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Oscillator strengths for lines of astrophysical interest in Rh II[★]

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ABSTRACT

Aims. This work reports oscillator strengths for transitions of astrophysical interest in singly ionized rhodium.

Methods. Seventeen radiative lifetimes in Rh⁺ have been measured with the time-resolved laser-induced fluorescence technique and combined with theoretical branching fractions calculated using a relativistic Hartree-Fock model including core-polarization effects to obtain oscillator strengths.

Results. On the basis of the good agreement between theory and experiment for the lifetimes, new reliable oscillator strengths have been deduced for a set of 113 Rh II transitions in the spectral range 153–418 nm.

Key words. atomic processes – atomic data

1. Introduction

The investigation of high resolution astronomical spectra depends directly on reliable atomic data such as transition probabilities and oscillator strengths. Although many data are now available from modern experimental techniques or sophisticated theoretical methods, they are still insufficient to meet all the needs of astrophysicists. This is particularly true for singly ionized rhodium for which no radiative data have been published so far in the literature despite the fact that several Rh II lines have been identified in different astrophysical spectra such as the solar spectrum (Moore et al. 1966) and the spectra of the HgMn type star χ Lupi (Lundberg et al. 1998), the super-rich mercury star HD 65949, the HgMn star HD 175640 and the peculiar Przybylski's star HD 101065 (Cowley 2009). As examples, for the three latter stars, lines observed at $\lambda = 309.35$, 316.22, 318.79, 320.73, 324.05, 330.74 and 347.78 nm were identified as radiative transitions in Rh II.

Rhodium has one stable isotope, ¹⁰³Rh, and 19 short-lived isotopes and isomers. In stellar nucleosynthesis, it is produced by both the *r*- and *s*-processes. The spectrum of singly ionized rhodium belongs to the Ru I isoelectronic sequence with 4d⁸ ³F₄ as the ground state. The laboratory term analysis was performed by Sancho (1958) who classified 814 spectral lines extending from 118.7 to 328.8 nm and established a list of 36 even and 84 odd energy levels belonging to the 4d⁸, 4d⁷5s and 4d⁷5p configurations. This work was taken as reference in subsequent atomic data compilations by Moore (1971), Meggers et al. (1975) and Reader et al. (1980). To our knowledge, the only determination of experimental transition probabilities in Rh II is due to Corliss & Bozman (1962) but their arc measurements have been recognized to be affected by large systematic errors.

In the present paper, we report on time-resolved laser-induced fluorescence (TR-LIF) lifetime measurements for 17 levels in Rh II. These new experimental lifetimes have been used to assess the reliability of theoretical results obtained within the framework of the relativistic Hartree-Fock (HFR) approach (Cowan 1981) modified by the inclusion of core-polarization effects (HFR+CPOL) (Quinet et al. 1999). From the combination of experimental lifetimes and theoretical branching fractions, it has been possible to obtain a new set of semi-empirical oscillator strengths for selected transitions of astrophysical interest. This work is an extension to longer wavelengths of our recent paper focused on VUV lines in singly ionized rhodium (Quinet et al. 2011).

2. Radiative lifetime measurements

The experimental setup used in the present experiments has been described elsewhere (Bergström et al. 1988; Xu et al. 2004; Nilsson et al. 2010) and only a brief description will be given here. The lifetime measurements were performed on ions in a laser-generated plasma employing the time-resolved laser-induced-fluorescence technique. Nd-YAG laser pulses at 532 nm with a duration of 10 ns were focused onto the surface of a rotating rhodium target in a vacuum chamber with a background pressure of about 10⁻⁵ mbar. For the excitation of the investigated levels, the expanding rhodium plasma was crossed at right angle by a pulsed laser beam tuned to a resonant transition of the upper level of interest. The laser used a DCM dye and was pumped by a second Nd:YAG laser. The pump laser pulses had a duration of 10 ns and were compressed to about 1.5 ns utilizing stimulated Brillouin scattering in a water cell. The two Nd:YAG lasers were synchronized by a pulse generator and had a repetition rate of 10 Hz. For the selective excitation of the investigated Rh⁺ levels the corresponding wavelengths were achieved using the third harmonic of the red dye laser light, obtained by harmonic

[★] Table 3 is also available at the CDS via anonymous ftp to cdsarc.u-strasbg.fr (130.79.128.5) or via <http://cdsarc.u-strasbg.fr/viz-bin/qcat?J/A+A/537/A74>

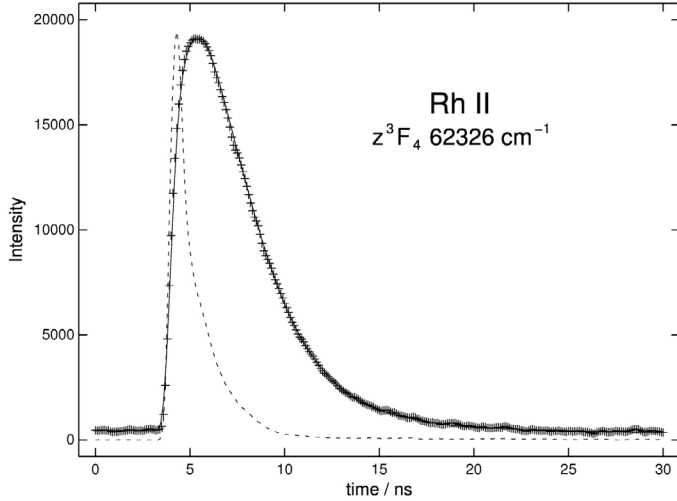


Fig. 1. Decay of the $4d^7(4F)5p\ z^3F_4^\circ$ level at $62\,326\text{ cm}^{-1}$, with an evaluated lifetime of $2.4 \pm 0.2\text{ ns}$. Background subtracted data points with typical error bars are plotted together with a fitted single exponential decay convoluted by the measured laser pulse (solid line). The actual measurement covers more than 90 ns. The dashed curve shows the recorded laser pulse with a $FWHM$ of 1.1 ns.

generation in KDP and BBO crystals and, if necessary, shifted by stimulated Raman scattering in hydrogen gas. In the measurements metastable levels of the same parity as the ground level were used as starting point for the selective excitation. These levels, with energies between $16\,885$ and $20\,647\text{ cm}^{-1}$, are only populated in an early stage of the plasma expansion. The measurements were performed about 5 mm above the target and the delay between the plasma-generating and excitation pulses was around 300 ns. This corresponds to an ion velocity larger than 10^4 m/s in the expanding plasma.

The TR-LIF signal was selected by a 1/8 m monochromator, detected by a fast photomultiplier tube with rise time 0.15 ns and digitized by an oscilloscope with 2.5 GHz analogue bandwidth. The temporal shape of the exciting laser pulses was recorded simultaneously using a photo diode. Each pair of curves were formed by averaging over 1000 laser pulses and then transferred to a PC for further treatment. The lifetimes were obtained after fitting the LIF curve with an exponential convoluted with the recorded laser pulse. An example of an experimental recording is shown in Fig. 1. In Table 1 the lifetime values are given together with the lower level used for the selective excitation, excitation wavelength, non-linear processes to obtain this wavelength from a red dye laser and strongest detection channel. Whenever possible recordings were made on several detection wavelengths. The lifetime values are averages of more than 10 recordings performed at at least two different occasions. The uncertainties in the table are mainly due to variation in results between repeated measurements and possible systematic errors, which were carefully checked for (Sikström et al. 2002). They correspond to at least a 95% confidence interval of the various measurements. Due to recombination in the plasma LIF curves for all investigated states were more or less affected by background light. The problem could not be avoided since the metastable platform levels were only populated during the early stage of the plasma evolution. The background was subtracted in the fitting procedure but remains as a major contribution to the error bars in the present measurements.

3. Transition probability and oscillator strength calculations

As the Rh^+ ion belongs to the ruthenium isoelectronic sequence, we considered a relativistic Hartree-Fock model with core-polarization (HFR+CPOL) similar to the one used with success in Ru I (Fivet et al. 2009). More precisely, the configurations included in the configuration interaction expansions were the following: $4d^8 + 4d^75s + 4d^76s + 4d^75d + 4d^76d + 4d^65s^2 + 4d^65p^2 + 4d^65d^2 + 4d^65s6s + 4d^65s5d + 4d^65s6d$ (even parity) and $4d^75p + 4d^76p + 4d^74f + 4d^75f + 4d^65s5p + 4d^65s6p + 4d^65p5d + 4d^65p6s$ (odd parity). The ionic core considered for the core-polarization model potential and the correction to the dipole operator was a Mo-like core, i.e. a $4d^6$ Rh IV core. The dipole polarizability, α_d , for such a core is, according to Fraga et al. (1976), equal to $4.79\ a_0^3$. For the cut-off radius, r_c , we used the HFR mean value $\langle r \rangle$ of the outermost 4d core orbital, i.e. $1.52\ a_0$.

Some radial integrals, considered as free parameters, were then adjusted with a least-squares optimization program minimizing the discrepancies between the calculated Hamiltonian eigenvalues and the experimental energy levels from Sancho (1958). More precisely, for the $4d^8$, $4d^75s$ and $4d^75p$ configurations, the average energies (E_{av}), the electrostatic direct (F^k) and exchange (G^k) integrals, the spin-orbit (ζ_{nl}) and the effective interaction (α) parameters were allowed to vary during the fitting process. An additional effective operator (β) for the $4d^75s$ configuration was also included in the adjustment. All other Slater integrals were scaled down by a factor 0.85 following a well-established procedure (Cowan 1981). The designations of the even levels at 8164.4 and $11\,643.7\text{ cm}^{-1}$ in Sancho (1958) were interchanged as indicated by the calculations of Shadmi (1961). The even level at 35012.0 cm^{-1} was excluded from the fit because its designation as $4d^7(2P)5s\ b^3P_0$ by Sancho (1958) appeared questionable. In fact the predicted eigenvalue for this state was found to be more than 1000 cm^{-1} above the experimental value. Actually, the closest even eigenstate with $J = 0$ is $4d^8\ ^1S_0$. Unfortunately, a comparison between the predicted transition probabilities and the intensities observed by Sancho (1958) for the 6 classified lines (of which 2 are doubly classified) involving this level was not conclusive in asserting this alternative designation. The standard deviations of the fits were 50 cm^{-1} for the even parity (35 levels, 12 parameters) and 111 cm^{-1} for the odd parity (84 levels, 9 parameters). The adopted radial parameter values with their standard deviations are given in Table 2.

Theoretical radiative lifetimes obtained in the present study are compared with the experimental values in Table 1. As shown in this table, the agreement between theory and experiment is good. However, the HFR+CPOL lifetimes are systematically about 10% longer than the measurements. This is probably due to the fact that core-polarization effects were slightly overestimated in our physical model. It is worth mentioning that calculated lifetimes were found to decrease by up to 5% when using a dipole polarizability equal to $4.3\ a_0^3$, i.e. 10% smaller than the one published by Fraga et al. (1976) for Rh IV. It was also verified that a variation of 10% of the cut-off radius did not modify the computed lifetimes.

Considering the experimental lifetime values and the theoretical branching fractions as obtained in the present work, it is possible to derive normalized transition probabilities and oscillator strengths. In Table 3, we present the gA - and $\log gf$ -values for the strongest lines ($\log gf > -2.0$) depopulating the levels for which the experimental lifetimes are reported in Table 1.

Table 1. Experimental and calculated lifetimes obtained in the present work for selected levels within the $4d^7(^4F)5p$ configuration of Rh II.

Level	Energy (cm ⁻¹) ^a	Excitation		Detection (nm)	τ_{exp} (ns)	τ_{calc} (ns)
		Origin (cm ⁻¹) ^a	λ_{vac} (nm)			
$z^5F_4^\circ$	56547.3	18540.4	263.03	$3\omega + 2S$	252	3.9 ± 0.5
$z^5F_5^\circ$	57020.8	18540.4	259.80	$3\omega + 2S$	249	3.8 ± 0.3
$z^5F_3^\circ$	58358.5	19792.4	259.22	$3\omega + 2S$	251	3.8 ± 0.3
$z^5F_2^\circ$	59698.6	20646.9	255.99	$3\omega + 2S$	251	3.8 ± 0.3
$z^5D_4^\circ$	59161.5	16884.8	236.47	$3\omega + S$	246/304	3.3 ± 0.2
$z^5D_3^\circ$	60448.4	18540.4	238.55	$3\omega + S$	246/303	3.4 ± 0.4
$z^5D_2^\circ$	61355.9	19792.4	240.52	$3\omega + S$	246/302	3.7 ± 0.5
$z^5G_6^\circ$	59702.4	16884.8	233.48	$3\omega + S$	233	3.0 ± 0.2
$z^5G_5^\circ$	59729.4	16884.8	233.33	$3\omega + S$	243	3.5 ± 0.2
$z^5G_4^\circ$	61173.1	16884.8	225.72	$3\omega + S$	242	3.3 ± 0.2
$z^5G_3^\circ$	61939.8	18540.4	230.35	$3\omega + S$	242	3.3 ± 0.3
$z^5G_2^\circ$	62288.3	20646.9	240.07	$3\omega + S$	243/235	3.3 ± 0.3
$z^3G_5^\circ$	62194.4	16884.8	220.64	3ω	272	3.2 ± 0.2
$z^3G_4^\circ$	63959.5	18540.4	220.10	3ω	274	3.4 ± 0.2
$z^3G_3^\circ$	65321.2	18540.4	213.69	3ω	274	2.0 ± 0.2
$z^3F_4^\circ$	62326.1	16884.8	219.99	3ω	271	2.4 ± 0.2
$z^3F_3^\circ$	63454.9	18540.4	222.58	3ω	278	2.3 ± 0.3

Notes. ^(a) From Sancho (1958); ^(b) 3ω : frequency tripling, S : Stokes Raman shifting.

Table 2. Adopted radial parameters for the $4d^8$, $4d^75s$ and $4d^75p$ configurations.

Configuration	Parameter	Ab initio (cm ⁻¹)	Fitted (cm ⁻¹)	Ratio
$4d^8$	E_{av}	10 882	$10\,421 \pm 21$	
	$F^2(4d,4d)$	65 044	$51\,938 \pm 222$	0.80
	$F^4(4d,4d)$	42 149	$35\,804 \pm 554$	0.85
	α	0	21 ± 5	
	ζ_{4d}	1163	1180 ± 20	1.01
$4d^75s$	E_{av}	36 719	$37\,656 \pm 26$	
	$F^2(4d,4d)$	68 421	$54\,908 \pm 332$	0.80
	$F^4(4d,4d)$	44 587	$39\,300 \pm 466$	0.88
	α	0	32 ± 2	
	β	0	-462 ± 142	
	ζ_{4d}	1256	1260 ± 10	1.00
	$G^2(4d,5s)$	13 647	$11\,376 \pm 42$	0.83
$4d^75p$	E_{av}	74 500	$77\,980 \pm 16$	
	$F^2(4d,4d)$	69 029	$55\,106 \pm 135$	0.80
	$F^4(4d,4d)$	45 033	$38\,083 \pm 194$	0.85
	α	0	24 ± 2	
	ζ_{4d}	1269	1269 ± 15	1.00
	ζ_{5p}	1135	1406 ± 33	1.24
	$F^2(4d,5p)$	17 482	$14\,722 \pm 134$	0.84
	$G^1(4d,5p)$	7027	5339 ± 57	0.76
	$G^3(4d,5p)$	5685	3798 ± 144	0.67

4. Conclusions

A new set of transition probabilities and oscillator strengths has been obtained for transitions depopulating 17 levels of Rh II belonging to the $4d^7(^4F)5p$ configuration. These results have been obtained from a combination of experimental lifetimes measured by laser-induced fluorescence spectroscopy and HFR+CPOL branching fractions.

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Table 3. Transition probabilities and oscillator strengths for Rh II selected lines. $X(Y)$ stands for $X \times 10^Y$. Only transitions with $\log gf \geq -2.0$ are listed in the table.

λ^a (nm)	Int. ^a	Lower level ^a		Upper level ^a		HFR+CPOL ^b		Normalized ^c	
		E (cm ⁻¹)	Desig.	E (cm ⁻¹)	Desig.	gA (s ⁻¹)	$\log gf$	gA (s ⁻¹)	$\log gf$
153.091	100	0.0	a ³ F ₄	65321.2	z ³ G ₃ ^o	8.55(8)	-0.52	1.03(9)	-0.44
156.348	100	0.0	a ³ F ₄	63959.5	z ³ G ₄ ^o	1.71(8)	-1.20	1.86(8)	-1.17
157.591	100	0.0	a ³ F ₄	63454.9	z ³ F ₃ ^o	2.17(8)	-1.09	2.36(8)	-1.06
158.932	90	2401.3	a ³ F ₃	65321.2	z ³ G ₃ ^o	1.92(8)	-1.14	2.30(8)	-1.06
160.445	500	0.0	a ³ F ₄	62326.1	z ³ F ₄ ^o	1.14(9)	-0.36	1.33(9)	-0.29
160.786	100	0.0	a ³ F ₄	62194.4	z ³ G ₅ ^o	1.02(8)	-1.40	1.12(8)	-1.36
162.447	200	2401.3	a ³ F ₃	63959.5	z ³ G ₄ ^o	6.06(7)	-1.62	6.59(7)	-1.58
163.472	200	0.0	a ³ F ₄	61173.1	z ⁵ G ₄ ^o	2.76(8)	-0.96	2.93(8)	-0.93
163.788	200	2401.3	a ³ F ₃	63454.9	z ³ F ₃ ^o	6.72(8)	-0.57	7.30(8)	-0.53
166.876	100	2401.3	a ³ F ₃	62326.1	z ³ F ₄ ^o	1.66(8)	-1.16	1.94(8)	-1.09
167.019	90	3580.7	a ³ F ₂	63454.9	z ³ F ₃ ^o	1.39(8)	-1.24	1.51(8)	-1.20
167.422	100	0.0	a ³ F ₄	59729.4	z ⁵ G ₅ ^o	1.41(8)	-1.23	1.61(8)	-1.17
167.958	50	2401.3	a ³ F ₃	61939.8	z ⁵ G ₃ ^o	1.11(8)	-1.33	1.21(8)	-1.29
170.337	50	3580.7	a ³ F ₂	62288.3	z ⁵ G ₂ ^o	4.60(7)	-1.70	5.02(7)	-1.66
174.958	100	8164.4	a ¹ D ₂	65321.2	z ³ G ₃ ^o	1.74(8)	-1.10	2.09(8)	-1.02
176.842	100	0.0	a ¹ F ₄	56547.3	z ⁵ F ₄ ^o	2.47(7)	-1.93	2.79(7)	-1.88
180.864	100	8164.4	a ¹ D ₂	63454.9	z ³ F ₃ ^o	1.63(8)	-1.10	1.77(8)	-1.06
186.298*		11643.7	a ³ P ₂	65321.2	z ³ G ₃ ^o	8.76(7)	-1.34	1.05(8)	-1.26
193.008*		11643.7	a ³ P ₂	63454.9	z ³ F ₃ ^o	4.45(7)	-1.60	4.84(7)	-1.57
213.696*		18540.4	a ⁵ F ₄	65321.2	z ³ G ₃ ^o	1.33(7)	-2.04	1.60(7)	-1.96
219.996	200	16884.8	a ⁵ F ₅	62326.1	z ³ F ₄ ^o	9.18(7)	-1.17	1.07(8)	-1.11
220.102	100	18540.4	a ⁵ F ₄	63959.5	z ³ G ₄ ^o	7.78(7)	-1.25	8.47(7)	-1.21
220.635	100	16884.8	a ⁵ F ₅	62194.4	z ³ G ₅ ^o	9.13(7)	-1.18	9.99(7)	-1.14
223.771	50	20646.9	a ⁵ F ₂	65321.2	z ³ G ₃ ^o	2.85(8)	-0.67	3.42(8)	-0.59
225.724	80	16884.8	a ⁵ F ₅	61173.1	z ⁵ G ₄ ^o	3.35(7)	-1.59	3.55(7)	-1.57
226.343	50	19792.4	a ⁵ F ₃	63959.5	z ³ G ₄ ^o	7.51(8)	-0.24	8.17(8)	-0.20
228.316	20	18540.4	a ⁵ F ₄	62326.1	z ³ F ₄ ^o	1.91(7)	-1.82	2.23(7)	-1.76
228.957	20	19792.4	a ⁵ F ₃	63454.9	z ³ F ₃ ^o	3.88(7)	-1.52	4.22(7)	-1.48
229.004	300	18540.4	a ⁵ F ₄	62194.4	z ³ G ₅ ^o	1.85(9)	0.16	2.02(9)	0.20
230.347	20	18540.4	a ⁵ F ₄	61939.8	z ⁵ G ₃ ^o	2.17(7)	-1.76	2.37(7)	-1.73
233.330	300	16884.8	a ⁵ F ₅	59729.4	z ⁵ G ₅ ^o	1.79(8)	-0.83	2.05(8)	-0.78
233.477	1000	16884.8	a ⁵ F ₅	59702.4	z ⁵ G ₆ ^o	4.18(9)	0.53	4.32(9)	0.55
233.530	10	20646.9	a ⁵ F ₂	63454.9	z ³ F ₃ ^o	1.14(8)	-1.03	1.24(8)	-0.99
234.489	80	18540.4	a ⁵ F ₄	61173.1	z ⁵ G ₄ ^o	1.34(7)	-1.96	1.42(7)	-1.93
235.035	100	19792.4	a ⁵ F ₃	62326.1	z ³ F ₄ ^o	1.44(8)	-0.92	1.68(8)	-0.86
236.467	100	16884.8	a ⁵ F ₅	59161.5	z ⁵ D ₄ ^o	1.17(8)	-1.00	1.38(8)	-0.94
238.545	200	18540.4	a ⁵ F ₄	60448.4	z ⁵ D ₃ ^o	8.21(7)	-1.15	9.42(7)	-1.10
240.071	80	20646.9	a ⁵ F ₂	62288.3	z ⁵ G ₂ ^o	4.73(7)	-1.39	5.16(7)	-1.35
240.522	150	19792.4	a ⁵ F ₃	61355.9	z ⁵ D ₂ ^o	1.09(8)	-1.02	1.18(8)	-0.99
241.584	500	19792.4	a ⁵ F ₃	61173.1	z ⁵ G ₄ ^o	1.80(9)	0.20	1.91(9)	0.22
242.100	500	20646.9	a ⁵ F ₂	61939.8	z ⁵ G ₃ ^o	1.62(9)	0.15	1.77(9)	0.19
242.709	300	18540.4	a ⁵ F ₄	59729.4	z ⁵ G ₅ ^o	1.54(9)	0.14	1.76(9)	0.19
243.185	300	21180.0	a ⁵ F ₁	62288.3	z ⁵ G ₂ ^o	1.20(9)	0.02	1.31(9)	0.06
245.571	200	20646.9	a ⁵ F ₂	61355.9	z ⁵ D ₂ ^o	1.00(9)	-0.04	1.08(9)	-0.01
245.890	300	19792.4	a ⁵ F ₃	60448.4	z ⁵ D ₃ ^o	1.57(9)	0.16	1.80(9)	0.21
246.103	300	18540.4	a ⁵ F ₄	59161.5	z ⁵ D ₄ ^o	2.09(9)	0.28	2.47(9)	0.35
248.829	50	21180.0	a ⁵ F ₁	61355.9	z ⁵ D ₂ ^o	1.84(7)	-1.77	1.99(7)	-1.73
249.079	150	16884.8	a ⁵ F ₅	57020.8	z ⁵ F ₅ ^o	2.60(9)	0.39	2.67(9)	0.39
250.276	50	25376.9	b ³ F ₄	65321.2	z ³ G ₃ ^o	2.53(8)	-0.62	3.04(8)	-0.55
250.512	100	19792.4	a ⁵ F ₃	59698.6	z ⁵ F ₂ ^o	9.82(8)	-0.03	1.09(9)	0.01
251.065	100	18540.4	a ⁵ F ₄	58358.5	z ⁵ F ₃ ^o	1.43(9)	0.13	1.58(9)	0.17
252.052	100	16884.8	a ⁵ F ₅	56547.3	z ⁵ F ₄ ^o	1.79(9)	0.24	2.02(9)	0.28
255.992	100	20646.9	a ⁵ F ₂	59698.6	z ⁵ F ₂ ^o	1.44(8)	-0.85	1.59(8)	-0.81
259.216	100	19792.4	a ⁵ F ₃	58358.5	z ⁵ F ₃ ^o	1.24(8)	-0.90	1.37(8)	-0.86
259.540	60	21180.0	a ⁵ F ₁	59698.6	z ⁵ F ₂ ^o	2.33(7)	-1.63	2.58(7)	-1.58
259.795	10	18540.4	a ⁵ F ₄	57020.8	z ⁵ F ₅ ^o	1.04(7)	-1.98	1.07(7)	-1.97
262.541	150	25376.9	b ³ F ₄	63454.9	z ³ F ₃ ^o	9.81(8)	0.01	1.07(9)	0.04
263.033	100	18540.4	a ⁵ F ₄	56547.3	z ⁵ F ₄ ^o	1.38(8)	-0.84	1.56(8)	-0.79
263.900*		27439.4	b ³ F ₃	65321.2	z ³ G ₃ ^o	2.26(8)	-0.63	2.71(8)	-0.55
265.093	30	20646.9	a ⁵ F ₂	58358.5	z ⁵ F ₃ ^o	1.50(7)	-1.80	1.66(7)	-1.76
266.448	50	27801.4	a ⁵ P ₃	65321.2	z ³ G ₃ ^o	6.44(7)	-1.16	7.73(7)	-1.08
270.560	150	25376.9	b ³ F ₄	62326.1	z ³ F ₄ ^o	1.53(9)	0.23	1.79(9)	0.29

Table 3. continued.

λ^a (nm)	Int. ^a	Lower level ^a		Upper level ^a		HFR+CPOL ^b		Normalized ^c	
		E (cm ⁻¹)	Desig.	E (cm ⁻¹)	Desig.	gA (s ⁻¹)	log gf	gA (s ⁻¹)	log gf
271.527	150	25376.9	b ³ F ₄	62194.4	z ³ G ₅ ^o	1.11(9)	0.09	1.21(9)	0.13
273.420	10	25376.9	b ³ F ₄	61939.8	z ⁵ G ₃ ^o	1.41(7)	-1.80	1.54(7)	-1.76
273.740	150	27439.4	b ³ F ₃	63959.5	z ³ G ₄ ^o	1.11(9)	0.10	1.21(9)	0.13
273.992	150	28834.6	b ³ F ₂	65321.2	z ³ G ₃ ^o	6.61(8)	-0.13	7.93(8)	-0.05
276.483	100	27801.4	a ⁵ P ₃	63959.5	z ³ G ₄ ^o	2.09(8)	-0.62	2.27(8)	-0.58
277.577	100	27439.4	b ³ F ₃	63454.9	z ³ F ₃ ^o	2.67(8)	-0.51	2.90(8)	-0.47
279.278	100	25376.9	b ³ F ₄	61173.1	z ⁵ G ₄ ^o	9.25(7)	-0.97	9.81(7)	-0.94
280.395	80	27801.4	a ⁵ P ₃	63454.9	z ³ F ₃ ^o	5.93(7)	-1.16	6.45(7)	-1.12
285.049	50	25376.9	b ³ F ₄	60448.4	z ⁵ D ₃ ^o	2.00(7)	-1.61	2.29(7)	-1.55
286.560	30	27439.4	b ³ F ₃	62326.1	z ³ F ₄ ^o	2.45(7)	-1.52	2.86(7)	-1.45
289.560	2	27801.4	a ⁵ P ₃	62326.1	z ³ F ₄ ^o	1.38(7)	-1.76	1.61(7)	-1.69
289.763	100	27439.4	b ³ F ₃	61939.8	z ⁵ G ₃ ^o	3.61(7)	-1.34	3.94(7)	-1.30
291.015	200	25376.9	b ³ F ₄	59729.4	z ⁵ G ₅ ^o	8.48(8)	0.03	9.69(8)	0.09
292.680	100	28131.4	a ⁵ P ₂	62288.3	z ⁵ G ₂ ^o	1.10(7)	-1.85	1.20(7)	-1.81
292.838	40	27801.4	a ⁵ P ₃	61939.8	z ⁵ G ₃ ^o	2.67(7)	-1.47	2.91(7)	-1.43
294.756	30	27439.4	b ³ F ₃	61355.9	z ⁵ D ₂ ^o	2.04(7)	-1.57	2.21(7)	-1.54
296.354	200	27439.4	b ³ F ₃	61173.1	z ⁵ G ₄ ^o	2.92(8)	-0.41	3.10(8)	-0.39
298.830	40	28834.6	b ³ F ₂	62288.3	z ⁵ G ₂ ^o	6.77(7)	-1.05	7.39(7)	-1.00
299.563	15	27801.4	a ⁵ P ₃	61173.1	z ⁵ G ₄ ^o	1.90(7)	-1.59	2.02(7)	-1.57
300.898	80	28131.4	a ⁵ P ₂	61355.9	z ⁵ D ₂ ^o	6.09(7)	-1.08	6.58(7)	-1.05
301.978	100	28834.6	b ³ F ₂	61939.8	z ⁵ G ₃ ^o	1.10(8)	-0.82	1.20(8)	-0.79
302.857	80	27439.4	b ³ F ₃	60448.4	z ⁵ D ₃ ^o	1.16(7)	-1.79	1.33(7)	-1.74
305.565	80	32604.7	a ³ G ₄	65321.2	z ³ G ₃ ^o	4.56(7)	-1.20	5.47(7)	-1.12
306.223	60	27801.4	a ⁵ P ₃	60448.4	z ⁵ D ₃ ^o	1.99(7)	-1.55	2.28(7)	-1.49
309.344	100	28131.4	a ⁵ P ₂	60448.4	z ⁵ D ₃ ^o	4.96(7)	-1.15	5.69(7)	-1.09
309.675	80	29073.0	a ⁵ P ₁	61355.9	z ⁵ D ₂ ^o	2.64(7)	-1.42	2.85(7)	-1.39
310.191	15	31730.5	a ³ G ₅	63959.5	z ³ G ₄ ^o	1.73(7)	-1.60	1.88(7)	-1.57
313.417	10	27801.4	a ⁵ P ₃	59698.6	z ⁵ F ₂ ^o	6.43(6)	-2.02	7.11(6)	-1.98
315.144	40	27439.4	b ³ F ₃	59161.5	z ⁵ D ₄ ^o	9.82(6)	-1.83	1.16(7)	-1.76
315.926	200	25376.9	b ³ F ₄	57020.8	z ⁵ F ₅ ^o	1.06(8)	-0.80	1.09(8)	-0.79
316.230	20	28834.6	b ³ F ₂	60448.4	z ⁵ D ₃ ^o	8.83(6)	-1.88	1.01(7)	-1.82
316.691	100	28131.4	a ⁵ P ₂	59698.6	z ⁵ F ₂ ^o	1.89(7)	-1.55	2.09(7)	-1.50
318.783	150	27801.4	a ⁵ P ₃	59161.5	z ⁵ D ₄ ^o	7.48(7)	-0.94	8.84(7)	-0.87
320.725	100	25376.9	b ³ F ₄	56547.3	z ⁵ F ₄ ^o	4.56(7)	-1.15	5.14(7)	-1.10
323.332	100	27439.4	b ³ F ₃	58358.5	z ⁵ F ₃ ^o	3.24(7)	-1.29	3.58(7)	-1.25
323.895	20	28834.6	b ³ F ₂	59698.6	z ⁵ F ₂ ^o	8.25(6)	-1.89	9.12(6)	-1.84
324.049	5	32604.7	a ³ G ₄	63454.9	z ³ F ₃ ^o	2.19(7)	-1.47	2.38(7)	-1.43
326.427	20	29073.0	a ⁵ P ₁	59698.6	z ⁵ F ₂ ^o	7.02(6)	-1.95	7.76(6)	-1.91
326.756	150	31730.5	a ³ G ₅	62326.1	z ³ F ₄ ^o	7.07(7)	-0.94	8.25(7)	-0.88
330.734*		28131.4	a ⁵ P ₂	58358.5	z ⁵ F ₃ ^o	2.74(7)	-1.35	3.03(7)	-1.30
336.361*		32604.7	a ³ G ₄	62326.1	z ³ F ₄ ^o	5.34(6)	-2.04	6.23(6)	-1.98
339.547*		31730.5	a ³ G ₅	61173.1	z ⁵ G ₄ ^o	1.46(7)	-1.60	1.55(7)	-1.57
340.791*		32604.7	a ³ G ₄	61939.8	z ⁵ G ₃ ^o	7.00(6)	-1.92	7.64(6)	-1.88
343.451*		27439.4	b ³ F ₃	56547.3	z ⁵ F ₄ ^o	1.09(7)	-1.71	1.23(7)	-1.66
345.266*		36366.3	c ³ P ₂	65321.2	z ³ G ₃ ^o	1.19(7)	-1.67	1.43(7)	-1.59
347.776*		27801.4	a ⁵ P ₃	56547.3	z ⁵ F ₄ ^o	3.86(7)	-1.15	4.35(7)	-1.10
352.232*		36938.9	a ³ D ₃	65321.2	z ³ G ₃ ^o	1.01(7)	-1.73	1.21(7)	-1.65
369.054*		36366.3	c ³ P ₂	63454.9	z ³ F ₃ ^o	5.34(6)	-1.96	5.80(6)	-1.93
377.024*		36938.9	a ³ D ₃	63454.9	z ³ G ₃ ^o	9.37(6)	-1.70	1.02(7)	-1.66
391.561*		36794.5	a ³ H ₅	62326.1	z ³ F ₄ ^o	5.05(6)	-1.93	5.89(6)	-1.87
417.555*		35787.2	a ³ H ₆	59729.4	z ⁵ G ₅ ^o	3.49(6)	-2.04	3.99(6)	-1.98

Notes. ^(a) From Sancho (1958). Wavelengths are given in vacuum and in air below and above 200 nm, respectively. Starred values are deduced from experimental levels. ^(b) This work : HFR+CPOL calculations (see the text). ^(c) This work : HFR+CPOL values normalized by the laser measurements of the present work (see the text).