Journal of Quantitative Spectroscopy & Radiative Transfer 179 (2016) 33–39

Contents lists available at ScienceDirect

Journal of Quantitative Spectroscopy & Radiative Transfer

journal homepage: www.elsevier.com/locate/jqsrt

Studies of Landé g_J-factors of singly ionized lanthanum by laser-induced fluorescence spectroscopy

S. Werbowy [a,c,*], C. Güney [b,c], L. Windholz [c]

[a] Institute of Experimental Physics, University of Gdansk, ul. Wita Stwosza 57, PL-80-952 Gdansk, Poland
[b] Physics Department, Faculty of Science, Istanbul University, Vezneciler, Tr-34134 Istanbul, Turkey
[c] Institut für Experimentalphysik, Technische Universität Graz, Petersgasse 16, A-8010 Graz, Austria

ARTICLE INFO

Article history:
Received 1 February 2016
Received in revised form
3 March 2016
Accepted 3 March 2016
Available online 17 March 2016

Keywords:
Zeeman effect
Landé factors
Rare-earth metals

ABSTRACT

Laser-induced fluorescence spectroscopy, using a cooled hollow cathode discharge lamp as source of ions, was used to observe the Zeeman splitting of 18 lines of La II in the wavelength range 629.6–680.9 nm, in external intermediate magnetic fields up to 800 G. The recorded hyperfine-Zeeman patterns were analyzed in detail using already known accurate hyperfine structure A- and B-constants. From the recordings the Landé g_J-factors for some levels belonging to the $5d^2$, 5d6s, 5d6p, 4f5d, 4f6s and 4f6p configurations of La II were determined. The obtained experimental g_J-factors are compared with earlier measurements and theoretical calculations.

1. Introduction

Lanthanum (Z=57) is a rare earth metal opening the entire lanthanides group. Lanthanum has a very complex spectrum including the neutral atom and its ions. Lanthanum occurs in the form of two stable isotopes: ^{139}La ($>99.9\%$) and ^{138}La. Both isotopes show hyperfine (hf) structure with nuclear spin quantum number $I=7/2$ for ^{139}La and $I=5$ for ^{138}La. Since the abundance of ^{138}La in the natural isotope mixture is very low, practically all spectroscopic results belong to the isotope ^{139}La.

One of the first large scale studies of the La spectrum was reported in [1,2]. With the use of classical spectroscopy, hundreds of lines of La I–III were classified and level designations were given. A short review on the literature status of La spectra before year 1976 can be found in [3]. One can notice that an interest in experimental studies of the Zeeman effect of lanthanum spectral lines suddenly disappeared in the late 1970s [3], although in the NIST compilation all La II g_J values steam from an even earlier period, i.e. from 1945 [4]. After that date, its hard to find any reports on Landé g_J-factors of lanthanum levels. One reason could be the growth of interest in measuring more subtile interactions, i.e. the isotope shifts between various (artificial) La isotopes [5] or the hyperfine structure. In the 1980s, narrow band tunable lasers became standard equipments in spectroscopic laboratories. Then high resolution spectroscopy allowed more precise studies of hyperfine interactions. Systematic experimental studies of fine and hyperfine structure of lanthanum are carried out for many years, also at Graz University of Technology, where many new levels were discovered [6–8]. However, studies of the Zeeman effect in La II have not been continued for many decades and experimental Landé factors present in the literature have been determined long time ago in 1945 [4].

A rich and dense hyperfine resolved spectrum makes it extremely difficult to interpret properly the observed Zeeman structure and to obtain accurate Landé g_J-factors.

* Corresponding author at: Institute of Experimental Physics, University of Gdansk, ul. Wita Stwosza 57, PL-80-952 Gdansk.
E-mail addresses: s.werbowy@ug.edu.pl (S. Werbowy), windholz@tugraz.at (L. Windholz).

http://dx.doi.org/10.1016/j.jqsrt.2016.03.009
0022-4073/

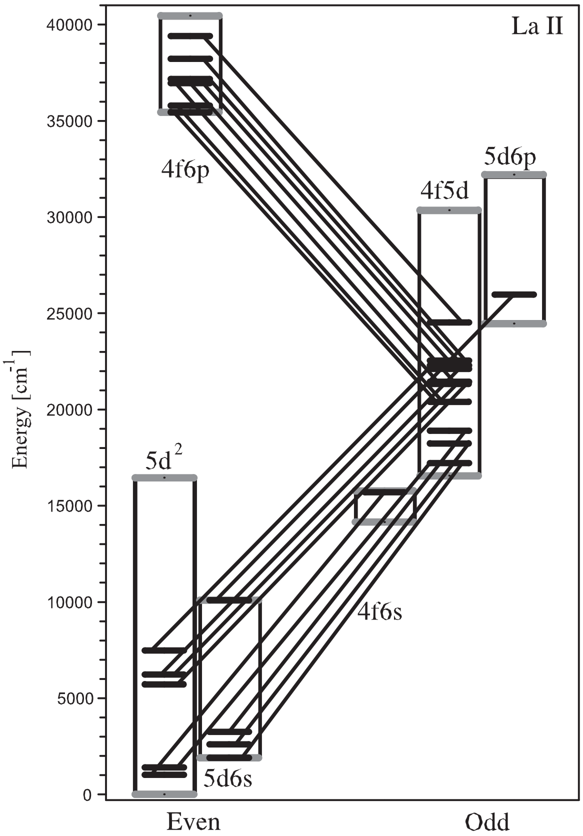

Fig. 1. Most important electronic configurations of the lanthanum ion. Horizontal lines indicate the investigated La II levels. The transitions excited in the present study are indicated by lines connecting the levels.

For studies of the electronic level structure of rare earth elements for many years very successful laser-induced fluorescence spectroscopy was used. As source of free atoms usually a hollow cathode discharge lamp, cooled by means of liquid nitrogen, was used. In such source not only atoms and ions in their ground state, but also in highly excited states are present, allowing selective laser excitation of nearly any desired energy level. Using this technique, many accurate experimental data have been gained, and a huge number of new energy levels of La, Pr, etc. were found. Although the spectral resolution of the hollow cathode technique is Doppler limited (line widths of the order of hundreds of MHz), the hollow cathode is more versatile and convenient than the Doppler-free fast ion beam laser spectroscopy methods [9,10] where line widths almost as narrow as the natural line widths can be achieved. Despite the lower resolution the hollow cathode can give access to much more levels to be investigated.

The purpose of this study is to re-investigate the Zeeman effect of some La II lines using laser excitation and selecting the laser induced fluorescence of the upper level in a cooled hollow cathode ion source. A motivation to perform the present work was also to verify the recently published theoretical calculations of the Landé factors by a multiconfiguration Hartree–Fock method within the framework of the Breit–Pauli Hamiltonian (MCHF+BP) and the relativistic Hartree–Fock (HFR) method [11]. In order to get accurate Landé factors for the interpretation of the recorded hf-Zeeman patterns we have used most accurate hyperfine structure constants. Fig. 1 shows the most important configurations of single ionized lanthanum. The investigated levels and the used transitions are also entered. From the investigated transitions, we have obtained accurate Landé factors for 27 even and odd levels of La II. We can infer the quality of the earlier data (determined over 70 years ago) from comparison with our results.

Recently, we have reported on Zeeman effect studies of some new levels in the La I and Pr I spectra using a modified hollow cathode source with laser excitation [12], showing the need for further studies of the Zeeman effect in the lanthanide series of elements. In the present paper we would like to demonstrate that as in the case of neutral atoms the application of the magnetic field to the hollow cathode has no negative effect on the discharge conditions and the quality of the obtained data for La II ionic species.

The newly determined accurate experimental Landé factors could find applications in many scientific areas, i.e. astrophysics or plasma diagnostic, where magnetic fields are present. These data are also helpful in interpretation of electronic properties of La II energy levels, which are involved in the creation of chemical bonds. The particular features of lanthanide ions, implanted in crystal lattice, make them ideal for applications in solid state lasers.

2. Experiment and computer analysis

A detailed description of the experimental apparatus has been given previously [13]. Lanthanum ions were produced by a sputtering process through a discharge from a lanthanum cathode. Low pressure Ar buffer gas was used to provide best discharge conditions.

The source was cooled down by liquid nitrogen to reduce the Doppler line broadening down to some hundreds of MHz and to increase the sputtering efficiency. The

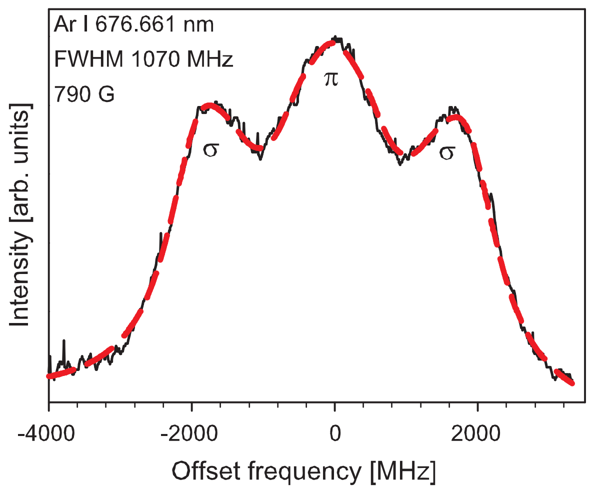

Fig. 2. Recorded hf-Zeeman pattern of the 676.661 nm Argon line used for the magnetic field calibration. Spectral line width is 1070 MHz FWHM. The classification data of this Argon line is given at the end of Section 2.