86*	$2\vert{}^4_3\mathrm{F})^3\mathrm{F}$	4.0	45378.75*	$1\vert{}^4_3\mathrm{F})^5\mathrm{F}$
2807.176	−2.208	3.0	10708.33*	$2\vert{}^4_3\mathrm{F})^3\mathrm{F}$	4.0	46320.83*	$1\vert{}^4_3\mathrm{F})^5\mathrm{D}$
2798.943	−2.789	2.0	11321.86*	$2\vert{}^4_3\mathrm{F})^3\mathrm{F}$	3.0	47039.10*	$1\vert{}^4_3\mathrm{F})^5\mathrm{D}$
2796.819	−2.685	3.0	10708.33*	$2\vert{}^4_3\mathrm{F})^3\mathrm{F}$	2.0	46452.70*	$1\vert{}^4_3\mathrm{F})^5\mathrm{F}$
2738.318	−2.979	4.0	9812.86*	$2\vert{}^4_3\mathrm{F})^3\mathrm{F}$	4.0	46320.83*	$1\vert{}^4_3\mathrm{F})^5\mathrm{D}$
2714.441	−1.256	2.0	11321.86*	$2\vert{}^4_3\mathrm{F})^3\mathrm{F}$	3.0	48150.94*	$1\vert{}^4_3\mathrm{F})^5\mathrm{G}$
2697.048	−1.982	2.0	11321.86*	$2\vert{}^4_3\mathrm{F})^3\mathrm{F}$	2.0	48388.44*	$1\vert{}^4_3\mathrm{F})^5\mathrm{G}$
2694.679	−.762	3.0	10708.33*	$2\vert{}^4_3\mathrm{F})^3\mathrm{F}$	4.0	47807.49*	$1\vert{}^4_3\mathrm{F})^5\mathrm{G}$
2693.091	−2.089	2.0	13260.69*	$1\vert{}^3_2\mathrm{P})$	3.0	50381.72*	$1\vert{}^4_3\mathrm{F})^3\mathrm{F}$
2669.960	−2.768	3.0	10708.33*	$2\vert{}^4_3\mathrm{F})^3\mathrm{F}$	3.0	48150.94*	$1\vert{}^4_3\mathrm{F})^5\mathrm{G}$
2665.163	−2.606	1.0	13404.32*	$1\vert{}^3_2\mathrm{P})$	2.0	50914.32*	$1\vert{}^4_3\mathrm{F})^3\mathrm{F}$
2663.531	−.324	4.0	9812.86*	$2\vert{}^4_3\mathrm{F})^3\mathrm{F}$	5.0	47345.84*	$1\vert{}^4_3\mathrm{F})^5\mathrm{G}$
2613.491	−.825	2.0	13260.69*	$1\vert{}^3_2\mathrm{P})$	3.0	51512.26*	$1\vert{}^4_3\mathrm{F})^3\mathrm{D}$
2604.402	−1.736	2.0	11651.28*	$1\vert{}^1_2\mathrm{D})$	3.0	50036.35*	$1\vert{}^4_3\mathrm{F})^3\mathrm{G}$
2587.220	.028	3.0	10708.33*	$2\vert{}^4_3\mathrm{F})^3\mathrm{F}$	4.0	49348.30*	$1\vert{}^4_3\mathrm{F})^3\mathrm{G}$
2582.240	.043	2.0	11321.86*	$2\vert{}^4_3\mathrm{F})^3\mathrm{F}$	3.0	50036.35*	$1\vert{}^4_3\mathrm{F})^3\mathrm{G}$
2581.176	−2.699	2.0	11651.28*	$1\vert{}^1_2\mathrm{D})$	3.0	50381.72*	$1\vert{}^4_3\mathrm{F})^3\mathrm{F}$
2580.326	.392	4.0	9812.86*	$2\vert{}^4_3\mathrm{F})^3\mathrm{F}$	5.0	48556.05*	$1\vert{}^4_3\mathrm{F})^3\mathrm{G}$
2574.862	−.934	1.0	13404.32*	$1\vert{}^3_2\mathrm{P})$	2.0	52229.72*	$1\vert{}^4_3\mathrm{F})^3\mathrm{D}$
2565.371	−1.528	2.0	13260.69*	$1\vert{}^3_2\mathrm{P})$	2.0	52229.72*	$1\vert{}^4_3\mathrm{F})^3\mathrm{D}$
2564.034	.072	3.0	10708.33*	$2\vert{}^4_3\mathrm{F})^3\mathrm{F}$	4.0	49697.68*	$1\vert{}^4_3\mathrm{F})^3\mathrm{F}$
2559.405	−.170	2.0	11321.86*	$2\vert{}^4_3\mathrm{F})^3\mathrm{F}$	3.0	50381.72*	$1\vert{}^4_3\mathrm{F})^3\mathrm{F}$
2557.344	−1.270	.0	13593.29*	$1\vert{}^3_2\mathrm{P})$	1.0	52684.63*	$1\vert{}^4_3\mathrm{F})^3\mathrm{D}$
2546.160	−1.636	2.0	11651.28*	$1\vert{}^1_2\mathrm{D})$	2.0	50914.32*	$1\vert{}^4_3\mathrm{F})^3\mathrm{F}$
2545.041	−1.398	1.0	13404.32*	$1\vert{}^3_2\mathrm{P})$	1.0	52684.63*	$1\vert{}^4_3\mathrm{F})^3\mathrm{D}$
2541.953	−.177	3.0	10708.33*	$2\vert{}^4_3\mathrm{F})^3\mathrm{F}$	3.0	50036.35*	$1\vert{}^4_3\mathrm{F})^3\mathrm{G}$
2535.768	−2.775	2.0	13260.69*	$1\vert{}^3_2\mathrm{P})$	1.0	52684.63*	$1\vert{}^4_3\mathrm{F})^3\mathrm{D}$
2528.616	.102	4.0	9812.86*	$2\vert{}^4_3\mathrm{F})^3\mathrm{F}$	4.0	49348.30*	$1\vert{}^4_3\mathrm{F})^3\mathrm{G}$
2524.974	.003	2.0	11321.86*	$2\vert{}^4_3\mathrm{F})^3\mathrm{F}$	2.0	50914.32*	$1\vert{}^4_3\mathrm{F})^3\mathrm{F}$
2519.823	−.110	3.0	10708.33*	$2\vert{}^4_3\mathrm{F})^3\mathrm{F}$	3.0	50381.72*	$1\vert{}^4_3\mathrm{F})^3\mathrm{F}$
2507.963	−1.138	2.0	11651.28*	$1\vert{}^1_2\mathrm{D})$	3.0	51512.26*	$1\vert{}^4_3\mathrm{F})^3\mathrm{D}$
2506.464	.062	4.0	9812.86*	$2\vert{}^4_3\mathrm{F})^3\mathrm{F}$	4.0	49697.68*	$1\vert{}^4_3\mathrm{F})^3\mathrm{F}$
2487.405	−1.588	2.0	11321.86*	$2\vert{}^4_3\mathrm{F})^3\mathrm{F}$	3.0	51512.26*	$1\vert{}^4_3\mathrm{F})^3\mathrm{D}$
2486.441	−.509	3.0	10708.33*	$2\vert{}^4_3\mathrm{F})^3\mathrm{F}$	2.0	50914.32*	$1\vert{}^4_3\mathrm{F})^3\mathrm{F}$
2485.360	−1.086	4.0	9812.86*	$2\vert{}^4_3\mathrm{F})^3\mathrm{F}$	3.0	50036.35*	$1\vert{}^4_3\mathrm{F})^3\mathrm{G}$
2464.199	−.394	4.0	9812.86*	$2\vert{}^4_3\mathrm{F})^3\mathrm{F}$	3.0	50381.72*	$1\vert{}^4_3\mathrm{F})^3\mathrm{F}$
2463.617	−2.784	2.0	11651.28*	$1\vert{}^1_2\mathrm{D})$	2.0	52229.72*	$1\vert{}^4_3\mathrm{F})^3\mathrm{D}$
2450.002	−.352	3.0	10708.33*	$2\vert{}^4_3\mathrm{F})^3\mathrm{F}$	3.0	51512.26*	$1\vert{}^4_3\mathrm{F})^3\mathrm{D}$
2449.160	−1.234	3.0	4560.79*	$2\vert{}^4_3\mathrm{F})^5\mathrm{F}$	4.0	45378.75*	$1\vert{}^4_3\mathrm{F})^5\mathrm{F}$
2443.777	−.498	2.0	11321.86*	$2\vert{}^4_3\mathrm{F})^3\mathrm{F}$	2.0	52229.72*	$1\vert{}^4_3\mathrm{F})^3\mathrm{D}$
2436.979	−1.026	2.0	4950.06*	$2\vert{}^4_3\mathrm{F})^5\mathrm{F}$	3.0	45972.03*	$1\vert{}^4_3\mathrm{F})^5\mathrm{F}$
2436.303	−1.799	2.0	11651.28*	$1\vert{}^1_2\mathrm{D})$	1.0	52684.63*	$1\vert{}^4_3\mathrm{F})^3\mathrm{D}$
2428.292	−1.227	4.0	4028.99*	$2\vert{}^4_3\mathrm{F})^5\mathrm{F}$	5.0	45197.71*	$1\vert{}^4_3\mathrm{F})^5\mathrm{F}$
2423.624	−1.003	1.0	5204.70*	$2\vert{}^4_3\mathrm{F})^5\mathrm{F}$	2.0	46452.70*	$1\vert{}^4_3\mathrm{F})^5\mathrm{F}$
2417.659	−.195	4.0	4028.99*	$2\vert{}^4_3\mathrm{F})^5\mathrm{F}$	4.0	45378.75*	$1\vert{}^4_3\mathrm{F})^5\mathrm{F}$
2416.899	−.095	2.0	11321.86*	$2\vert{}^4_3\mathrm{F})^3\mathrm{F}$	1.0	52684.63*	$1\vert{}^4_3\mathrm{F})^3\mathrm{D}$

Table 2. continued

λ(Å)	$\log(gf)$	J_f	$E_\mathrm{f}(\mathrm{cm}^{-1})$	even	J_i	$E_\mathrm{i}(\mathrm{cm}^{-1})$	odd
2414.069	−.294	3.0	4560.79*	$2\vert^{4}_{3}\mathrm{F})^{5}\mathrm{F}$	3.0	45972.03*	$1\vert^{4}_{3}\mathrm{F})^{5}\mathrm{F}$
2408.753	−.393	2.0	4950.06*	$2\vert^{4}_{3}\mathrm{F})^{5}\mathrm{F}$	2.0	46452.70*	$1\vert^{4}_{3}\mathrm{F})^{5}\mathrm{F}$
2407.665	.025	3.0	10708.33*	$2\vert^{4}_{3}\mathrm{F})^{3}\mathrm{F}$	2.0	52229.72*	$1\vert^{4}_{3}\mathrm{F})^{3}\mathrm{D}$
2404.172	−.400	1.0	5204.70*	$2\vert^{4}_{3}\mathrm{F})^{5}\mathrm{F}$	1.0	46786.41*	$1\vert^{4}_{3}\mathrm{F})^{5}\mathrm{F}$
2397.386	.161	4.0	9812.86*	$2\vert^{4}_{3}\mathrm{F})^{3}\mathrm{F}$	3.0	51512.26*	$1\vert^{4}_{3}\mathrm{F})^{3}\mathrm{D}$
2393.904	−1.191	3.0	4560.79*	$2\vert^{4}_{3}\mathrm{F})^{5}\mathrm{F}$	4.0	46320.83*	$1\vert^{4}_{3}\mathrm{F})^{5}\mathrm{D}$
2389.538	−.350	2.0	4950.06*	$2\vert^{4}_{3}\mathrm{F})^{5}\mathrm{F}$	1.0	46786.41*	$1\vert^{4}_{3}\mathrm{F})^{5}\mathrm{F}$
2388.917	.484	5.0	3350.49*	$2\vert^{4}_{3}\mathrm{F})^{5}\mathrm{F}$	5.0	45197.71*	$1\vert^{4}_{3}\mathrm{F})^{5}\mathrm{F}$
2386.368	−.047	3.0	4560.79*	$2\vert^{4}_{3}\mathrm{F})^{5}\mathrm{F}$	2.0	46452.70*	$1\vert^{4}_{3}\mathrm{F})^{5}\mathrm{F}$
2383.459	.127	4.0	4028.99*	$2\vert^{4}_{3}\mathrm{F})^{5}\mathrm{F}$	3.0	45972.03*	$1\vert^{4}_{3}\mathrm{F})^{5}\mathrm{F}$
2378.626	.247	5.0	3350.49*	$2\vert^{4}_{3}\mathrm{F})^{5}\mathrm{F}$	4.0	45378.75*	$1\vert^{4}_{3}\mathrm{F})^{5}\mathrm{F}$
2375.190	−1.104	2.0	4950.06*	$2\vert^{4}_{3}\mathrm{F})^{5}\mathrm{F}$	3.0	47039.10*	$1\vert^{4}_{3}\mathrm{F})^{5}\mathrm{D}$
2363.800	.250	4.0	4028.99*	$2\vert^{4}_{3}\mathrm{F})^{5}\mathrm{F}$	4.0	46320.83*	$1\vert^{4}_{3}\mathrm{F})^{5}\mathrm{D}$
2361.520	−1.177	1.0	5204.70*	$2\vert^{4}_{3}\mathrm{F})^{5}\mathrm{F}$	2.0	47537.36*	$1\vert^{4}_{3}\mathrm{F})^{5}\mathrm{D}$
2353.422	.110	3.0	4560.79*	$2\vert^{4}_{3}\mathrm{F})^{5}\mathrm{F}$	3.0	47039.10*	$1\vert^{4}_{3}\mathrm{F})^{5}\mathrm{D}$
2347.399	−.081	2.0	4950.06*	$2\vert^{4}_{3}\mathrm{F})^{5}\mathrm{F}$	2.0	47537.36*	$1\vert^{4}_{3}\mathrm{F})^{5}\mathrm{D}$
2344.273	−.365	1.0	5204.70*	$2\vert^{4}_{3}\mathrm{F})^{5}\mathrm{F}$	1.0	47848.79*	$1\vert^{4}_{3}\mathrm{F})^{5}\mathrm{D}$
2336.230	−.580	1.0	5204.70*	$2\vert^{4}_{3}\mathrm{F})^{5}\mathrm{F}$	.0	47995.59*	$1\vert^{4}_{3}\mathrm{F})^{5}\mathrm{D}$
2330.357	−.442	2.0	4950.06*	$2\vert^{4}_{3}\mathrm{F})^{5}\mathrm{F}$	1.0	47848.79*	$1\vert^{4}_{3}\mathrm{F})^{5}\mathrm{D}$
2326.473	−.214	5.0	3350.49*	$2\vert^{4}_{3}\mathrm{F})^{5}\mathrm{F}$	4.0	46320.83*	$1\vert^{4}_{3}\mathrm{F})^{5}\mathrm{D}$
2326.135	−.360	3.0	4560.79*	$2\vert^{4}_{3}\mathrm{F})^{5}\mathrm{F}$	2.0	47537.36*	$1\vert^{4}_{3}\mathrm{F})^{5}\mathrm{D}$
2324.321	−.286	4.0	4028.99*	$2\vert^{4}_{3}\mathrm{F})^{5}\mathrm{F}$	3.0	47039.10*	$1\vert^{4}_{3}\mathrm{F})^{5}\mathrm{D}$
2314.975	.110	1.0	5204.70*	$2\vert^{4}_{3}\mathrm{F})^{5}\mathrm{F}$	2.0	48388.44*	$1\vert^{4}_{3}\mathrm{F})^{5}\mathrm{G}$
2314.057	.262	2.0	4950.06*	$2\vert^{4}_{3}\mathrm{F})^{5}\mathrm{F}$	3.0	48150.94*	$1\vert^{4}_{3}\mathrm{F})^{5}\mathrm{G}$
2311.604	.373	3.0	4560.79*	$2\vert^{4}_{3}\mathrm{F})^{5}\mathrm{F}$	4.0	47807.49*	$1\vert^{4}_{3}\mathrm{F})^{5}\mathrm{G}$
2307.860	.432	4.0	4028.99*	$2\vert^{4}_{3}\mathrm{F})^{5}\mathrm{F}$	5.0	47345.84*	$1\vert^{4}_{3}\mathrm{F})^{5}\mathrm{G}$
2301.403	−.776	2.0	4950.06*	$2\vert^{4}_{3}\mathrm{F})^{5}\mathrm{F}$	2.0	48388.44*	$1\vert^{4}_{3}\mathrm{F})^{5}\mathrm{G}$
2293.390	−.779	3.0	4560.79*	$2\vert^{4}_{3}\mathrm{F})^{5}\mathrm{F}$	3.0	48150.94*	$1\vert^{4}_{3}\mathrm{F})^{5}\mathrm{G}$
2286.159	.591	5.0	3350.49*	$2\vert^{4}_{3}\mathrm{F})^{5}\mathrm{F}$	6.0	47078.49*	$1\vert^{4}_{3}\mathrm{F})^{5}\mathrm{G}$
2283.521	−.983	4.0	4028.99*	$2\vert^{4}_{3}\mathrm{F})^{5}\mathrm{F}$	4.0	47807.49*	$1\vert^{4}_{3}\mathrm{F})^{5}\mathrm{G}$
2280.961	−1.923	3.0	4560.79*	$2\vert^{4}_{3}\mathrm{F})^{5}\mathrm{F}$	2.0	48388.44*	$1\vert^{4}_{3}\mathrm{F})^{5}\mathrm{G}$
2272.265	−1.520	5.0	3350.49*	$2\vert^{4}_{3}\mathrm{F})^{5}\mathrm{F}$	5.0	47345.84*	$1\vert^{4}_{3}\mathrm{F})^{5}\mathrm{G}$
2265.745	−1.923	4.0	4028.99*	$2\vert^{4}_{3}\mathrm{F})^{5}\mathrm{F}$	3.0	48150.94*	$1\vert^{4}_{3}\mathrm{F})^{5}\mathrm{G}$
2248.668	−2.265	5.0	3350.49*	$2\vert^{4}_{3}\mathrm{F})^{5}\mathrm{F}$	4.0	47807.49*	$1\vert^{4}_{3}\mathrm{F})^{5}\mathrm{G}$
2245.129	−.289	4.0	4028.99*	$2\vert^{4}_{3}\mathrm{F})^{5}\mathrm{F}$	5.0	48556.05*	$1\vert^{4}_{3}\mathrm{F})^{3}\mathrm{G}$
2232.072	−1.063	3.0	4560.79*	$2\vert^{4}_{3}\mathrm{F})^{5}\mathrm{F}$	4.0	49348.30*	$1\vert^{4}_{3}\mathrm{F})^{3}\mathrm{G}$
2220.460	−2.821	3.0	950.32*	$1\vert^{3}_{2}\mathrm{F})$	3.0	45972.03*	$1\vert^{4}_{3}\mathrm{F})^{5}\mathrm{F}$
2217.279	−1.665	2.0	4950.06*	$2\vert^{4}_{3}\mathrm{F})^{5}\mathrm{F}$	3.0	50036.35*	$1\vert^{4}_{3}\mathrm{F})^{3}\mathrm{G}$
2214.793	−1.032	3.0	4560.79*	$2\vert^{4}_{3}\mathrm{F})^{5}\mathrm{F}$	4.0	49697.68*	$1\vert^{4}_{3}\mathrm{F})^{3}\mathrm{F}$
2211.428	−1.225	5.0	3350.49*	$2\vert^{4}_{3}\mathrm{F})^{5}\mathrm{F}$	5.0	48556.05*	$1\vert^{4}_{3}\mathrm{F})^{3}\mathrm{G}$
2205.877	−1.589	4.0	4028.99*	$2\vert^{4}_{3}\mathrm{F})^{5}\mathrm{F}$	4.0	49348.30*	$1\vert^{4}_{3}\mathrm{F})^{3}\mathrm{G}$
2202.987	−2.555	4.0	.00*	$1\vert^{3}_{2}\mathrm{F})$	4.0	45378.75*	$1\vert^{4}_{3}\mathrm{F})^{5}\mathrm{F}$
2200.421	−1.450	2.0	4950.06*	$2\vert^{4}_{3}\mathrm{F})^{5}\mathrm{F}$	3.0	50381.72*	$1\vert^{4}_{3}\mathrm{F})^{3}\mathrm{F}$
2198.297	−2.082	3.0	4560.79*	$2\vert^{4}_{3}\mathrm{F})^{5}\mathrm{F}$	3.0	50036.35*	$1\vert^{4}_{3}\mathrm{F})^{3}\mathrm{G}$
2188.999	−1.958	4.0	4028.99*	$2\vert^{4}_{3}\mathrm{F})^{5}\mathrm{F}$	4.0	49697.68*	$1\vert^{4}_{3}\mathrm{F})^{3}\mathrm{F}$
2187.039	−1.908	1.0	5204.70*	$2\vert^{4}_{3}\mathrm{F})^{5}\mathrm{F}$	2.0	50914.32*	$1\vert^{4}_{3}\mathrm{F})^{3}\mathrm{F}$
2181.726	−2.191	3.0	4560.79*	$2\vert^{4}_{3}\mathrm{F})^{5}\mathrm{F}$	3.0	50381.72*	$1\vert^{4}_{3}\mathrm{F})^{3}\mathrm{F}$
2174.922	−2.722	2.0	4950.06*	$2\vert^{4}_{3}\mathrm{F})^{5}\mathrm{F}$	2.0	50914.32*	$1\vert^{4}_{3}\mathrm{F})^{3}\mathrm{F}$
2173.335	−1.976	5.0	3350.49*	$2\vert^{4}_{3}\mathrm{F})^{5}\mathrm{F}$	4.0	49348.30*	$1\vert^{4}_{3}\mathrm{F})^{3}\mathrm{G}$
2172.884	−2.587	4.0	4028.99*	$2\vert^{4}_{3}\mathrm{F})^{5}\mathrm{F}$	3.0	50036.35*	$1\vert^{4}_{3}\mathrm{F})^{3}\mathrm{G}$

Table 2. continued

λ(Å)	log(gf)	J_f	E_f(cm^{-1})	even	J_i	E_i(cm^{-1})	odd
2156.950	−2.080	5.0	3350.49*	$2\|{}^{4}_{3}\mathrm{F})^{5}\mathrm{F}$	4.0	49697.68*	$1\|{}^{4}_{3}\mathrm{F})^{3}\mathrm{F}$
2156.692	−2.738	4.0	4028.99*	$2\|{}^{4}_{3}\mathrm{F})^{5}\mathrm{F}$	3.0	50381.72*	$1\|{}^{4}_{3}\mathrm{F})^{3}\mathrm{F}$
2146.989	−2.507	2.0	4950.06*	$2\|{}^{4}_{3}\mathrm{F})^{5}\mathrm{F}$	3.0	51512.26*	$1\|{}^{4}_{3}\mathrm{F})^{3}\mathrm{D}$
2136.478	−2.950	2.0	1597.20*	$1\|{}^{3}_{2}\mathrm{F})$	2.0	48388.44*	$1\|{}^{4}_{3}\mathrm{F})^{5}\mathrm{G}$
2133.472	−2.472	3.0	950.32*	$1\|{}^{3}_{2}\mathrm{F})$	4.0	47807.49*	$1\|{}^{4}_{3}\mathrm{F})^{5}\mathrm{G}$
2125.856	−2.675	1.0	5204.70*	$2\|{}^{4}_{3}\mathrm{F})^{5}\mathrm{F}$	2.0	52229.72*	$1\|{}^{4}_{3}\mathrm{F})^{3}\mathrm{D}$
2117.946	−2.634	3.0	950.32*	$1\|{}^{3}_{2}\mathrm{F})$	3.0	48150.94*	$1\|{}^{4}_{3}\mathrm{F})^{5}\mathrm{G}$
2114.405	−2.812	2.0	4950.06*	$2\|{}^{4}_{3}\mathrm{F})^{5}\mathrm{F}$	2.0	52229.72*	$1\|{}^{4}_{3}\mathrm{F})^{3}\mathrm{D}$
2111.449	−1.863	4.0	.00*	$1\|{}^{3}_{2}\mathrm{F})$	5.0	47345.84*	$1\|{}^{4}_{3}\mathrm{F})^{5}\mathrm{G}$
2105.485	−2.615	1.0	5204.70*	$2\|{}^{4}_{3}\mathrm{F})^{5}\mathrm{F}$	1.0	52684.63*	$1\|{}^{4}_{3}\mathrm{F})^{3}\mathrm{D}$
2105.337	−2.565	4.0	4028.99*	$2\|{}^{4}_{3}\mathrm{F})^{5}\mathrm{F}$	3.0	51512.26*	$1\|{}^{4}_{3}\mathrm{F})^{3}\mathrm{D}$
2097.136	−2.633	3.0	4560.79*	$2\|{}^{4}_{3}\mathrm{F})^{5}\mathrm{F}$	2.0	52229.72*	$1\|{}^{4}_{3}\mathrm{F})^{3}\mathrm{D}$
2094.252	−2.795	2.0	4950.06*	$2\|{}^{4}_{3}\mathrm{F})^{5}\mathrm{F}$	1.0	52684.63*	$1\|{}^{4}_{3}\mathrm{F})^{3}\mathrm{D}$
2091.058	−2.543	4.0	.00*	$1\|{}^{3}_{2}\mathrm{F})$	4.0	47807.49*	$1\|{}^{4}_{3}\mathrm{F})^{5}\mathrm{G}$
2065.542	−1.106	3.0	950.32*	$1\|{}^{3}_{2}\mathrm{F})$	4.0	49348.30*	$1\|{}^{4}_{3}\mathrm{F})^{3}\mathrm{G}$
2063.786	−1.211	2.0	1597.20*	$1\|{}^{3}_{2}\mathrm{F})$	3.0	50036.35*	$1\|{}^{4}_{3}\mathrm{F})^{3}\mathrm{G}$
2058.817	−1.241	4.0	.00*	$1\|{}^{3}_{2}\mathrm{F})$	5.0	48556.05*	$1\|{}^{4}_{3}\mathrm{F})^{3}\mathrm{G}$
2050.736	−2.913	3.0	950.32*	$1\|{}^{3}_{2}\mathrm{F})$	4.0	49697.68*	$1\|{}^{4}_{3}\mathrm{F})^{3}\mathrm{F}$
2049.173	−2.103	2.0	1597.20*	$1\|{}^{3}_{2}\mathrm{F})$	3.0	50381.72*	$1\|{}^{4}_{3}\mathrm{F})^{3}\mathrm{F}$
2036.585	−1.506	3.0	950.32*	$1\|{}^{3}_{2}\mathrm{F})$	3.0	50036.35*	$1\|{}^{4}_{3}\mathrm{F})^{3}\mathrm{G}$
2027.040	−.572	2.0	1597.20*	$1\|{}^{3}_{2}\mathrm{F})$	2.0	50914.32*	$1\|{}^{4}_{3}\mathrm{F})^{3}\mathrm{F}$
2025.760	−.982	4.0	.00*	$1\|{}^{3}_{2}\mathrm{F})$	4.0	49348.30*	$1\|{}^{4}_{3}\mathrm{F})^{3}\mathrm{G}$
2022.354	−.481	3.0	950.32*	$1\|{}^{3}_{2}\mathrm{F})$	3.0	50381.72*	$1\|{}^{4}_{3}\mathrm{F})^{3}\mathrm{F}$
2011.516	−.399	4.0	.00*	$1\|{}^{3}_{2}\mathrm{F})$	4.0	49697.68*	$1\|{}^{4}_{3}\mathrm{F})^{3}\mathrm{F}$
2000.793	−1.918	3.0	950.32*	$1\|{}^{3}_{2}\mathrm{F})$	2.0	50914.32*	$1\|{}^{4}_{3}\mathrm{F})^{3}\mathrm{F}$
1984.847	−2.667	4.0	.00*	$1\|{}^{3}_{2}\mathrm{F})$	3.0	50381.72*	$1\|{}^{4}_{3}\mathrm{F})^{3}\mathrm{F}$
1975.015	−2.300	2.0	1597.20*	$1\|{}^{3}_{2}\mathrm{F})$	2.0	52229.72*	$1\|{}^{4}_{3}\mathrm{F})^{3}\mathrm{D}$
1957.429	−.852	2.0	1597.20*	$1\|{}^{3}_{2}\mathrm{F})$	1.0	52684.63*	$1\|{}^{4}_{3}\mathrm{F})^{3}\mathrm{D}$
1950.101	−.629	3.0	950.32*	$1\|{}^{3}_{2}\mathrm{F})$	2.0	52229.72*	$1\|{}^{4}_{3}\mathrm{F})^{3}\mathrm{D}$
1941.285	−.457	4.0	.00*	$1\|{}^{3}_{2}\mathrm{F})$	3.0	51512.26*	$1\|{}^{4}_{3}\mathrm{F})^{3}\mathrm{D}$

level value is given. When unknown, the calculated energy value is given and used to approximate the wavelength. Full results including weaker lines and lines involving higher lying levels can be found on Internet.

To have an indication of the accuracy, we compare our results with data from three different experiments as well as with the calculations from the well known database of Kurucz (Kurucz 1993).

- First of all, we compare in Table 3 Kurucz's and our log(gf) values with the results of a recent "state of the art" experiment to determine absolute oscillator strengths (Mullman et al. 1997). It can be seen that the present results are always close to the experimental ones, and 16 out of 28 can be considered "equal" to within the uncertainties specified.
- In Table 4, we make a comparison with the intensity numbers obtained by the recent FTS experiment (Pickering et al. 1997). The intensity numbers given by Pickering et al. are signal-to-noise ratios of the lines of the FT spectra. These values are useful in the comparison of one line to another; however, they do not show absolute intensities. All transitions considered are based on the lowest even term, the 3d^8 (${}^{3}_{2}$F). The order of our log(gf) values completely agrees with the order of experimental intensity numbers, and confirms the present approach.
- In the region 2300 to 2800 Å a number of 3d^{7}4s−3d^{7}4p transition probabilities can be compared with measured oscillator strengths of the 28 strongest lines in the multiplets UV7, UV8 and UV9 published in 1985 (Salih et al. 1985). With respect to earlier work of Kurucz (Kurucz & Peytremann 1975), Salih et al. observe good agreement for strong lines but less so for intercombination ($\Delta S = 1$) lines. At this point we would like to emphasize that the agreement with the current data of Kurucz's database (Kurucz 1993, semi-empirical Fe-group) is much better. The present method is not inherently different, except that use of orthogonal operators stabilizes the fit and allows the introduction of higher order effects into the model. As a result the eigenvector compositions should be more reliable, which is most obvious in intercombination lines. From Table 5 it seems that our calculated log(gf) values agree somewhat better for $\Delta S = 0$ also.

In general, the current data turn out to prevail in all three cases.

Table 3. Comparison between theory and experiment[a] of log(gf)-values for the ($3d^8$+$3d^7 4s$) → $3d^7 4p$ transitions involving the lowest even multiplets

λ(Å)	exp.[a]	present	Kurucz[b]	J_f	E_f(cm^{-1})	even	J_i	E_i(cm^{-1})	odd
2693.091	−2.20	−2.09	−1.94	2.0	13260.69*	$1\|^3_2\mathrm{P})$	3.0	50381.72*	$1\|^4_3\mathrm{F})^3\mathrm{F}$
2587.220	0.037	0.028	−0.49	3.0	10708.33*	$2\|^4_3\mathrm{F})^3\mathrm{F}$	4.0	49348.30*	$1\|^4_3\mathrm{F})^3\mathrm{G}$
2580.326	0.36	0.39	0.43	4.0	9812.86*	$2\|^4_3\mathrm{F})^3\mathrm{F}$	5.0	48556.05*	$1\|^4_3\mathrm{F})^3\mathrm{G}$
2564.034	0.07	0.072	0.31	3.0	10708.33*	$2\|^4_3\mathrm{F})^3\mathrm{F}$	4.0	49697.68*	$1\|^4_3\mathrm{F})^3\mathrm{F}$
2559.405	−0.21	−0.17	0.17	2.0	11321.86*	$2\|^4_3\mathrm{F})^3\mathrm{F}$	3.0	50381.72*	$1\|^4_3\mathrm{F})^3\mathrm{F}$
2546.160	−1.61	−1.64	−1.61	2.0	11651.28*	$1\|^1_2\mathrm{D})$	2.0	50914.32*	$1\|^4_3\mathrm{F})^3\mathrm{F}$
2528.616	0.06	0.10	0.32	4.0	9812.86*	$2\|^4_3\mathrm{F})^3\mathrm{F}$	4.0	49348.30*	$1\|^4_3\mathrm{F})^3\mathrm{G}$
2524.974	−0.06	0.003	0.005	2.0	11321.86*	$2\|^4_3\mathrm{F})^3\mathrm{F}$	2.0	50914.32*	$1\|^4_3\mathrm{F})^3\mathrm{F}$
2519.823	−0.14	−0.11	−0.76	3.0	10708.33*	$2\|^4_3\mathrm{F})^3\mathrm{F}$	3.0	50381.72*	$1\|^4_3\mathrm{F})^3\mathrm{F}$
2506.464	0.05	0.062	−0.47	4.0	9812.86*	$2\|^4_3\mathrm{F})^3\mathrm{F}$	4.0	49697.68*	$1\|^4_3\mathrm{F})^3\mathrm{F}$
2486.441	−0.54	−0.51	−0.48	3.0	10708.33*	$2\|^4_3\mathrm{F})^3\mathrm{F}$	2.0	50914.32*	$1\|^4_3\mathrm{F})^3\mathrm{F}$
2464.199	−0.42	−0.39	−0.66	4.0	9812.86*	$2\|^4_3\mathrm{F})^3\mathrm{F}$	3.0	50381.72*	$1\|^4_3\mathrm{F})^3\mathrm{F}$
2245.129	−0.35	−0.29	−0.51	4.0	4028.99*	$2\|^4_3\mathrm{F})^5\mathrm{F}$	5.0	48556.05*	$1\|^4_3\mathrm{F})^3\mathrm{G}$
2232.072	−1.08	−1.06	−1.89	3.0	4560.79*	$2\|^4_3\mathrm{F})^5\mathrm{F}$	4.0	49348.30*	$1\|^4_3\mathrm{F})^3\mathrm{G}$
2214.793	−1.02	−1.03	−0.97	3.0	4560.79*	$2\|^4_3\mathrm{F})^5\mathrm{F}$	4.0	49697.68*	$1\|^4_3\mathrm{F})^3\mathrm{F}$
2211.428	−1.21	−1.22	−1.38	5.0	3350.49*	$2\|^4_3\mathrm{F})^5\mathrm{F}$	5.0	48556.05*	$1\|^4_3\mathrm{F})^3\mathrm{G}$
2200.421	−1.45	−1.45	−1.39	2.0	4950.06*	$2\|^4_3\mathrm{F})^5\mathrm{F}$	3.0	50381.72*	$1\|^4_3\mathrm{F})^3\mathrm{F}$
2188.999	−2.08	−1.96	−1.80	4.0	4028.99*	$2\|^4_3\mathrm{F})^5\mathrm{F}$	4.0	49697.68*	$1\|^4_3\mathrm{F})^3\mathrm{F}$
2187.039	−2.03	−1.91	−1.97	1.0	5204.70*	$2\|^4_3\mathrm{F})^5\mathrm{F}$	2.0	50914.32*	$1\|^4_3\mathrm{F})^3\mathrm{F}$
2173.335	−1.81	−1.98	−1.85	5.0	3350.49*	$2\|^4_3\mathrm{F})^5\mathrm{F}$	4.0	49348.30*	$1\|^4_3\mathrm{F})^3\mathrm{G}$
2156.950	−2.09	−2.08	−2.67	5.0	3350.49*	$2\|^4_3\mathrm{F})^5\mathrm{F}$	4.0	49697.68*	$1\|^4_3\mathrm{F})^3\mathrm{F}$
2065.542	−1.07	−1.11	−0.85	3.0	950.32*	$1\|^3_2\mathrm{F})$	4.0	49348.30*	$1\|^4_3\mathrm{F})^3\mathrm{G}$
2058.817	−1.17	−1.24	−0.93	4.0	.00*	$1\|^3_2\mathrm{F})$	5.0	48556.05*	$1\|^4_3\mathrm{F})^3\mathrm{G}$
2027.040	−0.57	−0.57	−0.29	2.0	1597.20*	$1\|^3_2\mathrm{F})$	2.0	50914.32*	$1\|^4_3\mathrm{F})^3\mathrm{F}$
2025.760	−0.95	−0.98	−0.26	4.0	.00*	$1\|^3_2\mathrm{F})$	4.0	49348.30*	$1\|^4_3\mathrm{F})^3\mathrm{G}$
2022.354	−0.49	−0.48	−0.44	3.0	950.32*	$1\|^3_2\mathrm{F})$	3.0	50381.72*	$1\|^4_3\mathrm{F})^3\mathrm{F}$
2011.516	−0.48	−0.40	−0.38	4.0	.00*	$1\|^3_2\mathrm{F})$	4.0	49697.68*	$1\|^4_3\mathrm{F})^3\mathrm{F}$
2000.793	−2.15	−1.92	−1.68	3.0	950.32*	$1\|^3_2\mathrm{F})$	2.0	50914.32*	$1\|^4_3\mathrm{F})^3\mathrm{F}$

[a] Mullman et al. (1997).
[b] Kurucz (1993).

Table 4. Comparison between experimental[a] intensity numbers and theoretical log(gf)-values for the $3d^8 - 3d^7 4p$ transitions involving the ground ${}^3_2\mathrm{F}$ term

λ(Å)	exp.[a]	present	Kurucz[b]	J_f	E_f(cm^{-1})	even	J_i	E_i(cm^{-1})	odd
2049.173	17	−2.10	−2.78	2.0	1597.20*	$1\|^3_2\mathrm{F})$	3.0	50381.72*	$1\|^4_3\mathrm{F})^3\mathrm{F}$
2036.585	56	−1.51	−0.49	3.0	950.32*	$1\|^3_2\mathrm{F})$	3.0	50036.35*	$1\|^4_3\mathrm{F})^3\mathrm{G}$
2027.040	394	−0.57	−0.29	2.0	1597.20*	$1\|^3_2\mathrm{F})$	2.0	50914.32*	$1\|^4_3\mathrm{F})^3\mathrm{F}$
2025.760	230	−0.98	−0.26	4.0	.00*	$1\|^3_2\mathrm{F})$	4.0	49348.30*	$1\|^4_3\mathrm{F})^3\mathrm{G}$
2022.354	543	−0.48	−0.44	3.0	950.32*	$1\|^3_2\mathrm{F})$	3.0	50381.72*	$1\|^4_3\mathrm{F})^3\mathrm{F}$
2011.516	688	−0.40	−0.38	4.0	.00*	$1\|^3_2\mathrm{F})$	4.0	49697.68*	$1\|^4_3\mathrm{F})^3\mathrm{F}$
2000.793	25	−1.92	−1.68	3.0	950.32*	$1\|^3_2\mathrm{F})$	2.0	50914.32*	$1\|^4_3\mathrm{F})^3\mathrm{F}$
1984.847	5	−2.67	−3.27	4.0	.00*	$1\|^3_2\mathrm{F})$	3.0	50381.72*	$1\|^4_3\mathrm{F})^3\mathrm{F}$
1975.015	12	−2.30	−2.08	2.0	1597.20*	$1\|^3_2\mathrm{F})$	2.0	52229.72*	$1\|^4_3\mathrm{F})^3\mathrm{D}$
1957.429	404	−0.85	−0.56	2.0	1597.20*	$1\|^3_2\mathrm{F})$	1.0	52684.63*	$1\|^4_3\mathrm{F})^3\mathrm{D}$

[a] Pickering et al. (1997).
[b] Kurucz (1993).

Table 5. Comparison between theory and experiment[a] of log(gf)-values for the $3d^74s - 3d^74p$ transitions involving the lower ^{3,5}F multiplets

λ(Å)	exp.[a]	present	Kurucz[b]	J_f	E_f(cm^{-1})	even	J_i	E_i(cm^{-1})	odd
2834.943	−2.07	−2.19	−2.20	3.0	10708.33*	$2\vert^4_3\mathrm{F})^3\mathrm{F}$	3.0	45972.03*	$1\vert^4_3\mathrm{F})^5\mathrm{F}$
2825.237	−1.65	−1.73	−1.93	4.0	9812.86*	$2\vert^4_3\mathrm{F})^3\mathrm{F}$	5.0	45197.71*	$1\vert^4_3\mathrm{F})^5\mathrm{F}$
2810.855	−1.83	−1.82	−1.83	4.0	9812.86*	$2\vert^4_3\mathrm{F})^3\mathrm{F}$	4.0	45378.75*	$1\vert^4_3\mathrm{F})^5\mathrm{F}$
2694.679	−0.53	−0.76	−0.94	3.0	10708.33*	$2\vert^4_3\mathrm{F})^3\mathrm{F}$	4.0	47807.49*	$1\vert^4_3\mathrm{F})^5\mathrm{G}$
2663.531	−0.21	−0.32	−0.54	4.0	9812.86*	$2\vert^4_3\mathrm{F})^3\mathrm{F}$	5.0	47345.84*	$1\vert^4_3\mathrm{F})^5\mathrm{G}$
2314.975	0.04	0.11	0.11	1.0	5204.70*	$2\vert^4_3\mathrm{F})^5\mathrm{F}$	2.0	48388.44*	$1\vert^4_3\mathrm{F})^5\mathrm{G}$
2314.057	0.20	0.26	0.27	2.0	4950.06*	$2\vert^4_3\mathrm{F})^5\mathrm{F}$	3.0	48150.94*	$1\vert^4_3\mathrm{F})^5\mathrm{G}$
2311.604	0.31	0.37	0.39	3.0	4560.79*	$2\vert^4_3\mathrm{F})^5\mathrm{F}$	4.0	47807.49*	$1\vert^4_3\mathrm{F})^5\mathrm{G}$
2307.860	0.36	0.43	0.47	4.0	4028.99*	$2\vert^4_3\mathrm{F})^5\mathrm{F}$	5.0	47345.84*	$1\vert^4_3\mathrm{F})^5\mathrm{G}$
2301.403	−0.82	−0.78	−0.74	2.0	4950.06*	$2\vert^4_3\mathrm{F})^5\mathrm{F}$	2.0	48388.44*	$1\vert^4_3\mathrm{F})^5\mathrm{G}$
2293.390	−0.74	−0.78	−0.72	3.0	4560.79*	$2\vert^4_3\mathrm{F})^5\mathrm{F}$	3.0	48150.94*	$1\vert^4_3\mathrm{F})^5\mathrm{G}$
2286.159	0.53	0.59	0.60	5.0	3350.49*	$2\vert^4_3\mathrm{F})^5\mathrm{F}$	6.0	47078.49*	$1\vert^4_3\mathrm{F})^5\mathrm{G}$
2283.521	−0.85	−0.98	−0.89	4.0	4028.99*	$2\vert^4_3\mathrm{F})^5\mathrm{F}$	4.0	47807.49*	$1\vert^4_3\mathrm{F})^5\mathrm{G}$

[a] Salih et al. (1985).

[b] Kurucz (1993).

Table 6. Values for the electric quadrupole transition integrals in Co II calculated by means of MCDF including core polarization

	$3d^8$	$3d^74s$	$3d^64s^2$	$3d^74d$	$3d^75s$	$3d^75d$	$3d^76s$
$3d^8$	1.60	−2.55	-	−1.55	0.20	−0.66	0.09
$3d^74s$	−2.55	1.31	−1.95	9.48	-	2.89	-
$3d^64s^2$	-	−1.95	1.12	-	-	-	-
$3d^74d$	−1.55	9.48	-	1.26	−38.26	−24.55	18.97
	-	-	-	35.53	-	-	-
$3d^75s$	0.20	-	-	−38.26	1.27	34.47	-
$3d^75d$	−0.66	2.89	-	−24.55	34.47	1.26	−141.78
	-	-	-	-	-	139.25	-
$3d^76s$	0.09	-	-	18.97	-	−141.78	1.26

2.2. Forbidden lines

Transition probabilities of forbidden, i.e. magnetic dipole (M1) or electric quadrupole (E2), transitions are only given for energy levels below 50 000 cm^{-1} in view of their astrophysical relevance.

The forbidden transitions observed in the infra-red at 18.8 μm, 10.52 μm and 1.547 μm by Jennings et al. (1993), are all M1 transitions. In their interpretation, Jennings et al. used a calculation of Nussbaumer & Storey (1988), with A-values 1.08, 2.23 and 2.89 10^{-2} s^{-1}. These values agree with ours at the percent level (in Table 7, we give 1.09, 2.24 and 2.81 10^{-2} s^{-1}), which is not very surprising as it concerns here strong transitions based on relatively pure levels; moreover, no radial transition integrals are needed for M1 transitions. For the (a^{3}F−b^{3}F) E2 transitions given by Nussbaumer & Storey the discrepancies are larger, our values being roughly 20% lower. For levels that are less pure, the present method is expected to be especially effective. Radiative data for infrared lines arising from forbidden transitions are needed to study the debris of Type II supernova explosions like SN 1987 A (Li et al. 1993).

Similar to the E1 case, the radial part of the E2 transitions is calculated from relativistic wavefunctions. In Table 6 the radial integrals for the electric quadrupole transitions are given in the form of a symmetric matrix. For E2-transitions within the $3d^74d$ configuration, there are two non-zero contributions, one for the 3d−3d and one for the 4d−4d transition. For this case, there are two rows in the table, the upper for the 3d−3d integral and the lower for the 4d−4d transition integral.

The A-values for the forbidden lines are restricted to the magnetic dipole (M1) and electric quadrupole (E2) transitions within the $3d^8$+$3d^74s$ configurations, from levels with an energy of less than 50 000 cm^{-1} above the ground and with A-values larger than 10^{-3} s^{-1}. The level with the lower J-value is given first in the designation of the transition. A specimen of the table available at CDS is included in the paper as Table 7. We selected data for this sample in three wavelength regions: the first includes the observed infra-red transitions, the second illustrates a region where M1 and E2 transitions occur simultaneously and the last gives ultra-violet transitions involving the lowest configuration $3d^8$. As the sample is

Table 7. Calculated A-values for the $(3d^8+3d^74s)$ − $(3d^8+3d^74s)$ M1 and E2 transition arrays of Co II; the notation $x(y)$ means $x \times 10^y$

λ(Å)	$A_{\mathrm{M1}}(\mathrm{s}^{-1})$	$A_{\mathrm{E2}}(\mathrm{s}^{-1})$	J_{f}	$E_{\mathrm{f}}(\mathrm{cm}^{-1})$	name	J_{i}	$E_{\mathrm{i}}(\mathrm{cm}^{-1})$	name
392610.422	1.79(−3)	-	1.0	5204.70*	$2\vert^{4}_{3}\mathrm{F})^{5}\mathrm{F}$	2.0	4950.06*	$2\vert^{4}_{3}\mathrm{F})^{5}\mathrm{F}$
256819.115	5.74(−3)	-	2.0	4950.06*	$2\vert^{4}_{3}\mathrm{F})^{5}\mathrm{F}$	3.0	4560.79*	$2\vert^{4}_{3}\mathrm{F})^{5}\mathrm{F}$
187989.017	1.09(−2)	-	3.0	4560.79*	$2\vert^{4}_{3}\mathrm{F})^{5}\mathrm{F}$	4.0	4028.99*	$2\vert^{4}_{3}\mathrm{F})^{5}\mathrm{F}$
162947.060	8.19(−3)	-	2.0	11321.86*	$2\vert^{4}_{3}\mathrm{F})^{3}\mathrm{F}$	3.0	10708.33*	$2\vert^{4}_{3}\mathrm{F})^{3}\mathrm{F}$
154547.719	9.73(−3)	-	2.0	1597.20*	$1\vert^{3}_{2}\mathrm{F})$	3.0	950.32*	$1\vert^{3}_{2}\mathrm{F})$
147345.071	1.24(−2)	-	4.0	4028.99*	$2\vert^{4}_{3}\mathrm{F})^{5}\mathrm{F}$	5.0	3350.49*	$2\vert^{4}_{3}\mathrm{F})^{5}\mathrm{F}$
111642.640	1.88(−2)	-	3.0	10708.33*	$2\vert^{4}_{3}\mathrm{F})^{3}\mathrm{F}$	4.0	9812.86*	$2\vert^{4}_{3}\mathrm{F})^{3}\mathrm{F}$
105198.591	2.24(−2)	-	3.0	950.32*	$1\vert^{3}_{2}\mathrm{F})$	4.0	.00*	$1\vert^{3}_{2}\mathrm{F})$
19034.915	5.05(−3)	-	3.0	4560.79*	$2\vert^{4}_{3}\mathrm{F})^{5}\mathrm{F}$	4.0	9812.86*	$2\vert^{4}_{3}\mathrm{F})^{3}\mathrm{F}$
17361.591	9.65(−3)	-	2.0	4950.06*	$2\vert^{4}_{3}\mathrm{F})^{5}\mathrm{F}$	3.0	10708.33*	$2\vert^{4}_{3}\mathrm{F})^{3}\mathrm{F}$
17284.738	3.07(−3)	-	4.0	4028.99*	$2\vert^{4}_{3}\mathrm{F})^{5}\mathrm{F}$	4.0	9812.86*	$2\vert^{4}_{3}\mathrm{F})^{3}\mathrm{F}$
16342.988	1.35(−2)	-	1.0	5204.70*	$2\vert^{4}_{3}\mathrm{F})^{5}\mathrm{F}$	2.0	11321.86*	$2\vert^{4}_{3}\mathrm{F})^{3}\mathrm{F}$
16262.224	4.57(−3)	-	3.0	4560.79*	$2\vert^{4}_{3}\mathrm{F})^{5}\mathrm{F}$	3.0	10708.33*	$2\vert^{4}_{3}\mathrm{F})^{3}\mathrm{F}$
16193.830	-	2.09(−3)	4.0	18973.73*	$1\vert^{1}_{2}\mathrm{G})$	4.0	25147.23*	$2\vert^{2}_{3}\mathrm{G})^{1}\mathrm{G}$
15689.873	4.39(−3)	-	2.0	4950.06*	$2\vert^{4}_{3}\mathrm{F})^{5}\mathrm{F}$	2.0	11321.86*	$2\vert^{4}_{3}\mathrm{F})^{3}\mathrm{F}$
15469.984	2.81(−2)	-	4.0	9812.86*	$2\vert^{4}_{3}\mathrm{F})^{3}\mathrm{F}$	5.0	3350.49*	$2\vert^{4}_{3}\mathrm{F})^{5}\mathrm{F}$
14967.444	3.97(−3)	-	3.0	10708.33*	$2\vert^{4}_{3}\mathrm{F})^{3}\mathrm{F}$	4.0	4028.99*	$2\vert^{4}_{3}\mathrm{F})^{5}\mathrm{F}$
11280.365	-	4.01(−3)	3.0	950.32*	$1\vert^{3}_{2}\mathrm{F})$	4.0	9812.86*	$2\vert^{4}_{3}\mathrm{F})^{3}\mathrm{F}$
10972.578	-	5.65(−3)	2.0	1597.20*	$1\vert^{3}_{2}\mathrm{F})$	3.0	10708.33*	$2\vert^{4}_{3}\mathrm{F})^{3}\mathrm{F}$
10280.316	-	2.57(−2)	2.0	1597.20*	$1\vert^{3}_{2}\mathrm{F})$	2.0	11321.86*	$2\vert^{4}_{3}\mathrm{F})^{3}\mathrm{F}$
10245.187	-	2.25(−2)	3.0	950.32*	$1\vert^{3}_{2}\mathrm{F})$	3.0	10708.33*	$2\vert^{4}_{3}\mathrm{F})^{3}\mathrm{F}$
10187.918	-	3.43(−2)	4.0	.00*	$1\vert^{3}_{2}\mathrm{F})$	4.0	9812.86*	$2\vert^{4}_{3}\mathrm{F})^{3}\mathrm{F}$
9943.486	-	1.27(−3)	2.0	1597.20*	$1\vert^{3}_{2}\mathrm{F})$	2.0	11651.28*	$1\vert^{1}_{2}\mathrm{D})$
9639.131	-	1.72(−2)	2.0	11321.86*	$2\vert^{4}_{3}\mathrm{F})^{3}\mathrm{F}$	3.0	950.32*	$1\vert^{3}_{2}\mathrm{F})$
9538.339	-	4.38(−3)	.0	13593.29*	$1\vert^{3}_{2}\mathrm{P})$	2.0	24074.42*	$2\vert^{4}_{3}\mathrm{P})^{3}\mathrm{P}$
9369.415	-	9.53(−3)	1.0	13404.32*	$1\vert^{3}_{2}\mathrm{P})$	2.0	24074.42*	$2\vert^{4}_{3}\mathrm{P})^{3}\mathrm{P}$
9335.963	-	1.51(−2)	3.0	10708.33*	$2\vert^{4}_{3}\mathrm{F})^{3}\mathrm{F}$	4.0	.00*	$1\vert^{3}_{2}\mathrm{F})$
3073.277	-	3.28(0)	2.0	11651.28*	$1\vert^{1}_{2}\mathrm{D})$	3.0	44180.39	$2\vert^{2}_{3}\mathrm{F})^{1}\mathrm{F}$
3042.464	6.27(−2)	4.13(−2)	2.0	11321.86*	$2\vert^{4}_{3}\mathrm{F})^{3}\mathrm{F}$	3.0	44180.39	$2\vert^{2}_{3}\mathrm{F})^{1}\mathrm{F}$
2986.695	9.39(−3)	-	3.0	10708.33*	$2\vert^{4}_{3}\mathrm{F})^{3}\mathrm{F}$	3.0	44180.39	$2\vert^{2}_{3}\mathrm{F})^{1}\mathrm{F}$
2908.871	6.87(−2)	4.09(−3)	3.0	44180.39	$2\vert^{2}_{3}\mathrm{F})^{1}\mathrm{F}$	4.0	9812.86*	$2\vert^{4}_{3}\mathrm{F})^{3}\mathrm{F}$
2810.814	9.30(−2)	2.08(−3)	1.0	5204.70*	$2\vert^{4}_{3}\mathrm{F})^{5}\mathrm{F}$	2.0	40771.11*	$2\vert^{2}_{3}\mathrm{F})^{3}\mathrm{F}$
2796.772	-	7.22(−2)	2.0	4950.06*	$2\vert^{4}_{3}\mathrm{F})^{5}\mathrm{F}$	4.0	40695.03*	$3\vert^{5}_{4}\mathrm{D})^{5}\mathrm{D}$
2790.832	2.88(−2)	-	2.0	4950.06*	$2\vert^{4}_{3}\mathrm{F})^{5}\mathrm{F}$	2.0	40771.11*	$2\vert^{2}_{3}\mathrm{F})^{3}\mathrm{F}$
2782.417	5.37(−2)	2.75(−3)	2.0	4950.06*	$2\vert^{4}_{3}\mathrm{F})^{5}\mathrm{F}$	3.0	40879.44*	$2\vert^{2}_{3}\mathrm{F})^{3}\mathrm{F}$
2768.541	-	1.80(−1)	1.0	5204.70*	$2\vert^{4}_{3}\mathrm{F})^{5}\mathrm{F}$	3.0	41314.15*	$3\vert^{5}_{4}\mathrm{D})^{5}\mathrm{D}$
2766.641	-	8.82(−1)	3.0	4560.79*	$2\vert^{4}_{3}\mathrm{F})^{5}\mathrm{F}$	4.0	40695.03*	$3\vert^{5}_{4}\mathrm{D})^{5}\mathrm{D}$
2760.828	5.41(−3)	-	2.0	40771.11*	$2\vert^{2}_{3}\mathrm{F})^{3}\mathrm{F}$	3.0	4560.79*	$2\vert^{4}_{3}\mathrm{F})^{5}\mathrm{F}$
2752.593	2.97(−2)	-	3.0	4560.79*	$2\vert^{4}_{3}\mathrm{F})^{5}\mathrm{F}$	3.0	40879.44*	$2\vert^{2}_{3}\mathrm{F})^{3}\mathrm{F}$
2749.153	-	1.94(0)	2.0	4950.06*	$2\vert^{4}_{3}\mathrm{F})^{5}\mathrm{F}$	3.0	41314.15*	$3\vert^{5}_{4}\mathrm{D})^{5}\mathrm{D}$
2551.953	-	1.90(0)	2.0	1597.20*	$1\vert^{3}_{2}\mathrm{F})$	2.0	40771.11*	$2\vert^{2}_{3}\mathrm{F})^{3}\mathrm{F}$
2544.915	-	6.99(−1)	2.0	1597.20*	$1\vert^{3}_{2}\mathrm{F})$	3.0	40879.44*	$2\vert^{2}_{3}\mathrm{F})^{3}\mathrm{F}$
2534.102	-	2.69(−2)	2.0	1597.20*	$1\vert^{3}_{2}\mathrm{F})$	4.0	41047.06*	$2\vert^{2}_{3}\mathrm{F})^{3}\mathrm{F}$
2510.495	-	9.40(−1)	2.0	40771.11*	$2\vert^{2}_{3}\mathrm{F})^{3}\mathrm{F}$	3.0	950.32*	$1\vert^{3}_{2}\mathrm{F})$
2503.684	-	1.58(0)	3.0	950.32*	$1\vert^{3}_{2}\mathrm{F})$	3.0	40879.44*	$2\vert^{2}_{3}\mathrm{F})^{3}\mathrm{F}$
2493.217	-	6.05(−1)	3.0	950.32*	$1\vert^{3}_{2}\mathrm{F})$	4.0	41047.06*	$2\vert^{2}_{3}\mathrm{F})^{3}\mathrm{F}$
2456.559	1.08(−3)	3.83(−3)	4.0	.00*	$1\vert^{3}_{2}\mathrm{F})$	4.0	40695.03*	$3\vert^{5}_{4}\mathrm{D})^{5}\mathrm{D}$
2451.975	-	5.03(−2)	2.0	40771.11*	$2\vert^{2}_{3}\mathrm{F})^{3}\mathrm{F}$	4.0	.00*	$1\vert^{3}_{2}\mathrm{F})$
2445.476	-	7.75(−1)	3.0	40879.44*	$2\vert^{2}_{3}\mathrm{F})^{3}\mathrm{F}$	4.0	.00*	$1\vert^{3}_{2}\mathrm{F})$
2435.489	-	2.58(0)	4.0	.00*	$1\vert^{3}_{2}\mathrm{F})$	4.0	41047.06*	$2\vert^{2}_{3}\mathrm{F})^{3}\mathrm{F}$
2416.607	-	6.35(−2)	.0	42964.95	$1\vert^{1}_{0}\mathrm{S})$	2.0	1597.20*	$1\vert^{3}_{2}\mathrm{F})$
2347.625	-	1.83(−2)	2.0	1597.20*	$1\vert^{3}_{2}\mathrm{F})$	3.0	44180.39	$2\vert^{2}_{3}\mathrm{F})^{1}\mathrm{F}$
2312.494	-	1.12(−2)	3.0	950.32*	$1\vert^{3}_{2}\mathrm{F})$	3.0	44180.39	$2\vert^{2}_{3}\mathrm{F})^{1}\mathrm{F}$
2262.747	-	1.87(−2)	3.0	44180.39	$2\vert^{2}_{3}\mathrm{F})^{1}\mathrm{F}$	4.0	.00*	$1\vert^{3}_{2}\mathrm{F})$

necessarily incomplete, only the full CDS table should be used to calculate radiative lifetimes.

3. Conclusion

With the presentation of absolute transition probabilities of Co II, we hope to provide data that allow for a better understanding of such objects as Co-stars and late-type supernovae; in the latter case, time evolution of Fe, Co and Ni lines provides a test of explosive nucleosynthesis models.

To avoid typing errors, all tables containing transition probabilities are computer processed. Complete results of the fits of both the odd and even energy system, as well as the corresponding complete transition arrays (without lower limits to the gf- and A-values or restriction of the configurations) can be found in our database (anonymous ftp) at ftp://nucleus.phys.uva.nl in the directory pub/orth/co2.

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