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Lifetime measurements and calculations in Y^+ and Y^{2+} ions

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ABSTRACT

We report a new set oftheoretical transition probabilities in Y II, obtained using a multiconfiguration relativistic Hartree–Fock method including core polarization. The overall quality of the calculations is assessed by comparisons with new and previous lifetime measurements. In this paper, we report new measurements of five lifetimes in the 4d5p and 5s5p configurations, in the energy range of 32 048–44 569 cm^{-1}, obtained by the time-resolved laser-induced fluorescence method. A similar theoretical model, applied to Y III, leads to results in good agreement with new laser measurements of two 5p levels obtained in this work and with previous beam-foil results for 5d and 6s levels. An extensive set of oscillator strengths is also proposed for Y III.

Key words: atomic data – atomic processes.

1 INTRODUCTION

Transition probabilities in yttrium ions are needed in astrophysics for the determination of the chemical composition of the Sun and the stars. A well-established procedure to obtain these parameters consists of combining measured radiative lifetimes using laser spectroscopy with theoretical or experimental determinations of branching fractions.

In Y II, the available lifetimes are scarce. The only measurements are those of Andersen, Ramanujan & Bahr (1978), Hannaford et al. (1982), Gorshkov & Komarovskii (1986) and Wännström et al. (1988).

Andersen et al. (1978) measured lifetimes of excited states in Y I and Y II by the beam-foil and beam-sputtering techniques. Hannaford et al. (1982) used a time-resolved (TR) laser-induced fluorescence (LIF) technique to measure 14 lifetimes in Y II. Transition probabilities were obtained for 66 transitions and the results were applied to the determination of the chemical composition of the Sun. In the work of Gorshkov & Komarovskii (1986), 10 levels of Y II were measured by the delayed coincidence method. Wännström et al. (1988) measured radiative lifetimes of the eight y $^3P^{\circ}_{0,1,2}$, $^1D^{\circ}_2$, z $^3D^{\circ}_{1,2,3}$ and z $^1F^{\circ}_3$ levels in Y^+ using the beam-laser technique.

When comparing the different sets of results, it appears that some discrepancies are present and that the different lifetime measurements for the same level do not necessarily agree within the experimental errors.

Previous experimental determinations of transition probabilities in Y II include the shock-tube measurements by Pitts & Newsom (1986) for 90 transitions and, more recently, the investigation by Reshetnikova & Skorokhod (1999) of eight lines emitted from a plasma of an erosion jet flowing out of a channel in a dielectric.

Theoretical efforts in the same ion are due to Pirronello & Strazzulla (1980) who used a scaled Thomas–Fermi method, to Migdalek & Baylis (1987) who applied a multiconfiguration Dirac–Fock approach to investigate the spin-allowed and spin-forbidden $5s^2\ ^1S_0$–5s5p $^3P^{\circ}_1$, $^1P^{\circ}_1$ transitions in Sr I and Y II and to Migdalek & Stanek (1993) who studied the same transitions along the strontium isoelectronic sequence.

Up to now, the measurements of radiative lifetimes in Y III are very limited, the only work being the beam-foil measurements of Maniak et al. (1994) for five levels. The experimental results were compared to theoretical data obtained using the Coulomb approximation with a Hartree–Slater core.

Theoretical transition probabilities and oscillator strengths in Y III are reported by Redfors (1991), who applied Cowan's codes, and by Brage et al. (1998), who adopted a multiconfiguration Hartree–Fock technique. More recent results in Sc III and Y III have been published by Sahoo et al. (2008) and Zhang & Zheng (2009). Radiative data along the rubidium isoelectronic sequence are also due to Lindgård & Nielsen (1977) (Coulomb approximation), Migdalek & Baylis (1979) (relativistic Hartree–Fock method), Sen & Puri (1989) (quasi-relativistic local spin density functional) and Zilitis (2007, 2009) (Dirac–Fock method).

In their paper aimed at the determination of elemental abundances in the χ Lupi star from *Hubble Space Telescope*/GHRS Echelle spectra, Brage et al. (1998) emphasized the importance of accurately including the core–valence correlation in the calculations to obtain reliable transition probabilities.

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In this work, new measurements of five lifetimes in the 4d5p and 5s5p configurations of Y II, between 32 048 and 44 569 cm^{-1}, have been performed using the TR LIF method. New measurements of two 5p levels in Y III are also reported. The experimental lifetimes are compared to theoretical results obtained with a relativistic Hartree–Fock method including core-polarization effects (HFR + CPOL method). The observed agreement between theory and experiment gives confidence to the oscillator strengths proposed in this work for 84 transitions of Y II in the wavelength range from 2243 to 10 605 Å and for 182 transitions of Y III between 643 and 9984 Å.

2 ATOMIC STRUCTURE AND MEASUREMENTS

The ground state of Y II is $5s^2\ ^1S_0$, and the most extensive analysis is reported by Nilsson, Johansson & Kurucz (1991) including 235 levels. Y III belongs to the Rb I isoelectronic sequence and its lowest term is 4d ^{2}D. The term system is dominated by configurations with one electron outside the closed $4p^6$ shell. The most detailed analysis of Y III is due to Epstein & Reader (1975) who analysed the spectrum emitted by a sliding spark.

On the experimental side, a TR LIF method was used in this work to measure the radiative lifetimes of excited Y II and Y III states. This method is able to provide radiative lifetimes of atomic and ionic states with uncertainties reaching typically a few per cent.

The experimental set-up used in this work has been previously described in details (Nilsson et al. 2010), and so only a brief description will be presented here. Free atoms or ions are obtained by laser ablation and excited by a second laser beam. A frequency-doubled (536 nm) Nd:YAG laser beam, with a pulse repetition rate of 10 Hz, was focused on the yttrium target foil. The target was placed in a vacuum chamber and was rotated during the experiment. The residual vacuum in the chamber was 10^{-5} mbar. The sputtered cloud of atoms and ions was crossed by an excitation laser beam at a distance of about 10 mm above the target surface. The excitation laser was produced by a system consisting of a dye laser, using a DCM dye, and a pump Nd:YAG laser. The second harmonic of the Nd:YAG laser was used. The laser pulses were temporally compressed by stimulated Brillouin scattering and frequency doubled or tripled by BBO and KDP crystals to obtain the required excitation wavelengths. The wavelength region was broadened using a Raman shifter in hydrogen, employing Stokes and anti-Stokes components at 4153 cm^{-1}. The excitation pulses had a final duration of about 1 ns. The two Nd:YAG lasers were temporally synchronized by a delay generator, which provided different time intervals between ablation and excitation pulses. The temporal shape of the excitation laser pulse was registered by a fast photodiode. The fluorescence emitted from the excited states under investigation after laser excitation was analysed by a 1/8-m grating monochromator and registered by a fast microchannel plate photomultiplier (Hamamatsu R3809U). Finally, both signals were digitized by an oscilloscope (Tektronix DPO 7254). After about 1000 laser pulses, the decay curves were averaged and transferred to a PC for treatment. The DECFIT code was used to analyse the decay curves after a deconvolution of the registered signal and of the laser pulses.

The measurements were carried out under different experimental conditions. The delay between ablation and excitation laser pulses was changed in a range extending from 1.9 to 7.5 μs for Y II and from 1.9 to 2.1 μs for Y III. The measurements were also made with different ion concentrations to verify the absence of radiation trapping. To eliminate the influence of saturation effects, we used different numbers of neutral density filters in the excitation laser beam.

Table 1. Odd Y II levels measured in this work and the corresponding excitation schemes.

Level[a]	Energy (cm^{-1})	Excitation λ_{air} (Å)	Excitation schemes[b]	Detection λ_{air} (Å)
4d5p y $^3P^\circ_0$	32 048.788	3203.3	2ω	3383, 5726
4d5p y $^3P^\circ_1$	32 124.054	3195.6	2ω	3217, 3397
4d5p y $^3P^\circ_2$	32 283.420	3179.4	2ω	3242
4d5p z $^1F^\circ_3$	33 336.727	3135.2, 3095.9	2ω	3328, 3508
5s5p y $^1P^\circ_1$	44 568.640	2422.2	3ω+S	2244, 2424

[a]Nilsson et al. (1991).
[b]2ω and 3ω indicate the second and third harmonic and S indicates the first Stokes component of the Raman scattering.

Table 2. Odd Y III levels measured in this work and the corresponding excitation schemes.

Level[a]	Energy (cm^{-1})	Excitation λ_{air} (Å)	Excitation schemes[b]	Detection λ_{air} (Å)
$4p^65p\ ^2P^\circ_{1/2}$	41 401.2	2414.6	3ω+S	3127, 2595
$4p^65p\ ^2P^\circ_{1/2}$	42 954.7	2327.3	3ω+S	2573

[a]Epstein & Reader (1975).
[b]3ω indicates the third harmonic and S indicates the first Stokes component of the Raman scattering.

For Y II measurements, the excitation was carried out from the levels which belong to low-lying even terms, i.e. 4d(^{2}D)5s a $^3D_{1,2,3}$ (840.1, 1045.0 and 1449.7 cm^{-1}), a $^1D_2$ (3296.2 cm^{-1}) and $4d^2$ a $^3P_1$ (14 018.2 cm^{-1}), whereas for Y III, the excitation from the ground state 4d $^2D_{3/2}$ was used. The excitation and detection channels used are presented in Table 1 for Y II and in Table 2 for Y III.

3 CALCULATIONS

The well-known suite of computer programs, originally written by Cowan (1981), was adopted for the calculations in this work. In the core-polarization model considered for Y II (referred to as HFR + CPOL; see e.g. Biémont & Quinet 2003; Biémont 2005 for more details), a Kr-like ionic core surrounded by two valence electrons was adopted. The static dipole polarizability, $\alpha_d = 4.59\ a_0^3$, was taken from Fraga, Karwowski & Saxena (1976). The HFR value of $1.442a_0$ corresponding to the mean radius of the outermost core orbital, i.e. 4p, was used as the cut-off radius r_c. In Y III, a similar core but surrounded by one outer electron was used. The same value of the static dipole polarizability was considered ($4.59a_0^3$) and the cut-off radius was calculated to be $1.453a_0$. It should be added that the value used for the dipole polarizability was not critical. Adopting e.g. a value of $4.05a_0^3$ for α_d, as calculated by Johnson, Kolb & Huang (1983), would only change the lifetime values by less than 5 per cent.

To account for the valence–valence interactions in the core-polarization models, we included the following vectorial basis in Y II: $5s^2$ + 5s6s + $6s^2$ + 5s4d + 5s5d + 5s6d + $4d^2$ + 4d6s + 4d5d + 4d6d + $5d^2$ + 5d6s + 5d6d + $5p^2$ + 5p4f + 5p5f + 5p6f + $6p^2$ (even parity) and 6p4f + 6p5f + 6p6f + 5s5p + 5s6p + 5s4f + 5s5f + 5s6f + 4d5p + 4d6p + 5p5d + 5p6d + 6p5d + 6p6d (odd parity). In the case of Y III, the model adopted was nd (n = 4–10) + ns (n = 5–10) + ng ($n = 5 - 10$) (even parity) and np ($n = 5 - 10$) + nf ($n = 4 - 10$) + nh ($n = 6 - 10$) (odd parity).

To account for the remaining interactions with distant configurations, not considered explicitly in the vectorial basis or implicitly

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by the polarization model, all the radial Coulomb parameters were scaled down by 0.85 according to a well-established procedure (Cowan 1981).

To optimize the calculation of the oscillator strengths, the HFR+CPOL method was combined with a least-squares fitting routine minimizing the discrepancies between the calculated energies and the experimental values published by Nilsson et al. (1991) for Y II and by Epstein & Reader (1975) for Y III.

4 RESULTS AND DISCUSSION

The present experimental lifetimes are compared to previous results in Table 3 for Y II and in Table 4 for Y III. Our quoted experimental values are typically the averages of 10 measurements under different experimental conditions, as discussed above. The uncertainties given include both the statistical errors in an individual analysis and the, typically somewhat larger, variation between the repeated measurements. As illustrated in Fig. 1, our new measurements in Y II are lower than most of the previous results including those of Hannaford et al. (1982), obtained by a similar LIF technique.

This is due to the shorter excitation pulses used in this work which allow us to measure shorter lifetimes more accurately as discussed in previous work e.g. by Sikström et al. (2001). Moreover, in this work, a deconvolution of the obtained signals and of the excitation laser pulses was used, whereas in the experiments of Hannaford et al. (1982) and Wännström et al. (1988) an exponential fit was performed.

This is probably related to the much shorter excitation laser pulses used in this paper. The difference with the values of

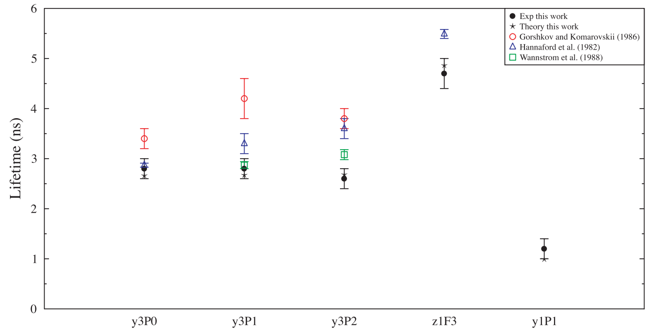

Figure 1. Y II: comparison of the lifetimes obtained in this work with previous results.

Table 3. Radiative lifetimes in Y II.

Level	Energy[a] (cm^{-1})	τ (ns) This work Exp.	This work HFR+CPOL	Previous Gorshkov & Komarovskii (1986)[b]	Hannaford et al. (1982)[c]	Wännström et al. (1988)[d]	Andersen et al. (1978)[e]
z $^1D^\circ_2$	26147.252		5.67	5.9 ± 0.6	6.3 ± 0.2	6.82 ± 0.05	6.7 ± 0.5
z $^3F^\circ_2$	27227.027		5.46	6.8 ± 0.8	6.3 ± 0.3		
z $^1P^\circ_1$	27516.699		5.58	5.6 ± 0.4	5.0 ± 2.0		
z $^3F^\circ_3$	27532.321		5.42	5.9 ± 0.7	6.3 ± 0.3		
z $^3F^\circ_4$	28394.177		5.17	6.0 ± 0.4	5.7 ± 0.3		
z $^3D^\circ_1$	28595.285		3.98		4.5 ± 0.3	4.58 ± 0.05	
z $^3D^\circ_2$	28 730.010		3.80	5.8 ± 0.8	4.3 ± 0.3	4.53 ± 0.09	6.4 ± 0.6
z $^3D^\circ_3$	29 213.958		3.75	5.2 ± 0.7	4.4 ± 0.3	4.43 ± 0.11	5.7 ± 0.8
y $^3P^\circ_0$	32 048.788	2.8 ± 0.2	2.66		3.4 ± 0.2	2.87 ± 0.04	
y $^3P^\circ_1$	32 124.054	2.8 ± 0.2	2.67	4.2 ± 0.4	3.3 ± 0.2	2.87 ± 0.07	
y $^3P^\circ_2$	32 283.420	2.6 ± 0.2	2.68	3.8 ± 0.2	3.6 ± 0.2	3.08 ± 0.10	
z $^1F^\circ_3$	33 336.727	4.7 ± 0.3	4.86	6.9 ± 0.7		5.49 ± 0.09	
y $^1P^\circ_1$	44 568.640	1.2 ± 0.2	0.99				

[a]From Nilsson et al. (1991).
[b]Delayed coincidence technique with electronic excitation.
[c]LIF spectroscopy.
[d]Beam-laser method.
[e]Beam-foil spectroscopy.

Table 4. Radiative lifetimes in Y III.

Level	Energy[a] (cm^{-1})	τ (ns) This work Exp.	This work HFR+CPOL	Previous Maniak et al. (1994)[b]	Maniak et al. (1994)[c]
5p $^2P^\circ_{1/2}$	41 401.46	1.9 ± 0.1	1.78	2.06 ± 0.08	2.146
5p $^2P^\circ_{3/2}$	42 954.87	1.8 ± 0.2	1.61	1.79 ± 0.08	1.948
6s $^2S_{1/2}$	86 717.59	–	1.19	1.23 ± 0.08	1.249
5d $^2D_{3/2}$	88 379.61	–	1.02	0.93 ± 0.07	1.098
5d $^2D_{5/2}$	88 578.29	–	1.10	1.06 ± 0.08	1.138

[a]Epstein & Reader (1975).
[b]Beam-foil spectroscopy with detailed treatment of cascades.
[c]Coulomb approximation with a Hartree–Slater core.

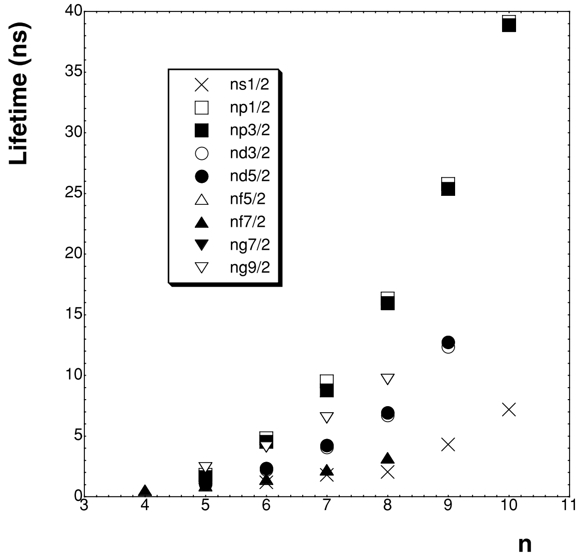

Figure 2. Behaviour of the HFR+CPOL lifetimes along the Rydberg series of Y III.

Gorshkov & Komarovskii (1986) could result from the fact that the cascading effects in their non-selective excitation measurements have not been taken into account in an adequate way. The present theoretical HFR+CPOL results, which are shown in Column 4 of Table 3, agree with our measurements within the experimental errors.

In Y III, our two measurements agree well (see Table 4) with the previous measurements of Maniak et al. (1994). This is not surprising, since the arbitrary normalized decay curve procedure was considered in their paper to accurately account for the cascade repopulation of the investigated levels. In this case, the HFR+CPOL calculations agree quite well both with the measurements of this work and with the measurements of Maniak et al. (1994). This agreement gives considerable support to the oscillator strengths calculated in this work. The smooth behaviour of the HFR+CPOL lifetimes along the Rydberg series of Y III is illustrated in Fig. 2.

New sets of weighted oscillator strengths (log *gf*) and weighted transition probabilities (*gA*) are presented in Tables 5 and 6 for Y II and Y III, respectively. The results of Table 5 concern the channels depopulating the levels measured in this work and additional

Table 5. Transition probabilities for the Y II transitions depopulating the levels measured in this work and the other levels of the configurations 4d5p and 5s5p. Only transitions for which log $gf > -2.0$ are included in the table. It was verified that all these transitions are not affected by pronounced cancellation effects.

E_{low}[a] (cm^{-1})	Lower level[a]	E_{upp}[a] (cm^{-1})	Upper level[a]	λ[b] (Å)	Int.[c]	log *gf*[d]	*gA*[d] (s^{-1})	τ[d] (ns)
840.198	4d5s a $^3D_1$	23 445.063	5s5p z $^3P^\circ_0$	4422.583	890	−1.05	3.071E+07	31.88
14 018.267	$4d^2$ a $^3P_1$	23 445.063	5s5p z $^3P^\circ_0$	10 605.150	–	−1.96	6.520E+05	
840.198	4d5s a $^3D_1$	23 776.245	5s5p z $^3P^\circ_1$	4358.723	800	−1.15	2.509E+07	31.60
1045.076	4d5s a $^3D_2$	23 776.245	5s5p z $^3P^\circ_1$	4398.008	1800	−0.75	6.168E+07	
13 883.379	$4d^2$ a $^3P_0$	23 776.245	5s5p z $^3P^\circ_1$	10 105.523	–	−1.89	8.540E+05	
14 098.076	$4d^2$ a $^3P_2$	23 776.245	5s5p z $^3P^\circ_1$	10 329.701	–	−1.76	1.101E+06	
1045.076	4d5s a $^3D_2$	24 647.121	5s5p z $^3P^\circ_2$	4235.727	600	−1.27	2.010E+07	33.41
1449.752	4d5s a $^3D_3$	24 647.121	5s5p z $^3P^\circ_2$	4309.620	2800	−0.49	1.160E+08	
3296.180	4d5s a $^1D_2$	24 647.121	5s5p z $^3P^\circ_2$	4682.321	260	−1.73	5.742E+06	
14 018.267	$4d^2$ a $^3P_1$	24 647.121	5s5p z $^3P^\circ_2$	9405.769	–	−1.72	1.446E+06	
14 098.076	$4d^2$ a $^3P_2$	24 647.121	5s5p z $^3P^\circ_2$	9476.928	–	−1.32	3.530E+06	
840.198	4d5s a $^3D_1$	26 147.252	4d5p z $^1D^\circ_2$	3950.349	4400	−0.73	7.917E+07	5.67
1045.076	4d5s a $^3D_2$	26 147.252	4d5p z $^1D^\circ_2$	3982.592	3600	−0.56	1.151E+08	
3296.180	4d5s a $^1D_2$	26 147.252	4d5p z $^1D^\circ_2$	4374.933	12 000	0.29	6.757E+08	
8003.126	$4d^2$ a $^3F_2$	26 147.252	4d5p z $^1D^\circ_2$	5509.894	250	−1.31	1.062E+07	
840.198	4d5s a $^3D_1$	27 227.027	4d5p z $^3F^\circ_2$	3788.693	7400	0.08	5.522E+08	5.46
1045.076	4d5s a $^3D_2$	27 227.027	4d5p z $^3F^\circ_2$	3818.341	1300	−0.77	7.773E+07	
1449.752	4d5s a $^3D_3$	27 227.027	4d5p z $^3F^\circ_2$	3878.285	480	−1.57	1.181E+07	
3296.180	4d5s a $^1D_2$	27 227.027	4d5p z $^3F^\circ_2$	4177.528	8 000	−0.32	1.841E+08	
8003.126	$4d^2$ a $^3F_2$	27 227.027	4d5p z $^3F^\circ_2$	5200.409	960	−0.47	8.442E+07	
8328.039	$4d^2$ a $^3F_3$	27 227.027	4d5p z $^3F^\circ_2$	5289.815	60	−1.68	4.952E+06	
0.00	$5s^2$ a $^1S_0$	27 516.699	4d5p z $^1P^\circ_1$	3633.121	7800	−0.17	3.405E+08	5.58
840.198	4d5s a $^3D_1$	27 516.699	4d5p z $^1P^\circ_1$	3747.551	1200	−0.95	5.377E+07	
1045.076	4d5s a $^3D_2$	27 516.699	4d5p z $^1P^\circ_1$	3776.556	1400	−0.83	6.867E+07	
8003.126	$4d^2$ a $^3F_2$	27 516.699	4d5p z $^1P^\circ_1$	5123.209	450	−0.79	4.091E+07	
13 883.379	$4d^2$ a $^3P_0$	27 516.699	4d5p z $^1P^\circ_1$	7332.949	5	−1.98	1.300E+06	
14 098.076	$4d^2$ a $^3P_2$	27 516.699	4d5p z $^1P^\circ_1$	7450.275	29	−1.44	4.356E+06	
14 832.862	$4d^2$ b $^1D_2$	27 516.699	4d5p z $^1P^\circ_1$	7881.878	110	−0.60	2.621E+07	
1045.076	4d5s a $^3D_2$	27 532.321	4d5p z $^3F^\circ_3$	3774.330	10 000	0.29	9.246E+08	5.42
1449.752	4d5s a $^3D_3$	27 532.321	4d5p z $^3F^\circ_3$	3832.889	4000	−0.34	2.069E+08	
3296.180	4d5s a $^1D_2$	27 532.321	4d5p z $^3F^\circ_3$	4124.904	320	−1.38	1.655E+07	
8003.126	$4d^2$ a $^3F_2$	27 532.321	4d5p z $^3F^\circ_3$	5119.110	210	−1.33	1.194E+07	

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Table 5 – *continued*

E_{low}[a] (cm^{-1})	Lower level[a]	E_{upp}[a] (cm^{-1})	Upper level[a]	λ[b] (Å)	Int.[c]	log gf[d]	gA[d] (s^{-1})	τ[d] (ns)
8328.039	4d^2 a $^3F_3$	27 532.321	4d5p z $^3F^\circ_3$	5205.722	1500	−0.28	1.307E+08	
1449.752	4d5s a $^3D_3$	28 394.177	4d5p z $^3F^\circ_4$	3710.287	13 000	0.51	1.550E+09	5.17
8328.039	4d^2 a $^3F_3$	28 394.177	4d5p z $^3F^\circ_4$	4982.128	120	−1.32	1.280E+07	
8743.322	4d^2 a $^3F_4$	28 394.177	4d5p z $^3F^\circ_4$	5087.418	1100	−0.16	1.794E+08	
0.00	5s^2 a $^1S_0$	28 595.285	4d5p z $^3D^\circ_1$	3496.079	1700	−0.71	1.063E+08	3.98
840.198	4d5s a $^3D_1$	28 595.285	4d5p z $^3D^\circ_1$	3601.915	6200	−0.15	3.666E+08	
1045.076	4d5s a $^3D_2$	28 595.285	4d5p z $^3D^\circ_1$	3628.700	1900	−0.70	1.002E+08	
3296.180	4d5s a $^1D_2$	28 595.285	4d5p z $^3D^\circ_1$	3951.590	150	−1.78	7.149E+06	
8003.126	4d^2 a $^3F_2$	28 595.285	4d5p z $^3D^\circ_1$	4854.861	890	−0.27	1.533E+08	
13 883.379	4d^2 a $^3P_0$	28 595.285	4d5p z $^3D^\circ_1$	6795.415	70	−1.54	4.217E+06	
14 018.267	4d^2 a $^3P_1$	28 595.285	4d5p z $^3D^\circ_1$	6858.221	14	−1.69	2.910E+06	
14 098.076	4d^2 a $^3P_2$	28 595.285	4d5p z $^3D^\circ_1$	6895.976	21	−1.67	2.951E+06	
14 832.862	4d^2 b $^1D_2$	28 595.285	4d5p z $^3D^\circ_1$	7264.159	35	−1.11	9.479E+06	
840.198	4d5s a $^3D_1$	28 730.010	4d5p z $^3D^\circ_2$	3584.514	3300	−0.42	1.978E+08	3.80
1045.076	4d5s a $^3D_2$	28 730.010	4d5p z $^3D^\circ_2$	3611.043	7800	0.05	5.692E+08	
1449.752	4d5s a $^3D_3$	28 730.010	4d5p z $^3D^\circ_2$	3664.610	3000	−0.41	1.946E+08	
3296.180	4d5s a $^1D_2$	28 730.010	4d5p z $^3D^\circ_2$	3930.658	240	−1.48	1.443E+07	
8003.126	4d^2 a $^3F_2$	28 730.010	4d5p z $^3D^\circ_2$	4823.304	190	−0.99	2.951E+07	
8328.039	4d^2 a $^3F_3$	28 730.010	4d5p z $^3D^\circ_2$	4900.118	1100	0.03	2.954E+08	
14 018.267	4d^2 a $^3P_1$	28 730.010	4d5p z $^3D^\circ_2$	6795.339	70	−1.03	1.349E+07	
14 098.076	4d^2 a $^3P_2$	28 730.010	4d5p z $^3D^\circ_2$	6832.480	14	−1.86	1.943E+06	
1045.076	4d5s a $^3D_2$	29 213.958	4d5p z $^3D^\circ_3$	3549.002	3900	−0.29	2.703E+08	3.75
1449.752	4d5s a $^3D_3$	29 213.958	4d5p z $^3D^\circ_3$	3600.731	10 000	0.34	1.117E+09	
8328.039	4d^2 a $^3F_3$	29 213.958	4d5p z $^3D^\circ_3$	4786.576	160	−1.09	2.365E+07	
8743.322	4d^2 a $^3F_4$	29 213.958	4d5p z $^3D^\circ_3$	4883.682	1900	0.19	4.305E+08	
14 098.076	4d^2 a $^3P_2$	29 213.958	4d5p z $^3D^\circ_3$	6613.731	95	−0.83	2.251E+07	
840.198	4d5s a $^3D_1$	32 048.788	4d5p y $^3P^\circ_0$	3203.320	2200	−0.28	3.443E+08	2.66
14 018.267	4d^2 a $^3P_1$	32 048.788	4d5p y $^3P^\circ_0$	5544.610	120	−0.83	3.199E+07	
840.198	4d5s a $^3D_1$	32 124.054	4d5p y $^3P^\circ_1$	3195.613	2300	−0.35	2.883E+08	2.67
1045.076	4d5s a $^3D_2$	32 124.054	4d5p y $^3P^\circ_1$	3216.680	3900	0.05	7.227E+08	
3296.180	4d5s a $^1D_2$	32 124.054	4d5p y $^3P^\circ_1$	3467.871	110	−1.77	9.375E+06	
13 883.379	4d^2 a $^3P_0$	32 124.054	4d5p y $^3P^\circ_1$	5480.730	90	−0.85	3.144E+07	
14 018.267	4d^2 a $^3P_1$	32 124.054	4d5p y $^3P^\circ_1$	5521.562	120	−0.94	2.496E+07	
14 098.076	4d^2 a $^3P_2$	32 124.054	4d5p y $^3P^\circ_1$	5546.008	90	−0.82	3.230E+07	
14 832.862	4d^2 b $^1D_2$	32 124.054	4d5p y $^3P^\circ_1$	5781.687	100	−1.47	6.549E+06	
840.198	4d5s a $^3D_1$	32 283.420	4d5p y $^3P^\circ_2$	3179.415	220	−1.43	2.458E+07	2.68
1045.076	4d5s a $^3D_2$	32 283.420	4d5p y $^3P^\circ_2$	3200.269	2200	−0.32	3.084E+08	
1449.752	4d5s a $^3D_3$	32 283.420	4d5p y $^3P^\circ_2$	3242.272	6200	0.33	1.351E+09	
3296.180	4d5s a $^1D_2$	32 283.420	4d5p y $^3P^\circ_2$	3448.804	200	−1.41	2.200E+07	
14 018.267	4d^2 a $^3P_1$	32 283.420	4d5p y $^3P^\circ_2$	5473.384	90	−0.78	3.672E+07	
14 098.076	4d^2 a $^3P_2$	32 283.420	4d5p y $^3P^\circ_2$	5497.405	240	−0.31	1.062E+08	
14 832.862	4d^2 b $^1D_2$	32 283.420	4d5p y $^3P^\circ_2$	5728.886	75	−1.15	1.383E+07	
1045.076	4d5s a $^3D_2$	33 336.727	4d5p z $^1F^\circ_3$	3095.872	95	−1.74	1.255E+07	4.86
1449.752	4d5s a $^3D_3$	33 336.727	4d5p z $^1F^\circ_3$	3135.168	95	−1.68	1.422E+07	
3296.180	4d5s a $^1D_2$	33 336.727	4d5p z $^1F^\circ_3$	3327.876	4700	0.14	8.269E+08	
14 098.076	4d^2 a $^3P_2$	33 336.727	4d5p z $^1F^\circ_3$	5196.421	120	−1.23	1.435E+07	
14 832.862	4d^2 b $^1D_2$	33 336.727	4d5p z $^1F^\circ_3$	5402.773	220	−0.31	1.081E+08	
15 682.905	4d^2 a $^1G_4$	33 336.727	4d5p z $^1F^\circ_3$	5662.922	740	0.34	4.599E+08	
0.00	5s^2 a $^1S_0$	44 568.640	5s5p y $^1P^\circ_1$	2243.045	350	0.10	1.667E+09	0.99
3296.180	4d5s a $^1D_2$	44 568.640	5s5p y $^1P^\circ_1$	2422.186	560	−0.08	9.352E+08	
14 098.076	4d^2 a $^3P_2$	44 568.640	5s5p y $^1P^\circ_1$	3280.909	310	−1.08	5.089E+07	
14 832.862	4d^2 b $^1D_2$	44 568.640	5s5p y $^1P^\circ_1$	3361.986	160	−0.25	3.292E+08	

[a]From Nilsson et al. (1991).
[b]Air wavelengths from Nilsson et al. (1991).
[c]From Meggers, Corliss & Scribner (1975).
[d]This work: HFR+CPOL values.

Table 6. Transition probabilities in Y III. Only the transitions for which log *gf* > −2.0 and λ < 10 000 Å are included in the table. It was verified that all these transitions are not affected by pronounced cancellation effects.

E_{low}[a] (cm^{-1})	Designation	E_{upp}[a] (cm^{-1})	Designation	λ (Å)	Int.[b]	log *gf*[c]	*gA*[c] (s^{-1})	τ[c] (ns)
0.00	4d $^2D_{3/2}$	41 401.46	5p $^2P^\circ_{1/2}$	2414.643a	40 000	−0.29	5.805E+08	1.78
7467.10	5s $^2S_{1/2}$	41 401.46	5p $^2P^\circ_{1/2}$	2946.014a	300 000	−0.15	5.420E+08	
0.00	4d $^2D_{3/2}$	42 954.87	5p $^2P^\circ_{3/2}$	2327.313a	10 000	−0.98	1.297E+08	1.61
724.15	4d $^2D_{5/2}$	42 954.87	5p $^2P^\circ_{3/2}$	2367.228a	50000	−0.03	1.109E+09	
7467.10	5s $^2S_{1/2}$	42 954.87	5p $^2P^\circ_{3/2}$	2817.037a	250 000	0.17	1.240E+09	
41 401.46	5p $^2P^\circ_{1/2}$	86 717.59	6s $^2S_{1/2}$	2206.029a	8000	−0.36	6.013E+08	1.19
42 954.87	5p $^2P^\circ_{3/2}$	86 717.59	6s $^2S_{1/2}$	2284.345a	10 000	−0.07	1.083E+09	
41 401.46	5p $^2P^\circ_{1/2}$	88 379.61	5d $^2D_{3/2}$	2127.979a	10 000	0.35	3.317E+09	1.02
42 954.87	5p $^2P^\circ_{3/2}$	88 379.61	5d $^2D_{3/2}$	2200.758a	8000	−0.36	5.998E+08	
42 954.87	5p $^2P^\circ_{3/2}$	88 578.29	5d $^2D_{5/2}$	2191.159a	16 000	0.60	5.469E+09	1.10
0.00	4d $^2D_{3/2}$	99 345.62	6p $^2P^\circ_{1/2}$	1006.582a	1000	−1.51	2.049E+08	4.80
86 717.59	6s $^2S_{1/2}$	99 345.62	6p $^2P^\circ_{1/2}$	7916.71a	8000	0.02	1.113E+08	
88 379.61	5d $^2D_{3/2}$	99 345.62	6p $^2P^\circ_{1/2}$	9116.59a	8000	0.02	8.353E+07	
724.15	4d $^2D_{5/2}$	99 943.71	6p $^2P^\circ_{3/2}$	1007.860a	1200	−1.25	3.674E+08	4.51
86 717.59	6s $^2S_{1/2}$	99 943.71	6p $^2P^\circ_{3/2}$	7558.71a	9000	0.34	2.557E+08	
88 379.61	5d $^2D_{3/2}$	99 943.71	6p $^2P^\circ_{3/2}$	8645.09a	4000	−0.66	1.959E+07	
88 578.29	5d $^2D_{5/2}$	99 943.71	6p $^2P^\circ_{3/2}$	8796.21a	10 000	0.29	1.674E+08	
724.15	4d $^2D_{5/2}$	101 088.23	4f $^2F^\circ_{7/2}$	996.370a	25 000	0.34	1.467E+10	0.53
88 578.29	5d $^2D_{5/2}$	101 088.23	4f $^2F^\circ_{7/2}$	7991.43a	10 000	0.58	3.963E+08	
0.00	4d $^2D_{3/2}$	101 091.42	4f $^2F^\circ_{5/2}$	989.206a	15 000	0.19	1.049E+10	0.52
724.15	4d $^2D_{5/2}$	101 091.42	4f $^2F^\circ_{5/2}$	996.341		−0.96	7.333E+08	
88 379.61	5d $^2D_{3/2}$	101 091.42	4f $^2F^\circ_{5/2}$	7864.53a	6000	0.43	2.907E+08	
88 578.29	5d $^2D_{5/2}$	101 091.42	4f $^2F^\circ_{5/2}$	7989.41a	400	−0.72	1.981E+07	
41 401.46	5p $^2P^\circ_{1/2}$	117 915.23	7s $^2S_{1/2}$	1306.960a	2500	−1.22	2.374E+08	1.79
42 954.87	5p $^2P^\circ_{3/2}$	117 915.23	7s $^2S_{1/2}$	1334.043a	4000	−0.92	4.465E+08	
99 345.62	6p $^2P^\circ_{1/2}$	117 915.23	7s $^2S_{1/2}$	5383.644a	4000	−0.17	1.543E+08	
99 943.71	6p $^2P^\circ_{3/2}$	117 915.23	7s $^2S_{1/2}$	5562.81a	6000	0.11	2.797E+08	
41 401.46	5p $^2P^\circ_{1/2}$	118 936.91	6d $^2D_{3/2}$	1289.738a	3000	−0.74	7.293E+08	2.22
42 954.87	5p $^2P^\circ_{3/2}$	118 936.91	6d $^2D_{3/2}$	1316.102a	1500	−1.45	1.373E+08	
99 345.62	6p $^2P^\circ_{1/2}$	118 936.91	6d $^2D_{3/2}$	5102.884a	7500	0.44	6.980E+08	
99 943.71	6p $^2P^\circ_{3/2}$	118 936.91	6d $^2D_{3/2}$	5263.582a	3000	−0.28	1.272E+08	
42 954.87	5p $^2P^\circ_{3/2}$	119 029.30	6d $^2D_{5/2}$	1314.510a	5000	−0.49	1.240E+09	2.33
99 943.71	6p $^2P^\circ_{3/2}$	119 029.30	6d $^2D_{5/2}$	5238.104a	10 000	0.68	1.162E+09	
101 091.42	4f $^2F^\circ_{5/2}$	119 029.30	6d $^2D_{5/2}$	5573.247		−1.42	8.239E+06	
101 088.23	4f $^2F^\circ_{7/2}$	119 029.30	6d $^2D_{5/2}$	5572.24a	4000	−0.12	1.647E+08	
0.00	4d $^2D_{3/2}$	124 041.76	7p $^2P^\circ_{1/2}$	806.182a	75	−1.98	1.065E+08	9.50
88 379.61	5d $^2D_{3/2}$	124 041.76	7p $^2P^\circ_{1/2}$	2803.267a	20	−1.73	1.595E+07	
0.00	4d $^2D_{3/2}$	124 192.92	5f $^2F^\circ_{5/2}$	805.195a	5000	−0.26	5.655E+09	0.88
724.15	4d $^2D_{5/2}$	124 192.92	5f $^2F^\circ_{5/2}$	809.921		−1.41	3.969E+08	
88 379.61	5d $^2D_{3/2}$	124 192.92	5f $^2F^\circ_{5/2}$	2791.441a	70	−0.10	6.760E+08	
88 578.29	5d $^2D_{5/2}$	124 192.92	5f $^2F^\circ_{5/2}$	2807.008		−1.25	4.749E+07	
724.15	4d $^2D_{5/2}$	124 193.02	5f $^2F^\circ_{7/2}$	809.921a	7000	−0.19	7.938E+09	0.89
88 578.29	5d $^2D_{5/2}$	124 193.02	5f $^2F^\circ_{7/2}$	2806.996a	100	0.05	9.498E+08	
724.15	4d $^2D_{5/2}$	124 338.78	7p $^2P^\circ_{3/2}$	808.966a	150	−1.73	1.898E+08	9.15
88 578.29	5d $^2D_{5/2}$	124 338.78	7p $^2P^\circ_{3/2}$	2795.558		−1.47	2.895E+07	
101 091.42	4f $^2F^\circ_{5/2}$	125 836.22	5g $^2G_{7/2}$	4040.112a	3000	0.90	3.251E+09	1.37
101 088.23	4f $^2F^\circ_{7/2}$	125 836.22	5g $^2G_{7/2}$	4039.591		−0.53	1.204E+08	
101 088.23	4f $^2F^\circ_{7/2}$	125 836.15	5g $^2G_{9/2}$	4039.602a	3800	1.01	4.214E+09	2.37

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Table 6 – *continued*

$E_{\rm low}{}^a$ (cm^{-1})	Designation	$E_{\rm upp}{}^a$ (cm^{-1})	Designation	λ (Å)	Int.^{b}	log gf^c	gA^c (s^{-1})	τ^c (ns)
41 401.46	5p ^{2}P$^\circ_{1/2}$	133 599.09	8s ^{2}S$_{1/2}$	1084.626a	75	−1.66	1.246E+08	2.82
42 954.87	5p ^{2}P$^\circ_{3/2}$	133 599.09	8s ^{2}S$_{1/2}$	1103.212a	150	−1.36	2.368E+08	
99 345.62	6p ^{2}P$^\circ_{1/2}$	133 599.09	8s ^{2}S$_{1/2}$	2918.561a	1600	−1.07	6.657E+07	
99 943.71	6p ^{2}P$^\circ_{3/2}$	133 599.09	8s ^{2}S$_{1/2}$	2970.424a	6000	−0.78	1.263E+08	
41 401.46	5p ^{2}P$^\circ_{1/2}$	134 206.87	7d ^{2}D$_{3/2}$	1077.523a	120	−1.30	2.885E+08	4.07
42 954.87	5p ^{2}P$^\circ_{3/2}$	134 206.87	7d ^{2}D$_{3/2}$	1095.869a	25	-2.00	5.485E+07	
99 345.62	6p ^{2}P$^\circ_{1/2}$	134 206.87	7d ^{2}D$_{3/2}$	2867.673a	6000	−0.55	2.281E+08	
99 943.71	6p ^{2}P$^\circ_{3/2}$	134 206.87	7d ^{2}D$_{3/2}$	2917.740a	1500	−1.26	4.331E+07	
101 091.42	4f ^{2}F$^\circ_{5/2}$	134 206.87	7d ^{2}D$_{3/2}$	3018.850a	1500	−1.23	4.297E+07	
124 041.76	7p ^{2}P$^\circ_{1/2}$	134 206.87	7d ^{2}D$_{3/2}$	9834.875		0.49	2.144E+08	
124 192.92	5f ^{2}F$^\circ_{5/2}$	134 206.87	7d ^{2}D$_{3/2}$	9983.332		0.03	7.203E+07	
42 954.87	5p ^{2}P$^\circ_{3/2}$	134 257.75	7d ^{2}D$_{5/2}$	1095.254a	250	−1.05	4.945E+08	4.23
99 943.71	6p ^{2}P$^\circ_{3/2}$	134 257.75	7d ^{2}D$_{5/2}$	2913.412a	6000	−0.30	3.916E+08	
101 088.23	4f ^{2}F$^\circ_{7/2}$	134 257.75	7d ^{2}D$_{5/2}$	3013.933a	1400	−1.08	6.166E+07	
124 192.92	5f ^{2}F$^\circ_{5/2}$	134 257.75	7d ^{2}D$_{5/2}$	9932.864		−1.11	5.224E+06	
124 193.02	5f ^{2}F$^\circ_{7/2}$	134 257.75	7d ^{2}D$_{5/2}$	9932.963		0.19	1.045E+08	
0.00	4d ^{2}D$_{3/2}$	136 894.08	6f ^{2}F$^\circ_{5/2}$	730.490a	600	−0.59	3.208E+09	1.42
724.15	4d ^{2}D$_{5/2}$	136 894.08	6f ^{2}F$^\circ_{5/2}$	734.377		−1.74	2.256E+08	
88 379.61	5d ^{2}D$_{3/2}$	136 894.08	6f ^{2}F$^\circ_{5/2}$	2060.579a	1500	−0.43	5.816E+08	
88 578.29	5d ^{2}D$_{5/2}$	136 894.08	6f ^{2}F$^\circ_{5/2}$	2069.056		−1.58	4.103E+07	
118 936.91	6d ^{2}D$_{3/2}$	136 894.08	6f ^{2}F$^\circ_{5/2}$	5567.27a	600	−0.25	1.210E+08	
119 029.30	6d ^{2}D$_{5/2}$	136 894.08	6f ^{2}F$^\circ_{5/2}$	5596.052		−1.40	8.509E+06	
125 836.22	5g ^{2}G$_{7/2}$	136 894.08	6f ^{2}F$^\circ_{5/2}$	9040.859		−0.96	8.994E+06	
724.15	4d ^{2}D$_{5/2}$	136 895.91	6f ^{2}F$^\circ_{7/2}$	734.364a	800	−0.44	4.511E+09	1.44
88 578.29	5d ^{2}D$_{5/2}$	136 895.91	6f ^{2}F$^\circ_{7/2}$	2068.979a	4000	−0.28	8.207E+08	
119 029.30	6d ^{2}D$_{5/2}$	136 895.91	6f ^{2}F$^\circ_{7/2}$	5595.48a	400	−0.10	1.702E+08	
125 836.15	5g ^{2}G$_{9/2}$	136 895.91	6f ^{2}F$^\circ_{7/2}$	9039.306		−0.85	1.166E+07	
118 936.91	6d ^{2}D$_{3/2}$	137 036.4	8p ^{2}P$^\circ_{1/2}$	5523.483		−1.76	3.758E+06	16.32
88 578.29	5d ^{2}D$_{5/2}$	137 205.5	8p ^{2}P$^\circ_{3/2}$	2055.804		−1.99	1.618E+07	15.94
119 029.30	6d ^{2}D$_{5/2}$	137 205.5	8p ^{2}P$^\circ_{3/2}$	5500.172		−1.51	6.851E+06	
101 091.42	4f ^{2}F$^\circ_{5/2}$	137 973.52	6g ^{2}G$_{7/2}$	2710.535a	90	0.06	1.042E+09	4.10
101 088.23	4f ^{2}F$^\circ_{7/2}$	137 973.52	6g ^{2}G$_{7/2}$	2710.304		−1.37	3.859E+07	
124 192.92	5f ^{2}F$^\circ_{5/2}$	137 973.52	6g ^{2}G$_{7/2}$	7254.58a	2000*	0.82	8.391E+08	
124 193.02	5f ^{2}F$^\circ_{7/2}$	137 973.52	6g ^{2}G$_{7/2}$	7254.58a	2000*	−0.61	3.107E+07	
10 1088.23	4f ^{2}F$^\circ_{7/2}$	137 973.63	6g ^{2}G$_{9/2}$	2710.300a	100	0.17	1.351E+09	4.10
124 193.02	5f ^{2}F$^\circ_{7/2}$	137 973.63	6g ^{2}G$_{9/2}$	7254.58a	2000*	0.93	1.088E+09	
125 836.22	5g ^{2}G$_{7/2}$	138 070.60	6h ^{2}H$^\circ_{9/2}$	8171.41a	8000*	1.13	1.343E+09	7.28
125 836.15	5g ^{2}G$_{9/2}$	138 070.60	6h ^{2}H$^\circ_{9/2}$	8171.41a	8000*	−0.52	3.051E+07	
125 836.15	5g ^{2}G$_{9/2}$	138 070.60	6h ^{2}H$^\circ_{11/2}$	8171.41a	8000*	1.22	1.648E+09	7.28
41 401.46	5p ^{2}P$^\circ_{1/2}$	142 620.7	9s ^{2}S$_{1/2}$	987.958a	15	−1.96	7.421E+07	4.30
42 954.87	5p ^{2}P$^\circ_{3/2}$	142 620.7	9s ^{2}S$_{1/2}$	1003.350a	25	−1.67	1.417E+08	
99 345.62	6p ^{2}P$^\circ_{1/2}$	142 620.7	9s ^{2}S$_{1/2}$	2310.088		−1.52	3.766E+07	
99 943.71	6p ^{2}P$^\circ_{3/2}$	142 620.7	9s ^{2}S$_{1/2}$	2342.465		−1.23	7.225E+07	
124 041.76	7p ^{2}P$^\circ_{1/2}$	142 620.7	9s ^{2}S$_{1/2}$	5380.942		−0.96	2.511E+07	
124 338.78	7p ^{2}P$^\circ_{3/2}$	142 620.7	9s ^{2}S$_{1/2}$	5468.365		−0.67	4.785E+07	
41 401.46	5p ^{2}P$^\circ_{1/2}$	143 004.2	8d ^{2}D$_{3/2}$	984.226a	25	−1.67	1.460E+08	6.70
99 345.62	6p ^{2}P$^\circ_{1/2}$	143 004.2	8d ^{2}D$_{3/2}$	2289.794		−1.06	1.101E+08	
99 943.71	6p ^{2}P$^\circ_{3/2}$	143 004.2	8d ^{2}D$_{3/2}$	2321.601		−1.77	2.113E+07	
101 091.42	4f ^{2}F$^\circ_{5/2}$	143 004.2	8d ^{2}D$_{3/2}$	2385.180		−1.72	2.212E+07	
124 041.76	7p ^{2}P$^\circ_{1/2}$	143 004.2	8d ^{2}D$_{3/2}$	5272.116		−0.45	8.487E+07	
124 192.92	5f ^{2}F$^\circ_{5/2}$	143 004.2	8d ^{2}D$_{3/2}$	5314.481		−0.88	3.085E+07	
124 338.78	7p ^{2}P$^\circ_{3/2}$	143 004.2	8d ^{2}D$_{3/2}$	5356.011		−1.16	1.619E+07	

Table 6 – *continued*

E_{low}[a] (cm^{-1})	Designation	E_{upp}[a] (cm^{-1})	Designation	λ (Å)	Int.[b]	log *gf*[c]	*gA*[c] (s^{-1})	τ[c] (ns)
118 936.91	6d $^2D_{3/2}$	137 036.4	8p $^2P^{\circ}_{1/2}$	5523.483		−1.76	3.758E+06	16.32
42 954.87	5p $^2P^{\circ}_{3/2}$	143 035.4	8d $^2D_{5/2}$	999.193a	20	−1.43	2.511E+08	6.91
99 943.71	6p $^2P^{\circ}_{3/2}$	143 035.4	8d $^2D_{5/2}$	2319.918a	3	−0.81	1.906E+08	
101 088.23	4f $^2F^{\circ}_{7/2}$	143 035.4	8d $^2D_{5/2}$	2383.224		−1.57	3.166E+07	
124 193.02	5f $^2F^{\circ}_{7/2}$	143 035.4	8d $^2D_{5/2}$	5305.709		−0.73	4.428E+07	
124 338.78	7p $^2P^{\circ}_{3/2}$	143 035.4	8d $^2D_{5/2}$	5347.073		−0.20	1.464E+08	
0.00	4d $^2D_{3/2}$	144 565.80	7f $^2F^{\circ}_{5/2}$	691.725a	100	−0.85	1.970E+09	2.19
724.15	4d $^2D_{5/2}$	144 565.80	7f $^2F^{\circ}_{5/2}$	695.209		-2.00	1.386E+08	
88 379.61	5d $^2D_{3/2}$	144 565.80	7f $^2F^{\circ}_{5/2}$	1779.797a	200	−0.71	4.104E+08	
88 578.29	5d $^2D_{5/2}$	144 565.80	7f $^2F^{\circ}_{5/2}$	1785.491		−1.86	2.900E+07	
118 936.91	6d $^2D_{3/2}$	144 565.80	7f $^2F^{\circ}_{5/2}$	3900.743a	3000	−0.53	1.280E+08	
119 029.30	6d $^2D_{5/2}$	144 565.80	7f $^2F^{\circ}_{5/2}$	3914.855		−1.68	9.047E+06	
125 836.22	5g $^2G_{7/2}$	144 565.80	7f $^2F^{\circ}_{5/2}$	5337.663		−1.74	4.270E+06	
134 206.87	7d $^2D_{3/2}$	144 565.80	7f $^2F^{\circ}_{5/2}$	9650.860		−0.35	3.216E+07	
134 257.75	7d $^2D_{5/2}$	144 565.80	7f $^2F^{\circ}_{5/2}$	9698.496		−1.50	2.263E+06	
724.15	4d $^2D_{5/2}$	144 567.59	7f $^2F^{\circ}_{7/2}$	695.198a	200	−0.70	2.773E+09	2.22
88 578.29	5d $^2D_{5/2}$	144 567.59	7f $^2F^{\circ}_{7/2}$	1786.054a	600	−0.56	5.800E+08	
119 029.30	6d $^2D_{5/2}$	144 567.59	7f $^2F^{\circ}_{7/2}$	3914.581a	4000	−0.38	1.809E+08	
125 836.15	5g $^2G_{9/2}$	144 567.59	7f $^2F^{\circ}_{7/2}$	5337.133		−1.63	5.535E+06	
134 257.75	7d $^2D_{5/2}$	144 567.59	7f $^2F^{\circ}_{7/2}$	9696.812		−0.20	4.527E+07	
134 206.87	7d $^2D_{3/2}$	144 741.1	9p $^2P^{\circ}_{1/2}$	9490.259		−1.80	1.179E+06	25.75
134 257.75	7d $^2D_{5/2}$	144 847.3	9p $^2P^{\circ}_{3/2}$	9440.682		−1.54	2.157E+06	25.36
101 091.42	4f $^2F^{\circ}_{5/2}$	145 294.65	7g $^2G_{7/2}$	2261.574a	80	−0.43	4.896E+08	6.49
10 1088.23	4f $^2F^{\circ}_{7/2}$	145 294.65	7g $^2G_{7/2}$	2261.415		−1.86	1.813E+07	
124 192.92	5f $^2F^{\circ}_{5/2}$	145 294.65	7g $^2G_{7/2}$	4737.625a	2000*	0.15	4.226E+08	
124 193.02	5f $^2F^{\circ}_{7/2}$	145 294.65	7g $^2G_{7/2}$	4737.625a	2000*	−1.28	1.565E+07	
10 1088.23	4f $^2F^{\circ}_{7/2}$	145 294.73	7g $^2G_{9/2}$	2261.414a	150	−0.31	6.346E+08	6.49
124 193.02	5f $^2F^{\circ}_{7/2}$	145 294.73	7g $^2G_{9/2}$	4737.625a	2000*	0.27	5.477E+08	
125 836.22	5g $^2G_{7/2}$	145 360.46	7h $^2H^{\circ}_{9/2}$	5120.40a	1300*	0.20	4.056E+08	11.60
125 836.15	5g $^2G_{9/2}$	145 360.46	7h $^2H^{\circ}_{9/2}$	5120.40a	1300*	−1.44	9.217E+06	
125 836.15	5g $^2G_{9/2}$	145 360.46	7h $^2H^{\circ}_{11/2}$	5120.40a	1300*	0.29	4.977E+08	11.60
0.00	4d $^2D_{3/2}$	149 536.28	8f $^2F^{\circ}_{5/2}$	668.735a	25	−1.06	1.292E+09	3.17
88 379.61	5d $^2D_{3/2}$	149 536.28	8f $^2F^{\circ}_{5/2}$	1635.145a	30	−0.94	2.878E+08	
118 936.91	6d $^2D_{3/2}$	149 536.28	8f $^2F^{\circ}_{5/2}$	3267.100a	3	−0.79	1.022E+08	
119 029.30	6d $^2D_{5/2}$	149 536.28	8f $^2F^{\circ}_{5/2}$	3276.994		−1.93	7.232E+06	
134 206.87	7d $^2D_{3/2}$	149 536.28	8f $^2F^{\circ}_{5/2}$	6521.606		−0.61	3.830E+07	
134 257.75	7d $^2D_{5/2}$	149 536.28	8f $^2F^{\circ}_{5/2}$	6543.325		−1.76	2.708E+06	
137 973.52	6g $^2G_{7/2}$	149 536.28	8f $^2F^{\circ}_{5/2}$	8646.079		−1.29	4.573E+06	
724.15	4d $^2D_{5/2}$	149 537.94	8f $^2F^{\circ}_{7/2}$	671.982a	40	−0.91	1.819E+09	3.20
88 578.29	5d $^2D_{5/2}$	149 537.94	8f $^2F^{\circ}_{7/2}$	1640.433a	75	−0.78	4.072E+08	
119 029.30	6d $^2D_{5/2}$	149 537.94	8f $^2F^{\circ}_{7/2}$	3276.801a	25	−0.63	1.446E+08	
134 257.75	7d $^2D_{5/2}$	149 537.94	8f $^2F^{\circ}_{7/2}$	6542.614		−0.46	5.417E+07	
137 973.63	6g $^2G_{9/2}$	149 537.94	8f $^2F^{\circ}_{7/2}$	8644.920		−1.18	5.927E+06	
101 091.42	4f $^2F^{\circ}_{5/2}$	150 045.68	8g $^2G_{7/2}$	2042.066a	5	−0.76	2.758E+08	9.66
124 192.92	5f $^2F^{\circ}_{5/2}$	150 045.68	8g $^2G_{7/2}$	3866.962a	500*	−0.26	2.450E+08	
124 193.02	5f $^2F^{\circ}_{7/2}$	150 045.68	8g $^2G_{7/2}$	3866.962a	500*	−1.69	9.074E+06	
136 894.08	6f $^2F^{\circ}_{5/2}$	150 045.68	8g $^2G_{7/2}$	7601.545		0.16	1.676E+08	
136 895.91	6f $^2F^{\circ}_{7/2}$	150 045.68	8g $^2G_{7/2}$	7602.603		−1.27	6.206E+06	
10 1088.23	4f $^2F^{\circ}_{7/2}$	150 045.78	8g $^2G_{9/2}$	2041.934a	10	−0.65	3.575E+08	9.66
124 193.02	5f $^2F^{\circ}_{7/2}$	150 045.78	8g $^2G_{9/2}$	3866.962a	500*	−0.15	3.176E+08	
136 895.91	6f $^2F^{\circ}_{7/2}$	150 045.78	8g $^2G_{9/2}$	7602.545		0.28	2.172E+08	

Table 6 – *continued*

E_{low}[a] (cm^{-1})	Designation	E_{upp}[a] (cm^{-1})	Designation	λ (Å)	Int.[b]	log *gf*[c]	*gA*[c] (s^{-1})	τ[c] (ns)
138 070.60	6h $^2H^\circ_{11/2}$	150 045.78	8g $^2G_{9/2}$	8348.311		−1.96	1.054E+06	
125 836.22	5g $^2G_{7/2}$	150 091.71	8h $^2H^\circ_{9/2}$	4121.608a	120*	−0.33	1.837E+08	17.32
125 836.15	5g $^2G_{9/2}$	150 091.71	8h $^2H^\circ_{9/2}$	4121.608a	120*	−1.97	4.175E+06	
137 973.52	6g $^2G_{7/2}$	150 091.71	8h $^2H^\circ_{9/2}$	8249.790		0.33	2.085E+08	
137 973.63	6g $^2G_{9/2}$	150 091.71	8h $^2H^\circ_{9/2}$	8249.865		−1.32	4.739E+06	
125 836.15	5g $^2G_{9/2}$	150 091.71	8h $^2H^\circ_{11/2}$	4121.608a	120*	−0.24	2.254E+08	17.32
137 973.63	6g $^2G_{9/2}$	150 091.71	8h $^2H^\circ_{11/2}$	8249.865		0.42	2.559E+08	
0.00	4d $^2D_{3/2}$	152 934.36	9f $^2F^\circ_{5/2}$	653.874a	6	−1.24	8.919E+08	4.40
88 379.61	5d $^2D_{3/2}$	152 934.36	9f $^2F^\circ_{5/2}$	1549.078a	8	−1.13	2.066E+08	
118 936.91	6d $^2D_{3/2}$	152 934.36	9f $^2F^\circ_{5/2}$	2940.530a	15	−1.00	7.797E+07	
134 206.87	7d $^2D_{3/2}$	152 934.36	9f $^2F^\circ_{5/2}$	5338.259		−0.85	3.304E+07	
134 257.75	7d $^2D_{5/2}$	152 934.36	9f $^2F^\circ_{5/2}$	5352.802		-2.00	2.341E+06	
137 973.52	6g $^2G_{7/2}$	152 934.36	9f $^2F^\circ_{5/2}$	6682.272		−1.74	2.713E+06	
724.15	4d $^2D_{5/2}$	152 935.4	9f $^2F^\circ_{7/2}$	656.981a	10	−1.09	1.256E+09	4.46
88 578.29	5d $^2D_{5/2}$	152 935.4	9f $^2F^\circ_{7/2}$	1553.814a	15	−0.98	2.924E+08	
119 029.30	6d $^2D_{5/2}$	152 935.4	9f $^2F^\circ_{7/2}$	2948.48a	20	−0.84	1.105E+08	
134 257.75	7d $^2D_{5/2}$	152 935.4	9f $^2F^\circ_{7/2}$	5352.504		−0.70	4.682E+07	
137 973.63	6g $^2G_{9/2}$	152 935.4	9f $^2F^\circ_{7/2}$	6681.856		−1.63	3.517E+06	
0.00	4d $^2D_{3/2}$	155 357.2	10f $^2F^\circ_{5/2}$	643.678a	1	−1.40	6.415E+08	6.03
88 379.61	5d $^2D_{3/2}$	155 357.2	10f $^2F^\circ_{5/2}$	1492.604		−1.29	1.523E+08	
118 936.91	6d $^2D_{3/2}$	155 357.2	10f $^2F^\circ_{5/2}$	2744.910		−1.17	5.954E+07	
134 206.87	7d $^2D_{3/2}$	155 357.2	10f $^2F^\circ_{5/2}$	4726.736		−1.05	2.671E+07	
143 004.2	8d $^2D_{3/2}$	155 357.2	10f $^2F^\circ_{5/2}$	8092.974		−0.90	1.279E+07	
145 294.65	7g $^2G_{7/2}$	155 357.2	10f $^2F^\circ_{5/2}$	9935.115		−1.47	2.316E+06	
724.15	4d $^2D_{5/2}$	155 358.7	10f $^2F^\circ_{7/2}$	646.686a	4	−1.25	9.036E+08	6.102
88 578.29	5d $^2D_{5/2}$	155 358.7	10f $^2F^\circ_{7/2}$	1497.020		−1.14	2.156E+08	
119 029.30	6d $^2D_{5/2}$	155 358.7	10f $^2F^\circ_{7/2}$	2751.778		−1.02	8.441E+07	
134 257.75	7d $^2D_{5/2}$	155 358.7	10f $^2F^\circ_{7/2}$	4737.798		−0.89	3.789E+07	
137 973.63	6g $^2G_{9/2}$	155 358.7	10f $^2F^\circ_{7/2}$	5750.467		−1.95	2.279E+06	
143 035.4	8d $^2D_{5/2}$	155 358.7	10f $^2F^\circ_{7/2}$	8112.479		−0.75	1.813E+07	
145 294.73	7g $^2G_{9/2}$	155 358.7	10f $^2F^\circ_{7/2}$	9933.713		−1.35	3.002E+06	

Note. Values indicated with * indicate blends.
[a]The levels are from Epstein & Reader (1975). The observed wavelengths are taken from Epstein & Reader (1975). Otherwise, the wavelengths have been calculated from the energy levels published by the same authors. Wavelengths of >2000 Å are given in air.
[b]Laboratory intensity according to Epstein & Reader (1975).
[c]This work: HFR+CPOL values.

levels belonging to the configurations 4d5p and 5s5p. Only the most intense transitions (log $gf > -2.0$) are quoted in the table.

In Table 6, we list the transition probabilities and the oscillator strengths of the transitions depopulating the levels included in Epstein & Reader (1975). Only the transitions for which log $gf > -2.0$ and $\lambda < 10\,000$ Å are quoted. It was verified that the transitions in Tables 5 and 6 are not affected by pronounced cancellation effects.

Having in mind the agreement between theory and experiment, the calculated transition probabilities are expected to be accurate within 5–15 per cent for most of the transitions considered in this paper, the uncertainties being eventually larger for the weakest transitions.

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