Radiative lifetimes in La III and oscillator strengths in La III and Lu III

Biemont, E; Li, Z. S; Palmeri, P; Quinet, P

Published in:
Journal of Physics B: Atomic, Molecular and Optical Physics

DOI:
10.1088/0953-4075/32/14/311

1999

Radiative lifetimes in La III and oscillator strengths in La III and Lu III

1999 J. Phys. B: At. Mol. Opt. Phys. 32 3409

(http://iopscience.iop.org/0953-4075/32/14/311)

J. Phys. B: At. Mol. Opt. Phys. **32** (1999) 3409–3419. Printed in the UK PII: S0953-4075(99)03406-9

Radiative lifetimes in La III and oscillator strengths in La III and Lu III

E Biémont†‡, Z S Li§, P Palmeri† and P Quinet†

† Astrophysique et Spectroscopie, Université de Mons-Hainaut, B-7000 Mons, Belgium
‡ Institut d'Astrophysique, Université de Liège, B-4000 Liège, Belgium
§ Department of Physics, Lund Institute of Technology, PO Box 118, S-22100 Lund, Sweden

Received 9 April 1999, in final form 4 June 1999

Abstract. New radiative lifetime measurements performed with time-resolved laser spectroscopy for the $6p_{1/2}$ and $6p_{3/2}$ levels of La III provide a unique opportunity for testing the adequacy of the relativistic Hartree–Fock approach for atomic structure calculations in this ion. As a consequence of the comparison, an extensive set of accurate f-values is provided for many La III and Lu III UV and visible transitions of astrophysical interest.

1. Introduction

Rare-earth elements are important in astrophysics in relation to nucleosynthesis and star formation. They are observed in A stars, particularly in the Cr–Eu–Sr subgroup of the Ap stars, and also in Am stars. However, their detection in the stellar spectra is frequently hindered by the fact that they appear under the form of many medium or weak intensity lines which are blended with contributions originating from the most abundant elements, particularly those of the iron group. In view of the frequent lack of atomic data for accurately predicting the intensity of the lines, the lanthanides are usually identified in Bp or Ap stars using statistical methods (see e.g. Cowley 1976, Cowley *et al* 1977, Cowley and Henry 1979). Accurate atomic data, and particularly oscillator strengths, are thus welcome to refine the line identifications in many stars. According to the well known odd–even pattern, La ($Z = 57$) and Lu ($Z = 71$) are expected to be less abundant than those lanthanides that are characterized by even atomic numbers although they have been observed in many stellar objects (see e.g. Jaschek and Jaschek 1995).

The doubly ionized rare-earth elements have been considered comparatively less in the literature than the neutral or singly ionized species. A summary of the present state of the art regarding the energy level values has been presented recently by Wyart (1995). In stars with strong rare-earth lines, they are, however, generally expected to also be observed, as pointed out by e.g. Ryabchikova *et al* (1990). As an example, some of these ions have been identified recently in the red spectrum of the Przybylski star (Cowley and Mathys 1998).

La III and Lu III are characterized by a simple atomic structure with only one outer electron (without or with a full $4f^{14}$ subshell appearing in the core). The calculations of transition probabilities are thus expected to be accurate, provided relativistic effects and core-polarization effects are properly taken into account. Up to now the transition probabilities available for La III were only obtained by semi-empirical or purely theoretical approaches (Glushkov 1992, Sen and Puri 1989, Migdalek and Wyrozumska 1987, Migdalek and Baylis 1979, Lindgard and Nielsen 1977). However, the results of measurements of ratios of line intensities in doublets of the principal series of La III were reported by Kunisz *et al* (1968). In Lu III, only two theoretical works have been published so far (Migdalek 1980, 1982). The feasability of accurate lifetime measurements of doubly ionized rare earths at the Lund Laser Centre (LLC) using time-resolved laser spectroscopy provides a unique opportunity for testing the adequacy and the accuracy of the physical models retained for the calculations. The purpose of this work is to present a new set of theoretical oscillator strengths for the La III and Lu III transitions of astrophysical interest. The core-polarization effects (which are expected to be important) and configuration-interaction effects (which play a more marginal role) have been introduced in the calculations. This work is part of a general programme of investigation of the transition probabilities of the first ionization degrees of the rare-earth elements for their incorporation in DREAM (database on rare-earths at Mons University) which is being created for the benefit of the astrophysicists. The detailed results will be accessible on the site `http://www.umh.ac.be/~astro/dream.shtml`.

2. Lifetime measurements

During the past few years, time-resolved laser spectroscopy has been used extensively at the LLC and has been able to provide the astrophysicists with many new and accurate radiative lifetimes and transition probabilities (Berzinsh *et al* 1997a,b, Biémont *et al* 1998a, 1999, Li *et al* 1998a,b, 1999). The radiative lifetime measurements in La III have been performed using that technique. Free La^{2+} ions were produced in a laser-induced plasma and selective excitation was obtained with narrow bandwith (1 ns) pulses produced by a tunable laser. Lifetime values were evaluated from the time-resolved signals collected by a fast detection system. The system incorporates a Brillouin-scattering cell where light pulses of 10 ns duration emitted from a conventional Nd:Yag laser are shortened to 1 ns before pumping the dye laser that provides the wavelength-tunable radiation used for excitation. Laser-photon energies sufficient to study energy levels up to around 70 000 cm^{-1} can be conveniently produced using frequency-mixing crystals. The full details of the experiment will be provided in a forthcoming publication (Li and Jiang Zhankui 1999).

3. Calculations

The theoretical approach considered in this paper is the well established relativistic Hartree–Fock (HFR) technique described by Cowan (1981) in which we have incorporated core-polarization effects. This method has been shown adequate for accurately predicting radiative lifetimes in complex configurations like those met in Yb II (Biémont and Quinet 1998, Biémont *et al* 1998b) or Lu II (Quinet *et al* 1999). The core-polarization effects were considered using the expression of the core-polarization potential, V_P, deduced from the work of Migdalek and Baylis (1978). In the case of the one-valence-electron systems investigated in our work, this potential can be written as follows:

$$V_P = -\frac{\alpha_d r^2}{2\,(r^2 + r_c^2)^3}. \tag{1}$$

There is a corresponding change to the radial matrix element of the length form of the line strength: the integral

$$\langle P_{nl}|r|P_{n'l'}\rangle \tag{2}$$

has to be replaced by

$$\langle P_{nl}|r\left(1-\frac{\alpha_d}{(r^2+r_c^2)^{3/2}}\right)|P_{n'l'}\rangle. \quad (3)$$

A further correction, introduced by Hameed and co-workers (Hameed *et al* 1968, Hameed 1972) to allow for a more accurate treatment of the penetration of the core by the valence electron, corresponds to adding to the integral

$$\langle P_{nl}|\frac{r}{(r^2+r_c^2)^{3/2}}|P_{n'l'}\rangle \quad (4)$$

in (3) the core-penetration term

$$\frac{1}{r_c^3}\int_0^{r_c} P_{nl}(r)r\,P_{n'l'}(r)\,\mathrm{d}r. \quad (5)$$

The estimate of the core-polarization contributions requires knowledge of the dipole polarizability of the ionic core, α_d, and the cut-off radius, r_c. For the first parameter, we have used the values of the static dipole polarizabilities computed by Johnson *et al* (1983) for La IV and by Fraga *et al* (1976) for Lu IV, i.e. α_d = 7.67 and 5.20 a_0^3, respectively. The cut-off radii, r_c, have been chosen to be equal to 1.79 a_0 (La III) and 1.39 a_0 (Lu III) which correspond to the HFR average values $\langle r\rangle$ for the outermost core orbitals ($5p^6$).

The configuration sets retained for the calculations were ns (n = 6–10), nd (n = 5–10), ng (n = 5–10) (even parity) and np (n = 6–10), nf (n = 4–10) (odd parity) for La III and $4f^{14}n$s (n = 6–10), $4f^{14}n$d (n = 5–10), $4f^{14}n$g (n = 5–10) (even parity) and $4f^{14}n$p (n = 6–10), $4f^{14}n$f (n = 5–10) (odd parity) for Lu III. Although introduced in the calculations, configuration interaction is expected to play a minor role here. In addition, the average energies, E_{av}, and the spin–orbit parameters, ζ_{nl}, were adjusted with a least-square optimization procedure minimizing the discrepancies between the calculated and the experimental energy levels compiled by Martin *et al* (1978).

4. Results and discussion

Tables 1 and 2 show the weighted oscillator strengths, gf (g being the statistical weight of the lower level of the transition), and radiative transition probabilities, gA (g being the statistical weight of the upper level of the transition), as calculated in this work for UV and visible transitions in La III and Lu III, respectively. Only transitions characterized by a wavelength shorter than 1 μm and a gf-value larger or equal to 0.001 are reported in the tables. Our results are also compared with the gA-values previously published.

For La III, Migdalek and Wyrozumska (1987) have reported oscillator strengths obtained using the relativistic model-potential approach in three different versions: a model-potential without valence–core electron exchange but with core-polarization included (RMP + CP), with semiclassical exchange and core-polarization (RMP + SCE + CP) and with empirically adjusted exchange and core-polarization (RMP + EX + CP). The results obtained in the latter approach are compared in table 1 with our calculated gA-values for the 17 lines common to both works and belonging to the 6s–6p, 5d–6p, 5d–5f, 5d–6f, 6p–6d and 6p–7d transition arrays. An excellent agreement (within 10%) is observed between both sets of results if we except the 5d–5f and 6p–7d transitions for which the discrepancies appear somewhat larger (∼20%). We also notice that our results are systematically larger than the Migdalek and Wyrozumska data for the nd–n'f arrays while they are smaller for the ns–n'p and np–n'd arrays. Our new results considerably extend the set of transitions for which f-values are now available.

Table 1. Oscillator strengths (gf) and transition probabilities (gA in s^{-1}) in La III ($\lambda < 10\,000$ Å and $gf \geqslant 0.001$). $A(+B)$ stands for $A \times 10^B$.

		This work		Previous
λ[a] (Å)	Transition	gf	gA	gA[b]
744.19	$5d_{3/2}$–$8f_{5/2}$	0.110	1.33(+9)	
753.03	$5d_{5/2}$–$8f_{7/2}$	0.155	1.83(+9)	
753.18	$5d_{5/2}$–$8f_{5/2}$	0.008	9.14(+7)	
758.12	$4f_{5/2}$–$8g_{7/2}$	0.014	1.67(+8)	
766.83	$4f_{7/2}$–$8g_{9/2}$	0.018	2.09(+8)	
781.65	$5d_{3/2}$–$9p_{3/2}$	0.001	1.54(+7)	
784.01	$5d_{3/2}$–$9p_{1/2}$	0.007	7.61(+7)	
786.64	$4f_{5/2}$–$7g_{7/2}$	0.021	2.23(+8)	
787.14	$5d_{3/2}$–$7f_{5/2}$	0.203	2.18(+9)	
791.57	$5d_{5/2}$–$9p_{3/2}$	0.013	1.33(+8)	
794.84	$4f_{5/2}$–$9d_{3/2}$	0.004	4.35(+7)	
796.03	$4f_{7/2}$–$7g_{9/2}$	0.026	2.78(+8)	
796.99	$5d_{5/2}$–$7f_{7/2}$	0.286	3.00(+9)	
797.20	$5d_{5/2}$–$7f_{5/2}$	0.014	1.50(+8)	
803.98	$4f_{7/2}$–$9d_{5/2}$	0.006	6.00(+7)	
835.02	$4f_{5/2}$–$6g_{7/2}$	0.030	2.87(+8)	
845.61	$4f_{7/2}$–$6g_{9/2}$	0.038	3.58(+8)	
845.62	$4f_{7/2}$–$6g_{7/2}$	0.001	1.02(+7)	
850.72	$4f_{5/2}$–$8d_{3/2}$	0.007	6.16(+7)	
860.39	$5d_{3/2}$–$8p_{3/2}$	0.003	2.76(+7)	
860.88	$4f_{7/2}$–$8d_{5/2}$	0.009	8.49(+7)	
865.04	$5d_{3/2}$–$8p_{1/2}$	0.015	1.36(+8)	
870.40	$5d_{3/2}$–$6f_{5/2}$	0.446	3.93(+9)	4.21(+9)
872.43	$5d_{5/2}$–$8p_{3/2}$	0.027	2.38(+8)	
874.56	$6s_{1/2}$–$9p_{3/2}$	0.005	3.89(+7)	
877.52	$6s_{1/2}$–$9p_{1/2}$	0.002	1.93(+7)	
882.34	$5d_{5/2}$–$6f_{7/2}$	0.629	5.39(+9)	5.95(+9)
882.72	$5d_{5/2}$–$6f_{5/2}$	0.031	2.69(+8)	2.99(+8)
929.72	$4f_{5/2}$–$5g_{7/2}$	0.040	3.06(+8)	
942.86	$4f_{7/2}$–$5g_{9/2}$	0.051	3.81(+8)	
942.87	$4f_{7/2}$–$5g_{7/2}$	0.001	1.09(+7)	
967.69	$4f_{5/2}$–$7d_{3/2}$	0.012	8.53(+7)	
974.33	$6s_{1/2}$–$8p_{3/2}$	0.007	4.55(+7)	
979.98	$4f_{7/2}$–$7d_{5/2}$	0.017	1.17(+8)	
980.29	$6s_{1/2}$–$8p_{1/2}$	0.003	2.24(+7)	
1058.63	$5d_{3/2}$–$7p_{3/2}$	0.010	5.72(+7)	
1072.59	$5d_{3/2}$–$7p_{1/2}$	0.048	2.75(+8)	
1076.91	$5d_{5/2}$–$7p_{3/2}$	0.085	4.89(+8)	
1081.61	$5d_{3/2}$–$5f_{5/2}$	1.377	7.85(+9)	9.06(+9)
1099.00	$6p_{1/2}$–$9d_{3/2}$	0.017	9.21(+7)	
1099.73	$5d_{5/2}$–$5f_{7/2}$	1.935	1.07(+10)	1.28(+10)
1100.70	$5d_{5/2}$–$5f_{5/2}$	0.097	5.32(+8)	6.49(+8)
1101.01	$6p_{1/2}$–$10s_{1/2}$	0.013	7.07(+7)	
1136.80	$6p_{3/2}$–$9d_{5/2}$	0.029	1.50(+8)	
1137.71	$6p_{3/2}$–$9d_{3/2}$	0.003	1.66(+7)	
1139.87	$6p_{3/2}$–$10s_{1/2}$	0.025	1.27(+8)	
1208.79	$6p_{1/2}$–$8d_{3/2}$	0.041	1.86(+8)	
1212.28	$6p_{1/2}$–$9s_{1/2}$	0.026	1.16(+8)	
1236.55	$6s_{1/2}$–$7p_{3/2}$	0.006	2.39(+7)	

Table 1. (Continued)

		This work		Previous
λ^a (Å)	Transition	gf	gA	gA^b
1254.00	$6p_{3/2}$–$8d_{5/2}$	0.071	3.00(+8)	
1255.63	$6s_{1/2}$–$7p_{1/2}$	0.003	1.14(+7)	
1255.79	$6p_{3/2}$–$8d_{3/2}$	0.008	3.32(+7)	
1259.55	$6p_{3/2}$–$9s_{1/2}$	0.049	2.07(+8)	
1322.42	$4f_{5/2}$–$6d_{5/2}$	0.002	7.00(+6)	
1330.04	$4f_{5/2}$–$6d_{3/2}$	0.026	9.64(+7)	
1349.18	$4f_{7/2}$–$6d_{5/2}$	0.036	1.32(+8)	
1459.45	$6p_{1/2}$–$7d_{3/2}$	0.156	4.88(+8)	4.26(+8)
1466.39	$6p_{1/2}$–$8s_{1/2}$	0.069	2.15(+8)	
1523.75	$6p_{3/2}$–$7d_{5/2}$	0.269	7.71(+8)	6.02(+8)
1528.51	$6p_{3/2}$–$7d_{3/2}$	0.030	8.49(+7)	6.23(+7)
1536.13	$6p_{3/2}$–$8s_{1/2}$	0.132	3.73(+8)	
1923.33	$6d_{3/2}$–$8f_{5/2}$	0.185	3.33(+8)	
1938.53	$6d_{5/2}$–$8f_{7/2}$	0.262	4.65(+8)	
1939.51	$6d_{5/2}$–$8f_{5/2}$	0.013	2.32(+7)	
2143.13	$5f_{5/2}$–$8g_{7/2}$	0.074	1.08(+8)	
2146.77	$5f_{7/2}$–$8g_{9/2}$	0.096	1.39(+8)	
2146.83	$5f_{7/2}$–$8g_{7/2}$	0.003	3.98(+6)	
2192.89	$7s_{1/2}$–$9p_{3/2}$	0.001	1.61(+6)	
2194.50	$6d_{3/2}$–$9p_{3/2}$	0.002	3.28(+6)	
2213.26	$6d_{3/2}$–$9p_{1/2}$	0.012	1.60(+7)	
2215.58	$6d_{5/2}$–$9p_{3/2}$	0.021	2.87(+7)	
2216.07	$5d_{3/2}$–$6p_{3/2}$	0.129	1.75(+8)	1.56(+8)
2238.35	$6d_{3/2}$–$7f_{5/2}$	0.358	4.76(+8)	
2258.61	$6d_{5/2}$–$7f_{7/2}$	0.507	6.62(+8)	
2260.30	$6d_{5/2}$–$7f_{5/2}$	0.025	3.30(+7)	
2297.74	$5d_{5/2}$–$6p_{3/2}$	1.120	1.41(+9)	1.33(+9)
2379.37	$5d_{3/2}$–$6p_{1/2}$	0.601	7.07(+8)	6.78(+8)
2387.99	$5f_{5/2}$–$7g_{7/2}$	0.196	2.29(+8)	
2392.49	$5f_{7/2}$–$7g_{9/2}$	0.254	2.96(+8)	
2392.57	$5f_{7/2}$–$7g_{7/2}$	0.007	8.45(+6)	
2460.95	$5f_{5/2}$–$9d_{5/2}$	0.002	1.67(+6)	
2465.22	$5f_{5/2}$–$9d_{3/2}$	0.021	2.33(+7)	
2465.82	$5f_{7/2}$–$9d_{5/2}$	0.030	3.33(+7)	
2476.60	$6p_{1/2}$–$6d_{3/2}$	2.365	2.57(+9)	2.27(+9)
2478.66	$6p_{1/2}$–$7s_{1/2}$	0.475	5.16(+8)	
2513.43	$7p_{1/2}$–$9d_{3/2}$	0.077	8.10(+7)	
2523.98	$7p_{1/2}$–$10s_{1/2}$	0.033	3.44(+7)	
2588.86	$7p_{3/2}$–$9d_{5/2}$	0.134	1.33(+8)	
2593.58	$7p_{3/2}$–$9d_{3/2}$	0.015	1.47(+7)	
2604.82	$7p_{3/2}$–$10s_{1/2}$	0.064	6.25(+7)	
2651.50	$6p_{3/2}$–$6d_{5/2}$	3.976	3.77(+9)	3.66(+9)
2682.34	$6p_{3/2}$–$6d_{3/2}$	0.437	4.05(+8)	4.01(+8)
2684.75	$6p_{3/2}$–$7s_{1/2}$	0.878	8.12(+8)	
2897.88	$5f_{5/2}$–$6g_{7/2}$	0.786	6.24(+8)	
2904.57	$5f_{7/2}$–$6g_{9/2}$	1.016	8.03(+8)	
2904.63	$5f_{7/2}$–$6g_{7/2}$	0.029	2.29(+7)	
2953.77	$6d_{3/2}$–$8p_{3/2}$	0.008	5.87(+6)	
2992.10	$6d_{5/2}$–$8p_{3/2}$	0.068	5.08(+7)	
3009.22	$6d_{3/2}$–$8p_{1/2}$	0.038	2.77(+7)	

Table 1. (Continued)

		This work		Previous
λ[a] (Å)	Transition	gf	gA	gA[b]
3075.17	$6d_{3/2}$–$6f_{5/2}$	0.822	5.80(+8)	
3085.38	$5f_{5/2}$–$8d_{5/2}$	0.005	3.13(+6)	
3093.03	$5f_{7/2}$–$8d_{5/2}$	0.089	6.21(+7)	
3096.26	$5f_{5/2}$–$8d_{3/2}$	0.062	4.33(+7)	
3111.97	$6d_{5/2}$–$6f_{7/2}$	1.161	7.99(+8)	
3116.74	$6d_{5/2}$–$6f_{5/2}$	0.058	3.98(+7)	
3171.69	$6s_{1/2}$–$6p_{3/2}$	1.527	1.01(+9)	9.40(+8)
3172.69	$7p_{1/2}$–$8d_{3/2}$	0.260	1.72(+8)	
3196.85	$7p_{1/2}$–$9s_{1/2}$	0.092	5.98(+7)	
3289.11	$7p_{3/2}$–$8d_{5/2}$	0.452	2.79(+8)	
3301.47	$7p_{3/2}$–$8d_{3/2}$	0.050	3.06(+7)	
3327.64	$7p_{3/2}$–$9s_{1/2}$	0.176	1.06(+8)	
3517.16	$6s_{1/2}$–$6p_{1/2}$	0.689	3.71(+8)	3.45(+8)
4129.24	$6f_{5/2}$–$8g_{7/2}$	0.394	1.54(+8)	
4137.43	$6f_{7/2}$–$8g_{9/2}$	0.509	1.98(+8)	
4137.64	$6f_{7/2}$–$8g_{7/2}$	0.015	5.67(+6)	
4193.51	$7d_{3/2}$–$8f_{5/2}$	0.292	1.11(+8)	
4225.12	$7d_{5/2}$–$8f_{7/2}$	0.414	1.54(+8)	
4229.73	$7d_{5/2}$–$8f_{5/2}$	0.021	7.70(+6)	
4482.98	$5f_{5/2}$–$5g_{7/2}$	8.277	2.75(+9)	
4499.06	$5f_{7/2}$–$5g_{9/2}$	10.692	3.52(+9)	
4499.15	$5f_{7/2}$–$5g_{7/2}$	0.306	1.01(+8)	
5089.12	$5g_{9/2}$–$8f_{7/2}$	0.003	7.82(+5)	
5095.70	$5g_{7/2}$–$8f_{5/2}$	0.002	6.01(+5)	
5145.72	$6f_{5/2}$–$7g_{7/2}$	1.239	3.12(+8)	
5158.39	$6f_{7/2}$–$7g_{9/2}$	1.602	4.01(+8)	
5158.76	$6f_{7/2}$–$7g_{7/2}$	0.046	1.15(+7)	
5467.81	$5f_{5/2}$–$7d_{5/2}$	0.035	7.89(+6)	
5491.90	$5f_{7/2}$–$7d_{5/2}$	0.704	1.56(+8)	
5496.88	$6f_{5/2}$–$9d_{5/2}$	0.009	2.06(+6)	
5511.76	$6f_{7/2}$–$9d_{5/2}$	0.186	4.09(+7)	
5518.19	$6f_{5/2}$–$9d_{3/2}$	0.130	2.85(+7)	
5529.54	$5f_{5/2}$–$7d_{3/2}$	0.490	1.07(+8)	
5640.03	$8s_{1/2}$–$9p_{3/2}$	0.003	5.58(+5)	
5744.08	$8p_{1/2}$–$9d_{3/2}$	0.334	6.75(+7)	
5745.26	$7d_{3/2}$–$9p_{3/2}$	0.007	1.49(+6)	
5765.63	$8s_{1/2}$–$9p_{1/2}$	0.001	2.61(+5)	
5778.14	$7p_{1/2}$–$7d_{3/2}$	2.967	5.92(+8)	
5799.48	$8p_{1/2}$–$10s_{1/2}$	0.115	2.27(+7)	
5813.45	$7d_{5/2}$–$9p_{3/2}$	0.066	1.30(+7)	
5875.63	$7d_{3/2}$–$9p_{1/2}$	0.036	6.98(+6)	
5888.63	$7p_{1/2}$–$8s_{1/2}$	0.718	1.38(+8)	
5932.73	$8p_{3/2}$–$9d_{5/2}$	0.582	1.10(+8)	
5957.57	$8p_{3/2}$–$9d_{3/2}$	0.064	1.21(+7)	
6017.18	$8p_{3/2}$–$10s_{1/2}$	0.221	4.06(+7)	
6055.85	$7d_{3/2}$–$7f_{5/2}$	0.604	1.10(+8)	
6119.27	$7d_{5/2}$–$7f_{7/2}$	0.854	1.52(+8)	
6131.67	$7d_{5/2}$–$7f_{5/2}$	0.043	7.55(+6)	
6141.99	$7p_{3/2}$–$7d_{5/2}$	5.024	8.88(+8)	
6219.99	$7p_{3/2}$–$7d_{3/2}$	0.551	9.50(+7)	

Table 1. (Continued)

		This work		Previous
λ[a] (Å)	Transition	gf	gA	gA[b]
6348.21	$7p_{3/2}$–$8s_{1/2}$	1.331	2.20(+8)	
8114.48	$5g_{9/2}$–$7f_{7/2}$	0.021	2.11(+6)	
8136.00	$5g_{7/2}$–$7f_{5/2}$	0.016	1.62(+6)	
8252.53	$7s_{1/2}$–$7p_{3/2}$	2.279	2.23(+8)	
8275.41	$6d_{3/2}$–$7p_{3/2}$	0.240	2.34(+7)	
8287.76	$6f_{5/2}$–$6g_{7/2}$	8.527	8.28(+8)	
8291.04	$7f_{5/2}$–$8g_{7/2}$	1.485	1.44(+8)	
8312.96	$7f_{7/2}$–$8g_{9/2}$	1.919	1.85(+8)	
8313.81	$7f_{7/2}$–$8g_{7/2}$	0.055	5.29(+6)	
8321.16	$6f_{7/2}$–$6g_{9/2}$	11.009	1.06(+9)	
8321.63	$6f_{7/2}$–$6g_{7/2}$	0.315	3.03(+7)	
8583.42	$6d_{5/2}$–$7p_{3/2}$	2.081	1.88(+8)	
9184.34	$7s_{1/2}$–$7p_{1/2}$	1.024	8.09(+7)	
9212.68	$6d_{3/2}$–$7p_{1/2}$	1.077	8.46(+7)	
9924.04	$6d_{3/2}$–$5f_{5/2}$	2.370	1.60(+8)	

[a] Deduced from the experimental energy levels compiled by Martin *et al* (1978). Wavelengths are given in air above 2000 Å and in vacuum below that limit.
[b] From Migdalek and Wyrozumska (1987): model potential approach with empirically adjusted exchange and core-polarization included (RMP + EX + CP).

In the case of Lu III, our results are compared in table 2 with the transition probabilities computed by Migdalek (1982) using the relativistic model-potential including the core-polarization effects in two different approaches. In the first one (RMP-CP Ia), the core-polarization potential and the corrected dipole radial integral, expressed by equations (1) and (3) of this work, were used with the value of the core polarizability computed by Fraga *et al* (1976), i.e. $\alpha_d = 5.20\ a_0^3$, while, in the second approach (RMP-CP Ib), the value of $\alpha_d = 8.20\ a_0^3$ was used as determined by Migdalek (1980) by matching core-polarization-corrected valence electron energies to experimental ionization energies. The agreement between our results and those obtained by Migdalek (1982) is rather good (within 20%), our gA-values being generally between the RMP-CP Ia and the RMP-CP Ib results published by this author. In fact, if we except the two transitions at 972.66 Å ($6s_{1/2}$–$7p_{3/2}$) and 1056.53 Å ($5d_{3/2}$–$7p_{1/2}$) for which large discrepancies are observed, we found, for the mean ratio gA (this work)/gA (Migdalek), the values 0.978 ± 0.088 (RMP-CP Ia) and 1.064 ± 0.080 (RMP-CP Ib), the uncertainties corresponding to one standard deviation from the mean.

Experimental and calculated radiative lifetimes obtained in this work for the $6p_{1/2,3/2}$ levels of La III are reported in table 3 where they are compared with previous theoretical results. It is worth mentioning that our HFR + CP lifetimes are in excellent agreement (1–5%) with the measurements (accurate at about 10%). This theoretical–experimental agreement, on the one hand, and the fact that, on a theoretical basis, the model adopted is expected to accurately describe the 'simple' configurations considered in this work, on the other hand, imply that our new sets of transition probabilities for La III and Lu III are probably accurate to between 5–10%. The experimental results reported in this work are also in favour of the RMP+EX+CP approach of Migdalek and Wyrozumska (1987) for La III. Concerning Lu III, the comparison of the different sets of theoretical values in table 3 shows that the agreement with our results is better when adopting the RMP-CP Ia approach of Migdalek (1982). The transition

Table 2. Oscillator strengths (gf) and transition probabilities (gA in s^{-1}) in Lu III ($\lambda < 10\,000$ Å and $gf \geqslant 0.001$). $A(+B)$ stands for $A \times 10^B$.

		This work		Previous	
λ^a (Å)	Transition	gf	gA	gA^b	gA^c
677.34	$5d_{3/2}$–$9f_{5/2}$	0.060	8.71(+8)	1.03(+9)	7.68(+8)
691.05	$5d_{5/2}$–$9f_{7/2}$	0.084	1.17(+9)	1.43(+9)	1.07(+9)
691.11	$5d_{5/2}$–$9f_{5/2}$	0.004	5.85(+7)	7.14(+7)	5.32(+7)
700.25	$5d_{3/2}$–$8f_{5/2}$	0.099	1.35(+9)	1.58(+9)	1.20(+9)
714.89	$5d_{5/2}$–$8f_{7/2}$	0.138	1.81(+9)	2.21(+9)	1.68(+9)
714.97	$5d_{5/2}$–$8f_{5/2}$	0.007	9.03(+7)	1.10(+8)	8.34(+7)
738.76	$5d_{3/2}$–$7f_{5/2}$	0.184	2.24(+9)	2.62(+9)	2.04(+9)
755.03	$5d_{5/2}$–$7f_{7/2}$	0.257	3.00(+9)	3.65(+9)	2.86(+9)
755.16	$5d_{5/2}$–$7f_{5/2}$	0.013	1.50(+8)	1.83(+8)	1.42(+8)
810.73	$5d_{3/2}$–$6f_{5/2}$	0.411	4.16(+9)	4.76(+9)	3.86(+9)
830.53	$5d_{5/2}$–$6f_{5/2}$	0.029	2.76(+8)	3.34(+8)	2.71(+8)
832.28	$5d_{5/2}$–$6f_{7/2}$	0.573	5.53(+9)	6.63(+9)	5.41(+9)
932.95	$6p_{1/2}$–$10s_{1/2}$	0.012	8.81(+7)	8.10(+7)	8.64(+7)
972.66	$6s_{1/2}$–$7p_{3/2}$	0.001	8.75(+6)	2.34(+5)	1.79(+7)
991.26	$6p_{3/2}$–$10s_{1/2}$	0.022	1.47(+8)	1.38(+8)	1.40(+8)
1001.17	$5d_{3/2}$–$5f_{5/2}$	1.283	8.53(+9)	9.42(+9)	8.10(+9)
1022.40	$6p_{1/2}$–$9s_{1/2}$	0.023	1.49(+8)	1.35(+8)	1.44(+8)
1029.83	$5d_{3/2}$–$7p_{3/2}$	0.003	2.13(+7)	2.42(+7)	1.86(+7)
1030.33	$5d_{5/2}$–$5f_{7/2}$	1.780	1.12(+10)	1.34(+10)	1.16(+10)
1031.54	$5d_{5/2}$–$5f_{5/2}$	0.089	5.57(+8)	6.78(+8)	5.84(+8)
1056.53	$5d_{3/2}$–$7p_{1/2}$	0.017	9.88(+7)	4.88(+7)	2.52(+7)
1061.99	$5d_{5/2}$–$7p_{3/2}$	0.030	1.75(+8)	1.70(+8)	1.23(+8)
1092.84	$6p_{3/2}$–$9s_{1/2}$	0.044	2.43(+8)	2.32(+8)	2.36(+8)
1187.34	$6p_{1/2}$–$7d_{3/2}$	0.204	9.64(+8)	9.56(+8)	8.04(+8)
1228.74	$6p_{1/2}$–$8s_{1/2}$	0.065	2.86(+8)	2.58(+8)	2.68(+8)
1277.53	$6p_{3/2}$–$7d_{5/2}$	0.341	1.39(+9)	1.31(+9)	1.09(+9)
1283.41	$6p_{3/2}$–$7d_{3/2}$	0.038	1.53(+8)	1.33(+8)	1.08(+8)
1331.92	$6p_{3/2}$–$8s_{1/2}$	0.120	4.49(+8)	4.48(+8)	4.52(+8)
1638.75	$6d_{3/2}$–$9f_{5/2}$	0.100	2.49(+8)	2.43(+8)	2.35(+8)
1659.84	$6d_{5/2}$–$9f_{7/2}$	0.141	3.42(+8)	3.55(+8)	3.46(+8)
1660.14	$6d_{5/2}$–$9f_{5/2}$	0.007	1.71(+7)	1.80(+7)	1.75(+7)
1779.61	$6d_{3/2}$–$8f_{5/2}$	0.169	3.56(+8)	3.44(+8)	3.37(+8)
1804.33	$6d_{5/2}$–$8f_{7/2}$	0.238	4.88(+8)	5.05(+8)	4.94(+8)
1804.85	$6d_{5/2}$–$8f_{5/2}$	0.012	2.44(+7)	2.56(+7)	2.50(+7)
1854.57	$6p_{1/2}$–$6d_{3/2}$	2.187	4.24(+9)	3.58(+9)	3.37(+9)
2050.71	$6d_{3/2}$–$7f_{5/2}$	0.323	5.11(+8)	4.85(+8)	4.84(+8)
2065.35	$6p_{3/2}$–$6d_{5/2}$	3.533	5.52(+9)	5.63(+9)	5.28(+9)
2070.56	$6p_{1/2}$–$7s_{1/2}$	0.496	7.70(+8)	6.18(+8)	6.38(+8)
2083.34	$6d_{5/2}$–$7f_{7/2}$	0.454	6.97(+8)	7.16(+8)	7.07(+8)
2084.32	$6d_{5/2}$–$7f_{5/2}$	0.023	3.48(+7)	3.65(+7)	3.60(+7)
2099.45	$6p_{3/2}$–$6d_{3/2}$	0.386	5.84(+8)	6.12(+8)	5.72(+8)
2210.22	$7p_{1/2}$–$10s_{1/2}$	0.030	4.12(+7)	3.74(+7)	3.88(+7)
2236.18	$6s_{1/2}$–$6p_{3/2}$	1.468	1.96(+9)	1.89(+9)	1.63(+9)
2337.02	$7p_{3/2}$–$10s_{1/2}$	0.057	6.98(+7)	6.58(+7)	6.52(+7)
2381.59	$6p_{3/2}$–$7s_{1/2}$	0.862	1.01(+9)	1.14(+9)	1.16(+9)
2563.49	$5d_{3/2}$–$6p_{3/2}$	0.093	9.40(+7)	9.68(+7)	8.96(+7)
2603.35	$6s_{1/2}$–$6p_{1/2}$	0.630	6.20(+8)	6.02(+8)	5.10(+8)
2721.65	$6d_{3/2}$–$6f_{5/2}$	0.706	6.30(+8)	5.46(+8)	5.33(+8)
2772.54	$5d_{5/2}$–$6p_{3/2}$	0.771	6.69(+8)	7.52(+8)	6.92(+8)

Table 2. (Continued)

		This work		Previous	
λ[a] (Å)	Transition	gf	gA	gA[b]	gA[c]
2781.16	$6d_{5/2}$–$6f_{5/2}$	0.049	4.22(+7)	4.31(+7)	4.22(+7)
2788.36	$7p_{1/2}$–$9s_{1/2}$	0.087	7.44(+7)	6.94(+7)	7.12(+7)
2800.91	$6d_{5/2}$–$6f_{7/2}$	0.987	8.43(+8)	8.40(+8)	8.24(+8)
2993.23	$7p_{3/2}$–$9s_{1/2}$	0.162	1.20(+8)	1.18(+8)	1.21(+8)
3057.87	$5d_{3/2}$–$6p_{1/2}$	0.388	2.77(+8)	3.10(+8)	2.76(+8)
3254.15	$7d_{3/2}$–$9f_{5/2}$	0.138	8.66(+7)		
3291.40	$7d_{5/2}$–$9f_{7/2}$	0.194	1.20(+8)		
3292.58	$7d_{5/2}$–$9f_{5/2}$	0.010	5.97(+6)		
3861.21	$7d_{3/2}$–$8f_{5/2}$	0.244	1.09(+8)		
3912.94	$7d_{5/2}$–$8f_{7/2}$	0.343	1.50(+8)		
3915.42	$7d_{5/2}$–$8f_{5/2}$	0.017	7.46(+6)		
4122.85	$5g_{9/2}$–$9f_{7/2}$	0.006	2.50(+6)		
4124.56	$5g_{7/2}$–$9f_{5/2}$	0.005	1.92(+6)		
4251.44	$5f_{5/2}$–$5g_{7/2}$	7.253	2.68(+9)		
4271.90	$5f_{7/2}$–$5g_{9/2}$	9.358	3.42(+9)		
4272.07	$5f_{7/2}$–$5g_{7/2}$	0.267	9.77(+7)		
4490.01	$7p_{1/2}$–$7d_{3/2}$	2.676	8.85(+8)	7.28(+8)	7.24(+8)
4956.43	$7p_{3/2}$–$7d_{5/2}$	4.364	1.18(+9)	1.21(+9)	1.19(+9)
5046.12	$7p_{3/2}$–$7d_{3/2}$	0.476	1.25(+8)	1.32(+8)	1.30(+8)
5145.87	$7p_{1/2}$–$8s_{1/2}$	0.767	1.93(+8)	1.52(+8)	1.54(+8)
5146.92	$5g_{9/2}$–$8f_{7/2}$	0.020	4.91(+6)		
5150.97	$5g_{7/2}$–$8f_{5/2}$	0.015	3.78(+6)		
5419.40	$7d_{3/2}$–$7f_{5/2}$	0.459	1.04(+8)		
5519.91	$7d_{5/2}$–$7f_{7/2}$	0.643	1.41(+8)		
5526.81	$7d_{5/2}$–$7f_{5/2}$	0.032	7.01(+6)		
5748.71	$5f_{5/2}$–$7d_{5/2}$	0.035	7.13(+6)		
5786.47	$5f_{7/2}$–$7d_{5/2}$	0.703	1.40(+8)		
5869.71	$5f_{5/2}$–$7d_{3/2}$	0.485	9.38(+7)		
5889.76	$7p_{3/2}$–$8s_{1/2}$	1.340	2.58(+8)	2.80(+8)	2.82(+8)
6198.06	$7s_{1/2}$–$7p_{3/2}$	2.305	4.00(+8)	3.90(+8)	3.83(+8)
7310.13	$7s_{1/2}$–$7p_{1/2}$	0.977	1.22(+8)	1.28(+8)	1.26(+8)
7534.29	$6d_{3/2}$–$5f_{5/2}$	2.736	3.21(+8)	3.26(+8)	3.29(+8)
7936.53	$6d_{5/2}$–$5f_{7/2}$	3.711	3.93(+8)	4.06(+8)	4.11(+8)
8008.69	$6d_{5/2}$–$5f_{5/2}$	0.184	1.91(+7)	1.97(+7)	1.99(+7)
8340.22	$5g_{7/2}$–$7f_{7/2}$	0.004	3.57(+5)		
8340.84	$5g_{9/2}$–$7f_{7/2}$	0.131	1.25(+7)		
8355.97	$5g_{7/2}$–$7f_{5/2}$	0.101	9.60(+6)		
9530.98	$6d_{3/2}$–$7p_{3/2}$	0.202	1.49(+7)	1.48(+7)	1.53(+7)

[a] Deduced from the experimental energy levels compiled by Martin *et al* (1978). Wavelengths are given in air above 2000 Å and in vacuum below that limit.
[b] From Migdalek (1982): model potential approach with core-polarization effects included using $\alpha_d = 5.20\ a_0^3$ (RMP-CP Ia).
[c] From Migdalek (1982): model potential approach with core-polarization effects included using $\alpha_d = 8.20\ a_0^3$ (RMP-CP Ib).

probabilities obtained by Migdalek for the same ion using the RMP-CP Ib method lead to somewhat higher lifetimes in relation to the fact that the core-polarizability parameter used in that case ($\alpha_d = 8.20\ a_0^3$) is larger than our value, which probably involves an overestimation of

Table 3. Radiative lifetimes (in ns) in La III and Lu III.

			This work		Previous		
Ion	Level	E^{a} (cm^{-1})	Experiment[b]	Theory[c]	MW87[d]	M82a[e]	M82b[f]
La III	$6p_{1/2}$	42 015.04	1.95 ± 0.20	1.86	1.96		
	$6p_{3/2}$	45 110.94	1.56 ± 0.20	1.54	1.65		
Lu III	$6p_{1/2}$	38 400.61		2.23		2.19	2.54
	$6p_{3/2}$	44 705.21		1.47		1.46	1.66

[a] From Martin *et al* (1978).
[b] Time-resolved laser spectroscopy (see the text). The standard deviation and an estimation of the possible residual systematic errors are included in the quoted error bars.
[c] HFR method including core-polarization effects (see the text).
[d] From Migdalek and Wyrozumska (1987): model potential approach with empirically adjusted exchange and core-polarization included (RMP + EX + CP).
[e] From Migdalek (1982): model potential approach with core-polarization effects included using $\alpha_d = 5.20\ a_0^3$ (RMP-CP Ia).
[f] From Migdalek (1982): model potential approach with core-polarization effects included using $\alpha_d = 8.20\ a_0^3$ (RMP-CP Ib).

the core-polarization effects. Accurate laser lifetime measurements in Lu III would be welcome to test the accuracy of the transition probabilities calculated in this ion.

Acknowledgments

EB, PP and PQ are, respectively, Research Director and Research Associates of the Belgian National Fund for Scientific Research (FNRS). Financial support from this organization is acknowledged. This work was partly supported by the European Community Access to Large-Scale Facilities Programme (Contract ERBFMGECT 950020) and partly by the Swedish National Science Research Council.

References

Berzinsh U, Caiyan L, Zerne R, Svanberg S and Biémont E 1997a *Phys. Rev.* A **55** 1836
Berzinsh U, Svanberg S and Biémont E 1997b *Astron. Astrophys.* **326** 412
Biémont E, Dutrieux J F, Martin I and Quinet P 1998b *J. Phys. B: At. Mol. Opt. Phys.* **31** 3321
Biémont E, Garnir H P, Federman S R, Li Z S and Svanberg S 1998a *Astrophys. J.* **502** 1010
Biémont E, Lyngå C, Li Z S, Svanberg S, Garnir H P and Doidge P S 1999 *Mon. Not. R. Astron. Soc.* **303** 721
Biémont E and Quinet P 1998 *Phys. Rev. Lett.* **81** 3345
Cowan R D 1981 *The Theory of Atomic Structure and Spectra* (Berkeley, CA: University of California Press)
Cowley C R 1976 *Astrophys. J. Suppl.* **32** 631
Cowley C R, Cowley A P, Aikman G C L and Crosswhite H 1977 *Astrophys. J.* **216** 37
Cowley C R and Henry R 1979 *Astrophys. J.* **233** 633
Cowley C R and Mathys G 1998 *Astron. Astrophys.* **339** 165
Fraga S, Karwowski J and Saxena K M S 1976 *Handbook of Atomic Data* (Amsterdam: Elsevier)
Glushkov A V 1992 *Opt. Spectrosc.* **72** 293
Hameed S 1972 *J. Phys. B: At. Mol. Phys.* **5** 746
Hameed S, Herzenberg A and James M G 1968 *J. Phys. B: At. Mol. Phys.* **1** 822
Jaschek C and Jaschek M 1995 *The Behavior of Chemical Elements in Stars* (Cambridge: Cambridge University Press)
Johnson W R, Kolb D and Huang K N 1983 *At. Data Nucl. Data Tables* **28** 333
Kunisz M D, Lubowiecka T, Muryn A, Niziol E and Szynarowska M 1968 *Acta Phys. Pol.* **33** 665
Li Z S and Jiang Zhankui 1999 *Phys. Scr.* to appear
Li Z S, Norin J, Persson A, Wahlström C G, Svanberg S, Doidge P S and Biémont E 1999 *Phys. Rev.* A at press

Li Z S, Persson A, Svanberg S, Garnir H P and Biémont E 1998a *Eur. Phys. J.* D **2** 11
Li Z S, Svanberg S, Biémont E, Palmeri P and Jiang Zhankui 1998b *Phys. Rev.* A **57** 3443
Lindgard A and Nielsen S E 1977 *At. Data Nucl. Data Tables* **19** 533
Martin W C, Zalubas R and Hagan L 1978 *Atomic Energy Levels—The Rare Earth Elements (NBS 60)* (Washington, DC: US Govt Printing Office)
Migdalek J 1980 *J. Phys. B: At. Mol. Phys.* **13** L169
——1982 *J. Quant. Spectrosc. Radiat. Transfer* **28** 417
Migdalek J and Baylis W E 1978 *J. Phys. B: At. Mol. Phys.* **11** L497
——1979 *J. Quant. Spectrosc. Radiat. Transfer* **22** 127
Migdalek J and Wyrozumska M 1987 *J. Quant. Spectrosc. Radiat. Transfer* **37** 581
Quinet P, Palmeri P, Biémont E, McCurdy M M, Rieger G, Pinnington E H, Wickliffe M E and Lawler J E 1999 *Mon. Not. R. Astron. Soc.* at press
Ryabchikova T A, Davisova E S and Adelman S J 1990 *Publ. Astron. Soc. Pac.* **102** 581
Sen K D and Puri A 1989 *Phys. Lett.* A **137** 128
Wyart J F 1995 *Laboratory and Astronomical High Resolution Spectra (ASP Conference Series)* ed J Sauval and N Grevesse **81** 182