Eur. Phys. J. D **7**, 499–502 (1999)

THE EUROPEAN PHYSICAL JOURNAL D

EDP Sciences


# Experimental investigations of oscillator strengths for ultraviolet transitions in LaII

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Received 10 February 1999 and Received in final form 22 April 1999

**Abstract.** $f$-values for ultraviolet transitions from nine excited levels in LaII have been deduced by a combination of lifetime and branching ratio measurements using time-resolved laser spectroscopy and the emission spectrum from a hollow cathode lamp. Part of the present results is compared with previous results.

**PACS.** 32.70.-n Intensities and shapes of atomic spectral lines

## 1 Introduction

The interest in oscillator strengths of rare earth elements is due primarily to their importance in astrophysical investigations, such as abundance determination of rare earth elements in the sun and a class of peculiar stars; the origin of the sun and other stars and testing the theories of nuclear synthesis. In the last decade, a lot of work has been done concerning lifetime and oscillator strength measurements in rare earth elements [1,2]. For LaII, relatively little has been done experimentally since Corliss and Bozman [3]. Andersen *et al.* [4] determined the lifetimes of six levels of LaII in the region 24 000–39 100 cm$^{-1}$ using the beam-foil method. When their data were used by Grevess [5] for the analysis of solar LaII lines, it turned out that the value of the solar abundance of La depended upon the excitation potential of the upper level. The same author revised this situation using new equivalent widths and only lines for which the lifetimes were measured by Arnesen *et al.* [6] utilizing the beam-laser technique. Thevenin [7, 8] published astrophysical $gf$-values for some 50 LaII lines. Recently Bord *et al.* [9] reported their computed oscillator strength and transition probability values for 70 transitions of LaII using a Hartree-plus-statistical-exchange-interaction approximation to the standard Hartree-Fork procedure.

To revise and extend atomic data for astrophysical analysis, and also to test the theoretical computation, we report in the present paper experimental oscillator strengths of 46 LaII lines deduced from our branching ratio and lifetime measurements. Part of the results is compared with previous results.

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## 2 Experimental

### 2.1 Lifetime measurements

The experimental setup for lifetime measurements of LaII is described in detail elsewhere [10], here we only give a brief outline. The 8 ns pulses from a seeder injected and frequency doubled Nd:YAG laser (Continum NY-82) were compressed to 1 ns by a SBS (Stimulated Brillouin Scattering) compressor, and were used to pump a dye laser (Continum Nd-60) with DCM dye. The output of the dye laser was frequency doubled in KDT or BBO crystals to produce UV laser pulses with 1 ns duration. Free LaII ions were produced in a laser-induced plasma by another frequency doubled YAG laser, which was focused onto the surface of La metal.

Laser induced fluorescence decay from the selected upper levels was detected by a Hamamatsu 1564U microchannel-plate photo-multiplier (200 ps rise-time) and the data acquisition was performed by a digital transient recorder (Tek DSA 602) with 1 GHz bandwidth. A typical decay curve is shown in Figure 1. An average of 1000–4000 pulses was necessary for each curve depending on the signal-to-noise ratio. About 30 curves for each level have been recorded and the averaged lifetime value was adopted as the final results, which were listed in Table 1. The lifetime measurements have been performed to eliminate different effects, *e.g.* collision quenching, radiation trapping, magnetic quantum beats and flight-out of view. The uncertainties quoted in Table 1 encompass the statistical scattering obtained from different runs as well as an additional allowance of about 2% for possible systematical errors.

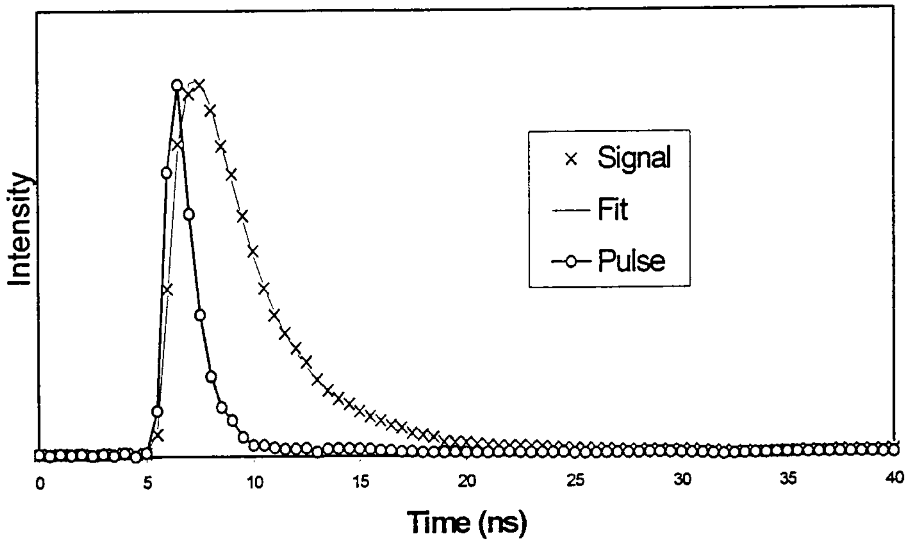


**Fig. 1.** Recording of a time-resolved fluorescence signal of the LaII $5d6px\,^3P_1$ level, the 2.6 ns laser pulse and a convolution fit of the laser pulse and single exponential decay curves induced during the pulse.

**Table 1.** Radiative lifetimes of LaII. $\tau_{\rm ref1}$ refers to the experimental results of both (b) Andersen *et al.* [4] and (a) Arnesen *et al.* [6]. $\tau_{\rm ref2}$ refers to the theoretical results of Bord *et al.* [9].

| Level (cm$^{-1}$) | $\tau_{\rm this\ work}$ (ns) | $\tau_{\rm ref1}^{4,6}$ (ns) | $\tau_{\rm ref2}^{9}$ (ns) |
|---|---|---|---|
| 22 537.30 | 65.(5) | 67.8(1.7)$_{\rm a}$ | 40.0 |
| 24 462.66 | 6.7(4) | 8.3(8)$_{\rm b}$ | 3.23 |
| 26 414.01 | 5.8(2) | 5.2(8)$_{\rm b}$ | 3.50 |
| 26 837.66 | 5.8(3) | 5.1(8)$_{\rm b}$ | 3.24 |
| 27 388.11 | 4.4(2) | | |
| 28 315.25 | 4.0(2) | 5.3(8)$_{\rm b}$ | 2.70 |
| 28 565.40 | 5.1(3) | 6.0(10)$_{\rm b}$ | 3.17 |
| 30 353.33 | 12.4(5) | | |
| 32 160.99 | 2.6(2) | | |
| 32 201.05 | 3.9(2) | | |
| 33 204.41 | 2.6(2) | | |

### 2.2 Branching ratio measurements

Branching ratios were measured from spectra recorded with a 1010-MPT monochromator with a spectral resolution of 0.001 nm. The source of the spectra was a hollow cathode discharge lamp, in which the cathode cavity was fashioned La powder. The scanning of the monochromator was controlled by a computer and the spectra data was stored in a computer file. As a test of self-absorption in the source, three spectral were recorded at different power levels, and all branching ratios were measured from each of the three spectra. No significant absorption was observed for the used LaII transitions.

The area under the line profile was integrated with a computer code to obtain the observed line intensity $A(\lambda)$. The relative line intensity is then given by $I(\lambda) = A(\lambda)/E(\lambda)$, where $E(\lambda)$ is the spectral response of the detection system which was measured using a standard lamp calibrated in the Changchun Institute of Optics and Fine Mechanics in China.

The branching ratio $BR(\lambda_1)$ for the transition $\lambda_1$ is then $BR(\lambda_1) = I(\lambda_1)/\sum I(\lambda_i)$, where the sum in the denominator includes all transitions from the same upper level. We have used the data of LaII energy levels given by Martin *et al.* [11] to calculate the wavelengths of electric dipole allowed transitions and identify lines in our recorded spectra. The intensities of most of LaII Lines, as measured with the hollow cathode lamp, were sufficiently high that the photon shot noise of the measurement was very small, and its effect on the final uncertainties in the branching ratio could be neglected. Infrared transitions which contribute to the uncertainties in usual branching ratio measurements were not involved for the present investigated levels. The main contribution to the uncertainty of the measured branching ratios came from two effects. One is the long-time intensity drift of the lamp, which caused less than 0.5% uncertainty; the other one is the intensity calibration of the spectral response of the detection system, which caused less than 1% uncertainty.

### 2.3 Oscillator strengths

From our measured lifetime and branching ratio values, the oscillator strengths ($f$) of LaII were deduced. The results together with branching ratio are listed in Table 2.

## 3 Comparison and discussion

Our measured lifetimes of LaII five of which are first reported are listed in Table 1 and compared with previous results. Three lifetimes measured by Andersen *et al.* are longer than ours. This may be caused by cascading effects in the beam-foil method. The lifetime value of the $5f5dz\,^3D^0$ level (22 537.30 cm$^{-1}$) is in agreement with the value measured by Arnesen using the beam-laser technique. The lifetime values computed by Bord *et al.*

**Table 2.** Branching ratios ($BR_{ki}$) and oscillator strengths ($gf$) in LaII.

| $E_k$ (cm$^{-1}$) | $E_i$ (cm$^{-1}$) | $\lambda_{ki}$ (nm) | $BR_{ki}$ | $g_kA_{ki}$ ($10^8$/s) | $g_if_{ik}$ | ln ($gf$) (this work) | ln ($gf$) [9] (Bord's) |
|---|---|---|---|---|---|---|---|
| 26 414.01 | 0.00 | 378.481 | 0.005(1) | 0.439(5) | 0.009(1) | −2.02(2) | |
| | 1016.10 | 393.622 | 0.023(1) | 1.94(2) | 0.045(2) | −1.34(2) | |
| | 1394.46 | 399.575 | 0.383(3) | 32.9(3) | 0.78(3) | −0.10(2) | |
| | 1895.15 | 407.735 | 0.353(3) | 30.4(3) | 0.75(3) | −0.12(2) | |
| | 2591.60 | 419.655 | 0.237(2) | 20.4(2) | 0.53(2) | −0.26(2) | |
| 26 837.66 | 0.00 | 372.505 | 0.005(1) | 0.556(5) | 0.012(1) | −1.93(3) | −1.439 |
| | 1016.10 | 387.164 | 0.247(2) | 29.8(3) | 0.67(4) | −0.17(3) | −0.016 |
| | 1394.46 | 392.922 | 0.142(1) | 17.1(2) | 0.39(2) | −0.40(3) | |
| | 2591.60 | 412.323 | 0.422(4) | 50.8(5) | 1.29(8) | 0.11(3) | 0.158 |
| | 3250.35 | 423.838 | 0.183(2) | 22.0(2) | 0.59(3) | −0.22(3) | −0.085 |
| | 6227.42 | 485.058 | 0.002(1) | 0.272(3) | 0.010(1) | −2.01(3) | −1.289 |
| 27 388.11 | 0.00 | 365.018 | 0.029(1) | 3.35(3) | 0.067(4) | −1.17(2) | −1.009 |
| | 1016.10 | 379.083 | 0.438(4) | 49.7(5) | 1.07(6) | 0.03(2) | 0.143 |
| | 1895.15 | 392.154 | 0.120(1) | 13.6(1) | 0.31(2) | −0.50(2) | −0.251 |
| | 2591.60 | 403.169 | 0.290(3) | 32.9(3) | 0.80(4) | −0.09(2) | −0.133 |
| | 3250.35 | 414.174 | 0.074(1) | 8.43(8) | 0.21(1) | −0.66(2) | −0.465 |
| | 5718.12 | 461.339 | 0.049(1) | 5.52(5) | 0.176(9) | −0.75(2) | −0.467 |
| 28 315.25 | 1016.10 | 366.208 | 0.052(1) | 9.08(9) | 0.183(6) | −0.73(2) | |
| | 1394.46 | 371.354 | 0.051(1) | 8.94(9) | 0.185(6) | −0.73(2) | |
| | 1970.70 | 379.478 | 0.374(4) | 65.3(7) | 1.41(5) | 0.14(2) | 0.318 |
| | 2591.60 | 388.637 | 0.123(1) | 21.4(2) | 0.48(2) | −0.31(2) | −0.135 |
| | 3250.35 | 398.852 | 0.359(4) | 62.8(6) | 1.49(5) | 0.17(2) | 0.244 |
| | 6227.42 | 452.612 | 0.041(1) | 7.25(7) | 0.223(8) | −0.65(2) | −0.350 |
| 28 565.40 | 1016.10 | 362.883 | 0.025(1) | 4.34(5) | 0.086(6) | −1.06(3) | −1.070 |
| | 1970.70 | 375.908 | 0.235(2) | 41.5(4) | 0.88(6) | −0.05(3) | 0.087 |
| | 3250.35 | 394.910 | 0.740(7) | 130.(1) | 3.0(2) | 0.48(3) | 0.615 |
| 30 353.33 | 1394.46 | 345.218 | 0.162(2) | 3.91(4) | 0.070(4) | −1.15(2) | |
| | 1895.15 | 351.293 | 0.112(1) | 2.72(3) | 0.050(3) | −1.29(2) | |
| | 2591.60 | 360.106 | 0.223(2) | 5.39(5) | 0.105(5) | −0.97(2) | |
| | 10094.9 | 493.483 | 0.503(5) | 12.1(1) | 0.44(2) | −0.35(2) | |
| 32 160.99 | 1394.46 | 324.935 | 0.034(1) | 3.90(4) | 0.062(5) | −1.20(4) | |
| | 1895.15 | 330.311 | 0.066(1) | 7.63(8) | 0.12(1) | −0.90(4) | |
| | 2591.60 | 338.091 | 0.856(9) | 98.7(9) | 1.6(1) | 0.22(4) | |
| | 5249.70 | 371.487 | 0.010(1) | 1.11(1) | 0.023(2) | −1.63(4) | |
| | 5718.12 | 378.067 | 0.022(1) | 2.49(2) | 0.054(5) | −1.27(4) | |
| | 6227.42 | 385.491 | 0.012(1) | 1.44(1) | 0.032(3) | −1.49(4) | |
| 32 201.05 | 1394.46 | 324.513 | 0.117(1) | 20.9(2) | 0.33(2) | −0.48(3) | |
| | 2591.60 | 337.633 | 0.050(1) | 9.00(9) | 0.154(9) | −0.81(3) | |
| | 3250.35 | 345.317 | 0.045(1) | 8.10(8) | 0.145(9) | −0.83(3) | |
| | 7473.32 | 404.291 | 0.492(5) | 88.2(9) | 2.1(1) | 0.33(3) | 0.490 |
| | 10094.9 | 452.237 | 0.296(3) | 53.1(5) | 1.63(9) | 0.21(3) | |
| 33 204.41 | 1394.46 | 314.276 | 0.008(1) | 1.54(1) | 0.023(2) | −1.64(4) | |
| | 1895.15 | 319.302 | 0.011(1) | 2.09(2) | 0.032(3) | −1.49(4) | |
| | 2591.60 | 326.567 | 0.135(1) | 25.8(3) | 0.41(3) | −0.38(4) | |
| | 3250.35 | 333.749 | 0.739(7) | 142.(1) | 2.3(2) | 0.37(4) | |
| | 5718.12 | 363.715 | 0.016(1) | 2.98(3) | 0.059(5) | −1.22(4) | |
| | 6227.42 | 370.582 | 0.092(1) | 17.6(2) | 0.36(3) | −0.44(4) | |

are systematically shorter than the measured values. This discrepancy has been partly attributed by the others to their incomplete treatment of core polarization effects.

The uncertainties assigned to the $\ln(gf)$ values have been evaluated from the uncertainties in the measured lifetimes and branching ratios. Some $\ln(gf)$ values measured in the present work are compared with computed values by Bord *et al.* in Table 2. Bord's values are systematically larger than ours. To find the reason for the discrepancy, we calculated the branching ratio for these transitions using Bord's lifetimes and $gf$ values. We found that our branching ratios are in agreement with theirs, which means that their short lifetimes caused their larger $\ln(gf)$ values.

The lifetime measurements were performed in the VUV system laboratory of the Lund Laser Center in Sweden. We thank Prof. S. Svanberg for his support and valuable discussions. This work was financially supported by the National Science Foundation of China.

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