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Time-resolved laser-induced fluorescence lifetime measurements and relativistic Hartree–Fock calculations of transition probabilities in Sm II

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Abstract
Radiative lifetime measurements were performed with time-resolved laser-induced fluorescence techniques for 47 levels of the astrophysically important ion Sm^{1+} over the energy range 21 000–36 000 cm^{-1}. The new results have been compared with previous measurements but also with theoretical calculations taking configuration interactions and core-polarization effects into account, and a satisfying agreement has been found for many levels of this complex ion. New calculated transition probabilities are deduced from the experimental lifetimes and from the theoretical branching fractions for 162 transitions of astrophysical interest. These results will help astrophysicists in the quantitative investigation of the chemical composition of CP stars.

1. Introduction

It has long been recognized that singly ionized samarium (Sm II) produces emission lines in the spectra of many different stellar objects like the Ap, Am or Bp stars, the Ba stars and the C- or S-type stars (see e.g. Jaschek and Jaschek 1995, and the references therein). Samarium is also well represented in the solar spectrum: in the period from the work of Grevesse and Blanquet (1969) to that of Biémont *et al* (1989), the abundance value of Sm has decreased from 1.66 (in the usual logarithmic scale used for solar abundances) to 1.01 (in the same scale), a substantial change largely connected to the improvement of the atomic data used for the analyses. Despite this progress, it remains true that a rather small number of Sm II transitions have been identified in stellar spectra and, on the basis of the analysis of the observed profiles, large overabundances of this element are generally found when compared to the solar system value. As an example, Sm II is well represented in the spectrum of the rapidly rotating star HD 101065 (Przybylski's star) and its abundance is several orders of magnitude larger than that found in the solar photosphere (Cowley *et al* 2000).

As a general rule, the detection of the rare-earths in numerous stellar spectra is hindered by the fact that many elements or ions have no outstanding strong lines but show a wealth of medium or weak intensity lines which, in addition, are frequently blended with contributions originating from the most astrophysically abundant elements (see e.g. Reyniers *et al* 2002). Making more reliable and more accurate abundance determinations requires the consideration, when possible, of a large number of transitions to avoid spurious identifications or analyses biased by blending problems. This in turn requires a larger set of radiative data which, for a limited number of transitions, can be obtained experimentally. In many cases however the required transition probabilities can only be deduced theoretically. But the theoretical models, in complex situations like those encountered in the lanthanide spectra, need detailed comparisons with experimental measurements in order to assess their reliability.

In the present work, we report on lifetime measurements in Sm II using a selective-laser excitation technique, and on transition probability determination in the same ion with the widely used relativistic Hartree–Fock (HFR) approach in order to expand the sample of Sm II lines usable in astrophysics for refining the chemical composition of some CP stars.

2. Levels and transition probabilities in Sm II

Samarium has 7 stable isotopes: 144 (3.1%), 147 (15.0%), 148 (11.3%), 149 (13.8%), 150 (7.4%), 152 (26.7%) and 154 (22.7%), the nuclear spin of the two odd isotopes being 7/2. In the stars, ^{148}Sm and ^{150}Sm are produced by the s process, ^{144}Sm by the p process, ^{154}Sm by the r process and ^{147}Sm, ^{149}Sm and ^{152}Sm are produced by both the r and s processes.

The ground state of Sm II is $4f^6(^7F)6s\ ^8F_{1/2}$. According to the NIST compilation (Martin *et al* 1978), very few energy levels are known in this ion. In fact, 70 even levels and about 300 odd levels have been determined by Albertson (1936), Albertson and King (1936) and by spectroscopists from the Aimé Cotton laboratory (Carlier 1967, Blaise *et al* 1969, Morillon 1970, Henny-Schweighofer 1970). They belong to the $4f^6(^7F)6s$, 5d configurations and to the $4f^7$ and, possibly, to the $4f^6(^7F)6p$, $4f^5(^6H^o)5d6s$ configurations, respectively. Most of the assignments for odd parity states, however, need confirmation.

Transition probabilities or lifetime values in Sm II are still very sparse. In addition, they are very difficult to obtain both experimentally and theoretically in view of, on the one hand, the fragmentary knowledge of the spectrum and, on the other hand, its complexity originating basically from the large number of closely spaced low-excitation levels. In addition, their reliability is hard to assess and requires the use of different independent methods applied to the same levels.

Published transition probabilities and branching fractions (BF) are due to Corliss and Bozman (1962) (arc measurements), to Saffman and Whaling (1979) (BF measurements), and to Kastberg *et al* (1993) (Rabi frequencies observed via optical nutation). Radiative lifetimes have been obtained by beam-foil spectroscopy (Andersen *et al* 1975), by the delayed-coincidence technique with electron-beam excitation by Blagoev *et al* (1978) and Gorshkov and Komarovskii (1986), and by the beam-laser method (Vogel *et al* 1988).

The two most extensive contributions concerning lifetime measurements in this ion are based on the use of the laser-induced fluorescence technique: they concern 35 levels up to 30 880 cm^{-1} with lifetimes in the range 10–88 ns excited in sputtered metal vapour (Biémont *et al* 1989) and 82 levels, with lifetimes in the range 9–190 ns, excited by the beam-laser method up to 29 600 cm^{-1} (Scholl *et al* 2002b).

Compilations of lifetimes and f-values in Sm II are due to Blagoev and Komarovskii (1994) and to Komarovskii (1991).

3. Lifetime measurements

The lifetime measurements were obtained, in the present work, by using selective excitation of the ionic levels by tunable laser radiation and time-resolved detection of the fluorescence released from the investigated levels. The Sm^+ particle source was produced by the method of laser ablation, which has the advantage of yielding high ionic populations in ground as well as metastable states that can be used as a starting point for laser excitation. The experimental apparatus used has been described elsewhere in detail (see e.g. Dai *et al* 2003) and, therefore, only a brief description is given here.

A pure samarium foil was placed on a rotating target located in a vacuum chamber with a pressure of about 10^{-6}–10^{-5} mbar. The ablation laser pulses, emitted from an Nd:YAG laser (Continuum Surelite) with a 532 nm wavelength, a 10 ns duration, and a variable pulse energy, normally in the range 2–10 mJ, were focused vertically onto the surface of the rotating samarium foil, from which a small plasma containing electrons, atoms and ions in various ionization stages was produced. When the plasma reached the interaction zone about 10 mm above the rotating target surface, it was crossed horizontally by an excitation laser beam with useful properties (hereafter described), which were obtained by combining the methods of stimulated Brillouin scattering (SBS) in water, and stimulated Stokes Raman scattering (SSRS) in hydrogen gas. A 532 nm laser pulse, emitted from an injection seeded and Q-switched Nd:YAG laser (Continuum NY-82) with an 8 ns pulse duration and a single pulse energy of 400 mJ, was first sent to the SBS compressor to be shortened to about 1 ns. Then the shortened laser pulse was employed to pump a dye laser (Continuum Nd-60), in which the DCM dye was operated. The radiation from the dye laser could be frequency doubled in a KDP crystal. The dye laser beam at its fundamental frequency or its second harmonic was focused into the SSRS cell with a hydrogen pressure of about 10 bars, in which different orders of stimulated Stokes and anti-Stokes Raman scattering were obtained. The different components of the laser beams from the SSRS cell were first isolated with a CaF_2 Pellin–Broca prism and then the appropriate excitation light was sent into the vacuum chamber for excitation of the ions. Both Nd:YAG lasers were externally triggered by the same digital delay generator (Stanford Research Systems Model 535) and remained at a 10 Hz repetition rate. The fluorescence was collected by a fused-silica lens and focused to the entrance slit of a $1/8$ m monochromator equipped with a Hamamatsu 1564U micro-channel-plate photomultiplier tube (200 ps risetime). A transient digitizer (Tektronix Model DSA 602) was used to record and average the signals. Finally the averaged time-resolved fluorescence signals were transferred to a personal computer for lifetime evaluations. The lifetimes measured and the corresponding excitation schemes are given in table 1.

In the measurements, the fluorescence signals in the different decay channels from excited upper levels to possible lower levels were checked and the strongest one was usually recorded for the lifetime evaluation. Special attention has been paid to all possible systematic effects, which can potentially affect the accuracy of the measured lifetimes, such as flight-out-of-view effects, radiation trapping and collisional effects by adjusting a variety of experimental conditions. A recording of the time-resolved signal of the laser-produced plasma and laser-induced fluorescence is shown in figure 1. The background intensity varies slowly compared with the fluorescence signal. By adjusting the experimental parameters containing the ablation laser intensity and the delay time, the background could be neglected. To check the collisional quenching and radiation trapping effects, measurements under different plasma conditions

Table 1. Levels measured in Sm II and corresponding excitation schemes.

Energy (cm^{-1})[a]	Configuration[a]	J	Origin[a] (cm^{-1})	Excitation λ_{vac} (nm)	Laser mode[b]	Detection λ_{vac} (nm)
21 702.33	$4f^6(^7F)6p$?	3/2	1518.29	495.44	$\omega + A$	468
21 904.12	$4f^6(^7F)6p$?	3/2	2003.23	502.49	$\omega + A$	475
22 429.49	$4f^6(^7F)6p$?	5/2	326.64	452.43	$2\omega + 2S$	463
22 875.41	$4f^6(^7F)6p$?	7/2	838.22	453.78	$2\omega + 2S$	468
23 177.49	$4f^6(^7F)6p$?	3/2	326.64	437.62	$2\omega + 2S$	462
23 842.20	$4f^6(^7F)6p$?	5/2	838.22	434.71	$2\omega + 2S$	458
23 962.25	$4f^6(^7F)6p$?	3/2	838.22	432.45	$2\omega + 2S$	423
24 257.37	$4f^6(^7F)6p$?	9/2	1489.16	439.21	$2\omega + 2S$	439
24 429.52	$4f^6(^7F)6p$?	3/2	838.22	423.89	$2\omega + 2S$	409
24 588.00	$4f^6(^7F)6p$?	11/2	2237.97	447.43	$2\omega + 2S$	464
25 178.45	$4f^5(^6H)5d6s$?	3/2	1518.29	422.65	$2\omega + 2S$	397
25 385.36	$4f^6(^7F)6p$?	11/2	2237.97	432.01	$2\omega + 2S$	432
25 565.97	$4f^6(^7F)6p$?	7/2	2237.97	428.67	$2\omega + 2S$	404
25 980.32	$4f^5(^6H)5d6s$?	5/2	2688.69	429.34	$2\omega + 2S$	417
26 357.90	?	5/2	326.64	384.15	$2\omega + S$	402
26 484.66	?	3/2	0.0	377.58	$2\omega + S$	408
26 565.61	$4f^6(^7F)6p$?	9/2	3052.65	425.30	$2\omega + 2S$	399
26 599.08	?	3/2	0.0	375.95	$2\omega + S$	388
26 690.30	$4f^55d6s$?	1/2	326.64	379.31	$2\omega + S$	405
26 828.29	$4f^6(^7F)6p$?	11/2	3909.62	436.33	$2\omega + 2S$	446
26 938.42	?	7/2	838.22	383.14	$2\omega + S$	393
26 974.67	?	5/2	326.64	375.26	$2\omega + S$	400
27 063.30	$4f^55d6s$?	3/2	0.0	369.50	$2\omega + S$	381
27 165.35	?	5/2	326.64	372.60	$2\omega + S$	408
27 210.12	?	1/2	0.0	367.51	$2\omega + S$	389
27 284.69	?	5/2	326.64	370.95	$2\omega + S$	406
27 464.20	$4f^6(^7F)6p$?	7/2	3499.12	417.27	$2\omega + 2S$	404
27 695.96	$4f^55d6s$?	13/2	5317.56	446.86	$2\omega + 2S$	420
30 756.88	?	3/2	0.0	325.13	2ω	325
31 045.47	?	5/2	326.64	325.53	2ω	338
31 171.00	?	3/2	0.0	320.81	2ω	330
31 774.52	?	7/2	838.22	323.24	2ω	330
31 915.67	?	7/2	838.22	321.78	2ω	337
32 358.56	?	3/2	1518.29	324.25	2ω	339
32 434.70	?	9/2	1489.16	323.15	2ω	331
32 857.54	?	9/2	1489.16	318.79	2ω	327
32 935.43	?	5/2	2003.23	323.29	2ω	340
32 945.19	?	9/2	1489.16	317.90	2ω	335
33 107.10	?	5/2	2003.23	321.50	2ω	329
33 598.70	?	11/2	2237.97	318.87	2ω	327
33 775.84	?	11/2	2237.97	317.08	2ω	325
33 881.94	?	7/2	2688.69	320.58	2ω	339
34 145.44	?	13/2	3052.65	321.62	2ω	331
34 734.70	?	9/2	3499.12	323.88	2ω	344
34 418.95	?	11/2	3052.65	318.81	2ω	328
34 768.41	?	13/2	3052.65	315.30	2ω	324
35 348.60	?	9/2	4386.03	322.97	2ω	323

[a] From the NIST compilation (Martin *et al* 1978).
[b] 2ω means the second harmonic, S and A are written for the first Stokes and anti-Stokes components of the Raman scattering.

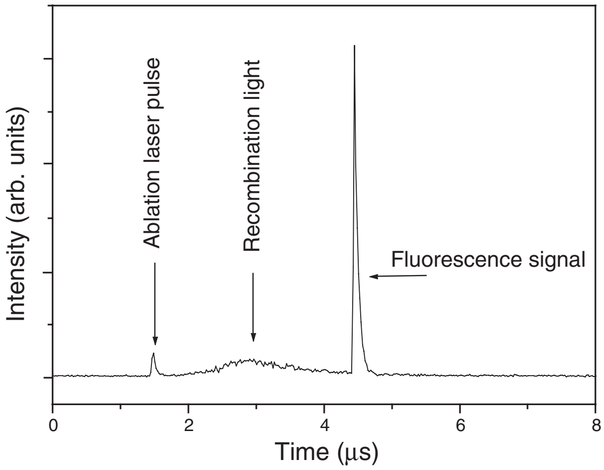

Figure 1. The detected light intensity at 400 nm as a function of time. The fluorescence is from the level of 26 974.67 cm^{-1} and the background light from recombination between electrons and the ions.

were performed. The delay time between the ablation pulse and the excitation pulse was varied between 1 and 7 μs.

In figure 2, the detected fluorescence intensity and the evaluated lifetime of 26 974.67 cm^{-1} as a function of the delay time between ablation and excitation pulses are shown. As the delay time was changed, the detected fluorescence intensity could be modified by a factor of more than 10, but still reasonably good signals were obtained and the evaluated lifetime values for delays longer than 2 μs were found to be well coincident. For delay times shorter than 2 μs, shorter lifetime values were obtained due to collisional deexcitation in the dense plasma. In this experiment, a static magnetic field of about 100 G, provided by a pair of Helmholtz coils, was added and removed over the interaction zone to check for possible quantum beats in long-lived states due to the Zeeman effect. The flight-out-of-view effects have also been minimized by adjusting the position and width of the entrance slit of the monochromator and the delay times between the ablation and the excitation pulses. To ensure a linear response of the detection system, the fluorescence signals were detected with different neutral density filters inserted in the exciting laser light path.

For each level measured, about 10 fluorescence decay curves, each smoothed by averaging fluorescence photons from 1000 pulses, were recorded under different experimental conditions, and lifetimes were evaluated by a least-square exponential fitting procedure. The average lifetime value was adopted. All the experimental lifetime results are given in table 2 with their uncertainties.

4. Branching fraction calculations

Obtaining transition rates from lifetime measurements requires the complementary determination of adequate branching fractions (BF). It has been shown in previous papers (see e.g. Biémont *et al* 2002, Dai *et al* 2003, Zhang *et al* 2002a, 2002b, 2002c) that, for heavy ions such as neutral, singly or doubly ionized lanthanides, the consideration of both intravalence and core-valence correlation is essential in atomic structure calculations. In many different situations, the HFR method, described by Cowan (1981), has appeared usable and reliable

Table 2. Experimental and theoretical radiative lifetimes for odd-parity levels in Sm II.

		This work		
E (cm^{-1})	J	Experiment[a]	Theory	Previous experiments[a]
21 702.33	3/2	41(3)	37.2	39(2)[b], 40.2(2)[c]
21 904.12	3/2	65(6)	67.1	70.8(6)[c]
22 429.49	5/2	72(7)	67.7	79.4(9)[c]
22 875.41	7/2	40(3)	35.2	39.9(1)[c]
23 177.49	3/2	48(3)	53.4	48.0(4)[c]
23 842.20	5/2	35(2)		23(3)[d], 34(2)[b], 33.6(3)[c]
23 962.25	3/2	24.7(1.5)		22.54(6)[c]
24 257.37	9/2	47(3)	47.6	46.6(3)[c]
24 429.52	3/2	27.5(1.5)	32.8	24.7(1)[c]
24 588.00	11/2	42(3)	57.6	41.5(0.3)[b], 40.7(5)[c]
25 178.45	3/2	25(2)		23.5(2)[c]
25 385.36	11/2	43(3)	56.3	69(4)[d], 42(1)[e], 38.7(2.0)[b], 42.2(2)[c]
25 565.97	7/2	31(2)		31.1(5)[c]
25 980.32	5/2	20.0(1.0)		20(1.5)[b], 19.9(4)[c]
26 357.90	5/2	33(2)	39.9	32.2(3)[c]
26 484.66	3/2	54(3)		
26 565.61	9/2	64(4)		65.6(4)[c]
26 599.08	3/2	20.0(1.0)		17.9(2)[c]
26 690.30	1/2	16.0(1.0)	10.9	
26 828.29	11/2	30(2)	25.2	27.6(0.7)[e], 27.3(4)[c]
26 938.42	7/2	38(2)		36.4(0.7)[e]
26 974.67	5/2	53(4)	48.9	54.4(7)[c]
27 063.30	3/2	10.6(0.5)	11.3	
27 165.35	5/2	60(4)	66.0	64(3)[c]
27 210.12	1/2	22(2)	16.1	
27 284.69	5/2	18.4(1.0)	18.4	21.9(1.4)[e], 17.6(0.9)[b], 17.3(2)[c]
27 464.20	7/2	39(3)	41.8	22(2)[d], 35(3)[b], 36.9(8)[c]
27 695.96	13/2	24(2)	15.0	16(4)[f], 16(2)[d], 24(0.6)[e], 24.6(5)[c]
30 756.88	3/2	75(6)		
31 045.47	5/2	11.2(0.8)		
31 171.00	3/2	17.9(1.0)		
31 774.52	7/2	25(2)		
31 915.67	7/2	29(2)		
32 358.56	3/2	16.6(1.2)		
32 434.70	9/2	15.5(0.9)		
32 857.54	9/2	41(3)		
32 935.43	5/2	24(2)		
32 945.19	9/2	42(3)		
33 107.10	5/2	68(6)		
33 598.70	11/2	33(2)		
33 775.84	11/2	35(2)		
33 881.94	7/2	29(2)		
34 145.44	13/2	16.0(0.9)		
34 734.70	9/2	52(4)		
34 418.95	11/2	38(2)		
34 768.41	13/2	32(2)		
35 348.60	9/2	97(9)		

[a] The number between parentheses corresponds to the estimated error on the last digit.
[b] Biémont *et al* (1989).
[c] Scholl *et al* (2002a).
[d] Gorshkov and Komarovskii (1986).
[e] Vogel *et al* (1988).
[f] Andersen *et al* (1975).

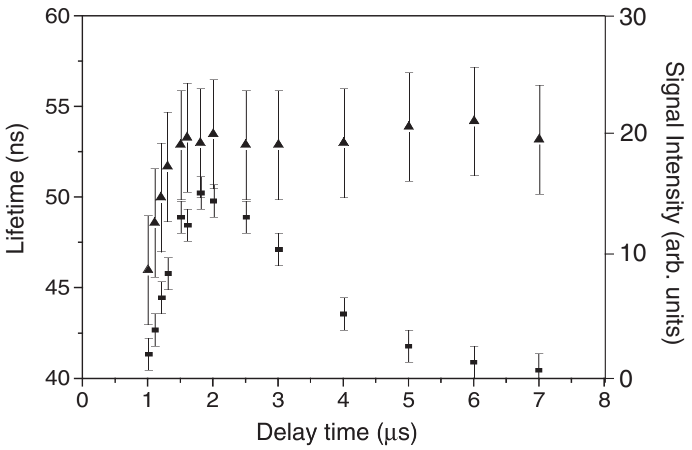

Figure 2. The detected fluorescence intensity (rectangles) and the evaluated lifetime values (triangles) of the Sm II level (26 974.67 cm^{-1}) as a function of delay between ablation and the excitation pulses.

(i.e. leading to lifetime values generally in agreement within a few per cent with experimental data obtained with laser spectroscopy techniques) for providing missing data.

In the case of Sm II, according to the NIST compilation (Martin *et al* 1978) and the predictions of Brewer (1971), the low-lying levels belong to the very complex configurations $4f^7$, $4f^5 5d6s$, $4f^5 5d^2$, $4f^6 6p$, $4f^5 6s^2$ in the odd parity and $4f^6 6s$, $4f^6 5d$, $4f^5 5d6p$, $4f^5 6s6p$ in the even parity. These configurations exhibit a huge number of levels and, in addition, simple calculations performed with the HFR approach show that these configurations overlap in a large range of energy and, consequently, are expected to interact strongly. This is illustrated in figure 3 where the energy ranges of the odd-parity configurations are estimated through monoconfigurational calculations.

Unfortunately, the consideration of all the possible levels belonging to these 9 configurations (i.e. 13 955 levels for the even parity and 16 540 levels for the odd parity) was prevented, in the present work, by the computer limitations (too large matrix dimensions). To overcome this difficulty, we have considered a physical model in which the sizes of the energy matrices were reduced by including only a limited number of terms of the subshell f^w ($w = 5, 6$) in setting up quantum states for the complete configurations. More precisely, only the sextet ($2S+1 = 6$) terms of $4f^5$ were retained in the calculation of $4f^5 5d6s$, $4f^5 5d^2$, $4f^5 6s^2$, $4f^5 5d6p$ and $4f^5 6s6p$ configurations and only the septet ($2S+1 = 7$) and quintet ($2S+1 = 5$) terms of $4f^6$ were retained for the configurations $4f^6 6p$, $4f^6 6s$ and $4f^6 5d$. This allowed us to considerably reduce the total number of energy levels from 13 955 to 1667 and from 16 540 to 1876 for the even and odd parities, respectively. In addition, it was verified that the omitted terms, i.e. the quadruplets and doublets in the case of $4f^5$ and the triplets and singlets in the case of $4f^6$, correspond to energy levels situated above 35 000 cm^{-1}, i.e. outside the energy range considered in the present work (see table 2).

In view of the scarcity of the experimentally determined energy levels available in Sm II (see Martin *et al* 1978), no semi-empirical adjustment of the radial parameters could be seriously considered. Instead, in order to obtain a more realistic representation of the Sm II energy spectrum, all the Slater integrals were scaled down by a factor 0.75, in agreement with a suggestion made by Cowan (1981) of a factor in the range 0.75–0.85. The choice of 0.75 was dictated by the best agreement between calculated and observed energy levels for the even parity. This choice, however, was not crucial because it was verified that

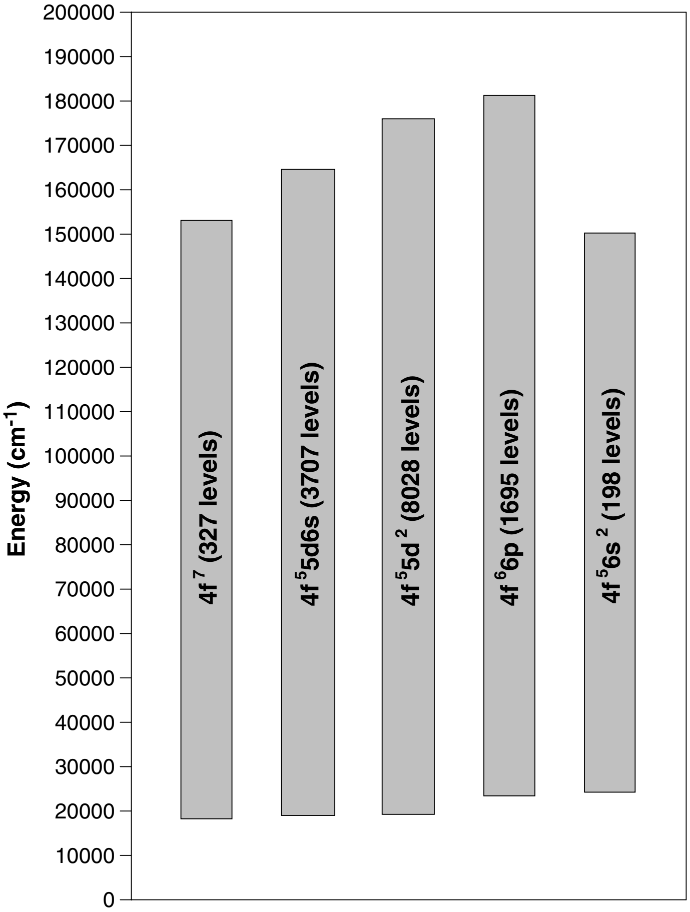

Figure 3. Predicted energies and theoretical numbers of levels for the low-lying odd configurations of Sm II. The energy ranges have been obtained through monoconfigurational HFR calculations.

adopting 0.80 instead of 0.75 would lead to a change in the lifetime values of a few (<10) per cent. The average energies were adjusted to reproduce adequately the levels given in the NIST compilation (Martin *et al* 1978) or predicted by Brewer (1971) for the lowest level of each configuration, i.e. $4f^6 6s\ ^8F_{1/2}$ (E = 0 cm^{-1}), $4f^6 5d\ ^8H_{3/2}$ (E = 7135 cm^{-1}), $4f^5 5d6p\ ^8L_{9/2}$ ($E = 44\,000 \pm 2000$ cm^{-1}), $4f^5 6s6p\ ^8I_{5/2}$ ($E = 49\,000 \pm 1000$ cm^{-1}), $4f^7\ ^8S_{7/2}$ ($E = 18\,289$ cm^{-1}), $4f^5 5d6s\ ^8K_{7/2}$ ($E = 19\,000$ cm^{-1}), $4f^5 5d^2\ ^8L_{9/2}$ ($E = 19\,000 \pm 1000$ cm^{-1}), $4f^6 6p\ ^8G_{1/2}$ ($E = 23\,400$ cm^{-1}), $4f^5 6s^2\ ^6H_{5/2}$ ($E = 24\,000 \pm 2000$ cm^{-1}).

Unfortunately, due to the huge number of calculated odd-parity levels and to the strong mixing between these states, it was extremely difficult to establish an unambiguous correspondence between the calculated and the experimental values. The use of the available Landé factors was not even of great help for making the identifications more reliable. It is worth emphasizing that, according to our HFR calculations, the average purity, in LS coupling, of odd-parity levels below 23 000 cm^{-1} is found to be equal to 77%, this value decreasing to 54% for the levels situated between 23 000 and 25 000 cm^{-1} and to 32% for those located between 25 000 and 35 000 cm^{-1}. In fact, among the 47 levels for which radiative lifetimes

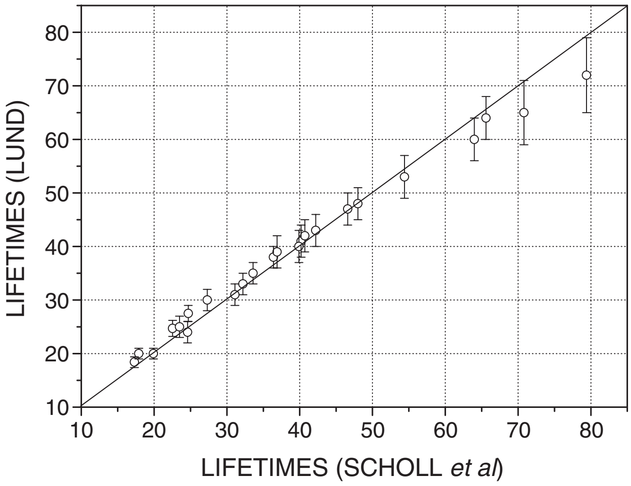

Figure 4. The dependence of the experimental lifetimes measured in the present work on those obtained by Scholl *et al* (2002a).

were measured in the present work (see table 2), only 19 were assigned with certainty in the calculations.

5. The radiative lifetimes

For the 19 levels mentioned in section 4, calculated lifetimes are compared in table 2 with the experimental measurements of the present work. Previous data are also quoted in the same table. For 23 levels, there were no measurements available. As it appears from the table, the new lifetime values agree quite well (within a few per cent) with the calculations for most of the levels, a situation that is encouraging in view of the complex configurations encountered in Sm II.

Our new experimental lifetime values agree, within the error bars, with the previous laser measurements of Biémont *et al* (1989) (7 levels in common). Similar considerations apply when comparing the results of the present work with the data of Scholl *et al* (2002b) (23 levels in common) with the exception of the level at 27 695.96 cm^{-1}. For this level, two groups of measurements have been published: some 'low' values (1 ns) (Andersen *et al* 1975, Gorshkov and Komarovskii 1986) and some 'high' values (24–25 ns) (Vogel *et al* 1988, Scholl *et al* 2002b, this work). The origin of this discrepancy is not clear, the theoretical value seeming to favour the 'low' results.

In a plot of the Lund results versus those of Scholl *et al* (2002b), a proportionality and good agreement were found for lifetimes less than 60 ns (see figure 4). However, a levelling off seems to be present in the figure when the lifetimes get longer than 60 ns, i.e. the Lund results are lower than those of Scholl *et al*. Although we have no reason to doubt our results, the disagreement with beam-laser measurements for this case is hard to understand since the two methods yielded very good agreement in other cases, for example, for Pr II (Scholl *et al* 2002a, Biémont *et al* 2003) and for Nd II (Pinciuc *et al* 2001, Xu *et al* 2003). Clearly a third, independent measurement would be useful for these longer values.

The delayed coincidence results of Gorshkov and Komarovskii (1986) disagree considerably from the present measurements and also from the other previous results for three

Table 3. Comparison between HFR BF as obtained in the present work and experimentally determined values (Saffman and Whaling 1979) for selected levels in Sm II.

Upper level		Lower level			BF (%)	
Configuration	E (cm^{-1})	Configuration	E (cm^{-1})	λ (Å)	EXP	HFR
4f^{5}5d6s? ^{8}G$^o_{1/2}$	26 690.30	4f^6(^{7}F)6s a ^{8}F$_{1/2}$	0.00	3745.605	81.7	64.5
		4f^6(^{7}F)6s a ^{8}F$_{3/2}$	326.64	3792.025	6.6	21.9
		4f^6(^{7}F)6s a ^{6}F$_{3/2}$	2 003.23	4049.584	2.8	0.8
		4f^6(^{7}F)5d a ^{8}H$_{3/2}$	7 135.06	5112.304	8.9	7.0
					100.0	94.2
4f^{5}5d6s? ^{8}G$^o_{3/2}$	27 063.30	4f^6(^{7}F)6s a ^{8}F$_{1/2}$	0.0	3693.989	26.4	20.5
		4f^6(^{7}F)6s a ^{8}F$_{3/2}$	326.64	3739.12	50.0	49.4
		4f^6(^{7}F)6s a ^{8}F$_{5/2}$	838.22	3812.067	7.2	13.2
		4f^6(^{7}F)5d a ^{8}H$_{3/2}$	7 135.06	5016.61	2.2	1.4
		4f^6(^{7}F)5d a ^{8}H$_{5/2}$	7 524.86	5116.700	14.2	5.1
					100.0	89.6
4f^{5}5d6s? ?$^o_{13/2}$	27 695.96	4f^6(^{7}F)6s a ^{8}F$_{13/2}$	3 909.62	4202.915	18.3	8.9
		4f^6(^{7}F)6s a ^{6}F$_{11/2}$	5 317.56	4467.342	76.2	77.9
		4f^6(^{7}F)5d a ^{8}H$_{15/2}$	11 094.06	6021.75	0.4	1.4
		4f^6(^{7}F)5d b ^{8}F$_{13/2}$	14 084.55	7344.76	2.1	1.2
		4f^6(^{7}F)5d a ^{8}G$_{15/2}$	14 503.67	7578.09	3.1	2.2
					100.1	91.6

levels, indicating that the three lifetime values published by these authors have to be considered cautiously. For the fourth level, a good agreement is observed with our measurement.

HFR BF are compared in table 3 to measured values published by Saffman and Whaling (1979). Some discrepancies are observed between the two sets of results, not only for the weakest lines, but also for some strong transitions. They are directly related to missing branches in the experimental results whose contributions reach 5.8, 10.4 and 8.4%, respectively, according to the last column of table 3.

6. Oscillator strengths and transition probabilities

Calculated oscillator strengths (log gf) and transition probabilities (gA) as obtained in the present work are reported in table 4 for 162 transitions involving the 19 upper odd levels for which a comparison between experimental and theoretical lifetimes was possible (see section 4 and table 2). For these transitions, the combination of HFR BF with the measured lifetimes has allowed us to 'normalize' the gf- and gA-values. Although it is always hard to estimate the accuracy of a new set of f-values, the present oscillator strengths are expected to be characterized by an accuracy of a few per cent for the strongest transitions. The transition probabilities for the weaker lines could be less accurate at least for some specific transitions involving strongly perturbed levels.

According to the comparisons of table 3, we have labelled the transitions of table 4 by the letters A, B and C (last column of the table) in order to provide some information about the expected accuracy of the transition probabilities obtained in the present work: A means an accuracy $\leqslant$10%, B $\leqslant$ 30% and C $\geqslant$ 30%.

It is anticipated that the new results obtained in the present work will help astrophysicists in a quantitative investigation of the chemical composition of some stars.

The present results will be incorporated in the database DREAM accessible at the web site http://www.umh.ac.be/~astro/dream.shtml.

Table 4. Calculated oscillator strengths (log gf) and transition probabilities (gA in s^{-1}) for selected transitions of Sm II. Only transitions with log $gf_{HFR} > -2.00$ are given in the table. A(B) stands for A × 10^B.

λ[a]	Lower level[b]			Upper level[b]			log gf HFR[c]	gA HFR[c]	log gf NORM[d]	gA NORM[d]	Note[e]
3674.057	0	(e)	1/2	27 210	(o)	1/2	−1.94	6.09(6)	−2.08	4.46(6)	C
3693.989	0	(e)	1/2	27 063	(o)	3/2	−0.89	7.25(7)	−0.86	7.73(7)	B
3708.412	327	(e)	3/2	27 285	(o)	5/2	−1.19	3.48(7)	−1.19	3.48(7)	B
3724.902	327	(e)	3/2	27 165	(o)	5/2	−1.49	1.78(7)	−1.45	1.96(7)	B
3739.120	327	(e)	3/2	27 063	(o)	3/2	−0.49	1.76(8)	−0.47	1.88(8)	A
3745.615	0	(e)	1/2	26 690	(o)	1/2	−0.67	1.19(8)	−0.83	8.11(7)	B
3754.663	838	(e)	5/2	27 464	(o)	7/2	−0.88	6.40(7)	−0.85	6.86(7)	B
3792.023	327	(e)	3/2	26 690	(o)	1/2	−1.13	4.01(7)	−1.29	2.73(7)	B
3812.062	838	(e)	5/2	27 063	(o)	3/2	−1.05	4.69(7)	−1.02	5.00(7)	B
3840.446	327	(e)	3/2	26 358	(o)	5/2	−0.86	6.64(7)	−0.78	8.03(7)	B
3848.758	1489	(e)	7/2	27 464	(o)	7/2	−1.27	2.47(7)	−1.24	2.65(7)	B
3891.185	1518	(e)	1/2	27 210	(o)	1/2	−1.36	2.07(7)	−1.50	1.51(7)	B
3893.556	1489	(e)	7/2	27 165	(o)	5/2	−1.69	1.01(7)	−1.65	1.11(7)	B
3922.687	1489	(e)	7/2	26 975	(o)	5/2	−1.76	8.17(6)	−1.79	7.54(6)	C
3963.006	2238	(e)	9/2	27 464	(o)	7/2	−1.23	2.54(7)	−1.20	2.72(7)	B
3966.047	2003	(e)	3/2	27 210	(o)	1/2	−0.74	8.28(7)	−0.88	6.06(7)	B
3973.104	2003	(e)	3/2	27 165	(o)	5/2	−1.29	2.47(7)	−1.25	2.72(7)	B
4003.443	2003	(e)	3/2	26 975	(o)	5/2	−0.87	6.12(7)	−0.90	5.65(7)	B
4019.976	1489	(e)	7/2	26 358	(o)	5/2	−1.48	1.44(7)	−1.40	1.74(7)	B
4035.104	2689	(e)	5/2	27 464	(o)	7/2	−1.24	2.42(7)	−1.21	2.59(7)	B
4064.554	2689	(e)	5/2	27 285	(o)	5/2	−0.49	1.45(8)	−0.49	1.45(8)	A
4084.372	2689	(e)	5/2	27 165	(o)	5/2	−1.74	8.28(6)	−1.70	9.11(6)	C
4092.253	0	(e)	1/2	24 430	(o)	3/2	−0.95	5.23(7)	−0.88	6.24(7)	B
4101.472	2689	(e)	5/2	27 063	(o)	3/2	−1.50	1.46(7)	−1.47	1.56(7)	B
4104.830	2003	(e)	3/2	26 358	(o)	5/2	−1.58	1.09(7)	−1.50	1.32(7)	B
4116.440	2689	(e)	5/2	26 975	(o)	5/2	−1.27	2.30(7)	−1.30	2.12(7)	B
4171.562	3499	(e)	7/2	27 464	(o)	7/2	−1.69	8.00(6)	−1.66	8.57(6)	C
4202.909	3910	(e)	13/2	27 696	(o)	13/2	−0.71	8.31(7)	−0.80	6.74(7)	B
4203.045	3499	(e)	7/2	27 285	(o)	5/2	−0.61	1.04(8)	−0.61	1.04(8)	A
4204.801	3053	(e)	11/2	26 828	(o)	11/2	−0.95	4.70(7)	−1.03	3.95(7)	B
4223.708	2689	(e)	5/2	26 358	(o)	5/2	−1.32	1.87(7)	−1.24	2.26(7)	B
4237.657	838	(e)	5/2	24 430	(o)	3/2	−1.79	7.06(6)	−1.72	8.42(6)	C
4258.552	3499	(e)	7/2	26 975	(o)	5/2	−1.59	1.01(7)	−1.63	9.32(6)	C
4318.927	2238	(e)	9/2	25 385	(o)	11/2	−0.44	1.39(8)	−0.32	1.82(8)	A
4362.029	3910	(e)	13/2	26 828	(o)	11/2	−1.47	1.33(7)	−1.54	1.12(7)	B
4374.975	327	(e)	3/2	23 177	(o)	3/2	−1.77	6.60(6)	−1.73	7.34(6)	C
4390.855	1489	(e)	7/2	24 257	(o)	9/2	−0.92	4.36(7)	−0.91	4.42(7)	B
4454.629	4386	(e)	9/2	26 828	(o)	11/2	−0.04	3.45(8)	−0.11	2.90(8)	A
4457.801	2003	(e)	3/2	24 430	(o)	3/2	−1.18	2.65(7)	−1.10	3.16(7)	B
4467.341	5318	(e)	11/2	27 696	(o)	13/2	0.28	7.30(8)	0.19	5.92(8)	A
4473.012	2238	(e)	9/2	24 588	(o)	11/2	−0.75	6.45(7)	−0.62	8.85(7)	B
4476.481	3053	(e)	11/2	25 385	(o)	11/2	−1.88	4.71(6)	−1.76	6.17(6)	C
4536.512	838	(e)	5/2	22 875	(o)	7/2	−0.64	8.21(7)	−0.70	7.22(7)	B
4540.177	2238	(e)	9/2	24 257	(o)	9/2	−0.58	8.76(7)	−0.58	8.87(7)	B
4598.352	2689	(e)	5/2	24 430	(o)	3/2	−1.78	6.29(6)	−1.70	7.50(6)	C
4606.510	0	(e)	1/2	21 702	(o)	3/2	−1.09	2.81(7)	−1.14	2.55(7)	B
4615.683	1518	(e)	1/2	23 177	(o)	3/2	−0.83	5.30(7)	−0.78	5.90(7)	B
4630.205	838	(e)	5/2	22 429	(o)	5/2	−1.11	2.66(7)	−1.14	2.50(7)	B
4633.164	327	(e)	3/2	21 904	(o)	3/2	−1.77	6.01(6)	−1.75	6.20(6)	C
4642.228	3053	(e)	11/2	24 588	(o)	11/2	−0.66	7.50(7)	−0.52	1.03(8)	A

Table 4. (Continued.)

λ[a]	Lower level[b]			Upper level[b]			log gf HFR[c]	gA HFR[c]	log gf NORM[d]	gA NORM[d]	Note[e]
4655.114	3910	(e)	13/2	25385	(o)	11/2	−1.76	5.73(6)	−1.64	7.50(6)	C
4674.593	1489	(e)	7/2	22875	(o)	7/2	−0.67	7.23(7)	−0.73	6.36(7)	B
4676.902	327	(e)	3/2	21702	(o)	3/2	−0.89	4.31(7)	−0.94	3.91(7)	B
4714.612	3053	(e)	11/2	24257	(o)	9/2	−1.34	1.41(7)	−1.34	1.43(7)	B
4745.681	838	(e)	5/2	21904	(o)	3/2	−1.05	2.96(7)	−1.04	3.06(7)	B
4774.139	1489	(e)	7/2	22429	(o)	5/2	−1.03	3.04(7)	−1.05	2.86(7)	B
4791.580	838	(e)	5/2	21702	(o)	3/2	−1.82	4.88(6)	−1.86	4.43(6)	C
4816.016	3499	(e)	7/2	24257	(o)	9/2	−1.61	7.41(6)	−1.60	7.50(6)	C
4834.618	3910	(e)	13/2	24588	(o)	11/2	−1.79	5.12(6)	−1.65	7.02(6)	C
4844.209	2238	(e)	9/2	22875	(o)	7/2	−1.58	8.25(6)	−1.64	7.26(6)	C
4948.631	4386	(e)	9/2	24588	(o)	11/2	−1.70	5.98(6)	−1.56	8.20(6)	C
4952.370	2689	(e)	5/2	22875	(o)	7/2	−1.75	5.39(6)	−1.80	4.74(6)	C
4979.916	7135	(e)	3/2	27210	(o)	1/2	−1.84	4.30(6)	−1.97	3.15(6)	C
5016.605	7135	(e)	3/2	27063	(o)	3/2	−1.81	4.92(6)	−1.78	5.24(6)	C
5090.104	7525	(e)	5/2	27165	(o)	5/2	−1.62	7.35(6)	−1.58	8.09(6)	C
5112.294	7135	(e)	3/2	26690	(o)	1/2	−1.38	1.28(7)	−1.55	8.72(6)	C
5116.690	7525	(e)	5/2	27063	(o)	3/2	−1.22	1.83(7)	−1.20	1.95(7)	B
5196.412	8046	(e)	7/2	27285	(o)	5/2	−1.99	2.88(6)	−1.99	2.88(6)	C
5281.522	8046	(e)	7/2	26975	(o)	5/2	−1.88	3.45(6)	−1.92	3.18(6)	C
5738.389	9407	(e)	11/2	26828	(o)	11/2	−1.81	3.65(6)	−1.88	3.07(6)	C
5784.261	10181	(e)	7/2	27464	(o)	7/2	−1.52	6.21(6)	−1.49	6.66(6)	C
5898.801	9410	(e)	5/2	26358	(o)	5/2	−1.67	4.39(6)	−1.59	5.31(6)	C
5913.890	7525	(e)	5/2	24430	(o)	3/2	−1.78	3.99(6)	−1.70	4.76(6)	C
6017.386	10214	(e)	13/2	26828	(o)	11/2	−1.35	9.50(6)	−1.43	7.98(6)	C
6021.739	11094	(e)	15/2	27696	(o)	13/2	−1.22	1.32(7)	−1.31	1.07(7)	B
6025.732	10873	(e)	5/2	27464	(o)	7/2	−1.66	4.19(6)	−1.63	4.49(6)	C
6042.522	10519	(e)	3/2	27063	(o)	3/2	−1.58	6.04(6)	−1.55	6.44(6)	C
6057.445	10960	(e)	9/2	27464	(o)	7/2	−1.58	4.95(6)	−1.55	5.31(6)	C
6125.793	10743	(e)	1/2	27063	(o)	3/2	−1.78	3.71(6)	−1.75	3.95(6)	C
6126.210	10372	(e)	1/2	26690	(o)	1/2	−1.65	5.07(6)	−1.81	3.45(6)	C
6156.921	11047	(e)	3/2	27285	(o)	5/2	−1.72	3.64(6)	−1.72	3.64(6)	C
6174.943	10873	(e)	5/2	27063	(o)	3/2	−1.48	7.30(6)	−1.45	7.78(6)	C
6179.829	10181	(e)	7/2	26358	(o)	5/2	−1.40	7.42(6)	−1.32	8.97(6)	C
6181.893	10519	(e)	3/2	26690	(o)	1/2	−1.69	4.55(6)	−1.85	3.10(6)	C
6221.519	11395	(e)	7/2	27464	(o)	7/2	−1.50	5.65(6)	−1.47	6.06(6)	C
6256.589	9407	(e)	11/2	25385	(o)	11/2	−1.70	3.70(6)	−1.59	4.84(6)	C
6284.103	8679	(e)	9/2	24588	(o)	11/2	−1.36	8.51(6)	−1.22	1.17(7)	B
6285.628	11791	(e)	11/2	27696	(o)	13/2	−1.54	5.81(6)	−1.64	4.71(6)	C
6291.807	11395	(e)	7/2	27285	(o)	5/2	−1.92	2.39(6)	−1.92	2.39(6)	C
6311.625	10519	(e)	3/2	26358	(o)	5/2	−1.94	2.10(6)	−1.86	2.54(6)	C
6325.603	11660	(e)	5/2	27464	(o)	7/2	−1.61	4.31(6)	−1.58	4.62(6)	C
6386.937	7525	(e)	5/2	23177	(o)	3/2	−1.49	6.31(6)	−1.44	7.02(6)	C
6417.478	8679	(e)	9/2	24257	(o)	9/2	−1.05	1.52(7)	−1.05	1.54(7)	B
6455.624	11799	(e)	5/2	27285	(o)	5/2	−1.15	1.20(7)	−1.15	1.20(7)	B
6456.245	10873	(e)	5/2	26358	(o)	5/2	−1.66	3.84(6)	−1.58	4.64(6)	C
6483.700	12045	(e)	9/2	27464	(o)	7/2	−1.18	1.09(7)	−1.15	1.17(7)	B
6563.373	12232	(e)	7/2	27464	(o)	7/2	−1.72	3.08(6)	−1.69	3.30(6)	C
6576.006	11155	(e)	3/2	26358	(o)	5/2	−1.97	1.82(6)	−1.89	2.20(6)	C
6585.202	9407	(e)	11/2	24588	(o)	11/2	−1.77	2.96(6)	−1.64	4.06(6)	C
6587.502	11799	(e)	5/2	26975	(o)	5/2	−1.82	2.33(6)	−1.85	2.15(6)	C
6589.712	10214	(e)	13/2	25385	(o)	11/2	−1.02	1.59(7)	−0.91	2.08(7)	B
6648.320	11791	(e)	11/2	26828	(o)	11/2	−1.57	4.75(6)	−1.65	3.99(6)	C

Table 4. (Continued.)

λ[a]	Lower level[b]			Upper level[b]			log gf HFR[c]	gA HFR[c]	log gf NORM[d]	gA NORM[d]	Note[e]
6656.164	9 410	(e)	5/2	24 430	(o)	3/2	−1.35	8.54(6)	−1.27	1.02(7)	B
6681.530	11 395	(e)	7/2	26 358	(o)	5/2	−1.33	7.66(6)	−1.25	9.26(6)	C
6707.473	7 525	(e)	5/2	22 429	(o)	5/2	−1.88	2.26(6)	−1.91	2.13(6)	C
6731.813	9 407	(e)	11/2	24 257	(o)	9/2	−0.85	2.21(7)	−0.84	2.24(7)	B
6741.495	8 046	(e)	7/2	22 875	(o)	7/2	−0.99	1.72(7)	−1.05	1.51(7)	B
6862.810	7 135	(e)	3/2	21 702	(o)	3/2	−1.34	7.50(6)	−1.38	6.80(6)	C
6930.401	10 960	(e)	9/2	25 385	(o)	11/2	−1.48	5.03(6)	−1.36	6.59(6)	C
6950.498	8 046	(e)	7/2	22 429	(o)	5/2	−1.59	4.14(6)	−1.61	3.89(6)	C
6955.271	10 214	(e)	13/2	24 588	(o)	11/2	−0.72	2.98(7)	−0.59	4.09(7)	B
6992.629	12 988	(e)	7/2	27 285	(o)	5/2	−1.80	2.22(6)	−1.80	2.22(6)	C
7025.736	13 467	(e)	11/2	27 696	(o)	13/2	−1.67	3.55(6)	−1.76	2.88(6)	C
7042.206	8 679	(e)	9/2	22 875	(o)	7/2	−0.69	3.19(7)	−0.74	2.81(7)	B
7051.500	7 525	(e)	5/2	21 702	(o)	3/2	−0.92	1.86(7)	−0.96	1.69(7)	B
7121.315	12 790	(e)	11/2	26 828	(o)	11/2	−1.70	3.09(6)	−1.78	2.60(6)	C
7186.565	10 519	(e)	3/2	24 430	(o)	3/2	−1.91	2.11(6)	−1.83	2.52(6)	C
7344.754	14 085	(e)	13/2	27 696	(o)	13/2	−1.12	1.15(7)	−1.22	9.32(6)	C
7353.993	11 791	(e)	11/2	25 385	(o)	11/2	−1.53	4.03(6)	−1.41	5.28(6)	C
7374.656	10 873	(e)	5/2	24 430	(o)	3/2	−1.43	6.11(6)	−1.35	7.29(6)	C
7494.081	12 045	(e)	9/2	25 385	(o)	11/2	−1.83	1.96(6)	−1.71	2.57(6)	C
7560.047	13 605	(e)	13/2	26 828	(o)	11/2	−1.37	5.93(6)	−1.45	4.98(6)	C
7578.099	14 504	(e)	15/2	27 696	(o)	13/2	−0.84	2.07(7)	−0.94	1.68(7)	B
7678.679	9 410	(e)	5/2	22 429	(o)	5/2	−1.96	1.42(6)	−1.99	1.34(6)	C
7863.621	14 115	(e)	9/2	26 828	(o)	11/2	−1.94	1.27(6)	−2.02	1.07(6)	C
7923.804	14 668	(e)	7/2	27 285	(o)	5/2	−1.78	2.01(6)	−1.78	2.01(6)	C
7969.899	12 842	(e)	9/2	25 385	(o)	11/2	−1.83	1.74(6)	−1.71	2.28(6)	C
7999.470	14 668	(e)	7/2	27 165	(o)	5/2	−1.96	1.36(6)	−1.92	1.50(6)	C
8001.564	9 410	(e)	5/2	21 904	(o)	3/2	−1.66	2.72(6)	−1.64	2.81(6)	C
8123.415	14 668	(e)	7/2	26 975	(o)	5/2	−1.84	1.54(6)	−1.88	1.42(6)	C
8125.078	10 873	(e)	5/2	23 177	(o)	3/2	−2.00	1.25(6)	−1.95	1.39(6)	C
8161.828	10 181	(e)	7/2	22 429	(o)	5/2	−1.73	2.17(6)	−1.76	2.04(6)	C
8180.220	15 243	(e)	9/2	27 464	(o)	7/2	−1.79	1.54(6)	−1.76	1.65(6)	C
8186.282	12 045	(e)	9/2	24 257	(o)	9/2	−1.32	5.06(6)	−1.32	5.12(6)	C
8313.702	12 232	(e)	7/2	24 257	(o)	9/2	−1.09	8.47(6)	−1.08	8.58(6)	C
8387.759	13 467	(e)	11/2	25 385	(o)	11/2	−1.03	1.00(7)	−0.91	1.31(7)	B
8473.548	12 790	(e)	11/2	24 588	(o)	11/2	−1.51	3.35(6)	−1.38	4.59(6)	C
8486.013	13 605	(e)	13/2	25 385	(o)	11/2	−0.73	1.92(7)	−0.61	2.51(7)	B
8510.908	12 842	(e)	9/2	24 588	(o)	11/2	−1.20	6.97(6)	−1.06	9.56(6)	C
8552.014	14 668	(e)	7/2	26 358	(o)	5/2	−1.70	1.86(6)	−1.62	2.25(6)	C
8650.995	10 873	(e)	5/2	22 429	(o)	5/2	−1.35	4.84(6)	−1.37	4.55(6)	C
8708.402	11 395	(e)	7/2	22 875	(o)	7/2	−1.49	3.42(6)	−1.55	3.01(6)	C
8717.856	12 790	(e)	11/2	24 257	(o)	9/2	−1.71	1.83(6)	−1.70	1.85(6)	C
8757.407	12 842	(e)	9/2	24 257	(o)	9/2	−1.48	3.11(6)	−1.47	3.15(6)	C
8780.597	10 519	(e)	3/2	21 904	(o)	3/2	−1.38	4.45(6)	−1.37	4.59(6)	C
8867.382	11 155	(e)	3/2	22 429	(o)	5/2	−1.16	7.06(6)	−1.19	6.64(6)	C
8913.697	11 660	(e)	5/2	22 875	(o)	7/2	−1.57	2.71(6)	−1.63	2.38(6)	C
8920.593	16 078	(e)	3/2	27 285	(o)	5/2	−1.87	1.25(6)	−1.87	1.25(6)	C
8957.536	10 743	(e)	1/2	21 904	(o)	3/2	−1.37	4.40(6)	−1.36	4.54(6)	C
8980.348	16 078	(e)	3/2	27 210	(o)	1/2	−1.88	1.10(6)	−2.02	8.05(5)	C
8989.125	13 467	(e)	11/2	24 588	(o)	11/2	−1.40	3.91(6)	−1.26	5.36(6)	C
9022.419	16 616	(e)	13/2	27 696	(o)	13/2	−1.64	2.26(6)	−1.73	1.83(6)	C
9060.335	11 395	(e)	7/2	22 429	(o)	5/2	−1.33	4.55(6)	−1.36	4.28(6)	C
9063.021	10 873	(e)	5/2	21 904	(o)	3/2	−1.39	4.09(6)	−1.38	4.22(6)	C

Table 4. (Continued.)

λ[a]	Lower level[b]			Upper level[b]			log gf HFR[c]	gA HFR[c]	log gf NORM[d]	gA NORM[d]	Note[e]
9102.067	13 605	(e)	13/2	24 588	(o)	11/2	−1.75	1.69(6)	−1.61	2.32(6)	C
9145.993	15 898	(e)	11/2	26 828	(o)	11/2	−1.70	1.83(6)	−1.78	1.54(6)	C
9231.904	10 873	(e)	5/2	21 702	(o)	3/2	−1.60	2.37(6)	−1.64	2.15(6)	C
9282.771	11 660	(e)	5/2	22 429	(o)	5/2	−1.70	1.86(6)	−1.73	1.75(6)	C
9702.242	17 392	(e)	15/2	27 696	(o)	13/2	−0.19	5.61(7)	−0.28	4.55(7)	B
9725.536	17 005	(e)	7/2	27 285	(o)	5/2	−1.36	3.38(6)	−1.36	3.38(6)	C
9788.959	16 616	(e)	13/2	26 828	(o)	11/2	−0.45	2.89(7)	−0.52	2.43(7)	B
9844.162	17 055	(e)	1/2	27 210	(o)	1/2	−1.49	2.75(6)	−1.63	2.01(6)	C

[a] Wavelengths in air are deduced from experimental energies compiled by Martin *et al* (1978).
[b] Each level is represented by its experimental value, its parity ((o) for odd and (e) for even) and its J-value as compiled in the NIST tables (Martin *et al* 1978).
[c] Computed using the HFR model (see text).
[d] HFR values normalized using the radiative lifetimes measured in the present work.
[e] The letters A, B and C represent estimated uncertainties of 10%, 30% and 50%, respectively, on the normalized gf- and gA-values.

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