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Laser spectroscopic investigation of isotope shifts in Nd II lines

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Abstract

The isotope shift of 11 optical transitions in Nd II in the spectral range 420–450 nm have been recorded (in all cases but one for all pairs of even Nd isotopes). For all observed transitions the values of the field shifts, the specific mass shifts and $\Delta|\psi(0)|^2$ have been evaluated. Using our new data, combined with data reported in earlier papers, term isotope shifts for all pairs of even Nd isotopes have been determined for 27 energy levels and for the configurations: $4f^46s$, $4f^45d$, $4f^35d6s$ and $4f^46p$ as well. It is shown that configuration assignment of a level on the basis of term shift values only is in some cases not satisfactory (as e.g. of the level at 22,696 cm^{-1}) and obviously additional information is required.

Keywords: Neodymium ion; Isotope shift; Laser spectroscopy

1. Introduction

The investigation of isotope shift (IS) and hyperfine structure (HFS) in atomic spectra is an important tool to improve our precise knowledge of the designation of fine structure levels and the classification of new lines (see e.g. [1,2]), the structure of the nucleus, such as charge radius and distribution and also of the magnetic moment (and its distribution within the nucleus in cases of hyperfine anomalies). The complex structure of the spectral lines of the neodymium ion is caused by four factors: a large number of isotopes, small values of the IS, often very small HFS splittings for the odd isotopes and partially overlap of the HFS with the stronger components of the even isotopes. Investigations of the HFS are only possible with high-resolution methods (see e.g. [3]).

In Nd II IS of all even isotopes and HFS results for transitions starting from low-lying, thermally populated, levels can be found in the literature for 34 lines [2–9]. For these investigations well known laser spectroscopic methods at high resolution could be used. But for transitions starting from the higher levels, which are not accessible by usual laser spectroscopy, only one line has been investigated so far at high resolution [2]. Attempts were made using fast beam laser spectroscopy of the neodymium ion to investigate lines starting from metastable levels, but they failed [10]. This paper presents our IS results between all even isotopes for 11 transitions. The HFS of the odd isotopes could not be resolved. The transitions start from levels lying between 513 and 14,090 cm^{-1}, their wavelengths lay between 420 and 450 nm (wavelengths in air). The method used was laser induced fluorescence (LIF) in a hollow cathode (HC) discharge. Neodymium samples with natural isotope abundance were used. The presence of the components belonging to all the isotopes in the same spectrum makes determination of the sign of isotope shift unequivocal, since all the observed components can be identified beyond any doubt on the basis of the observed relative intensities, corresponding to their relative abundance in the sample. Information about the structure of spectral lines, consisting of the components corresponding to all naturally occurring

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isotopes, can be very interesting for astronomers, especially in the case of elements abundant in the stars. This is one of the more important markers for the chemically peculiar (CP) stars [11,12].

The IS available in the literature and the IS results presented in this paper have been evaluated for individual energy levels with respect to the $4f^4 5d^6 K_{9/2}$ level at 6005 cm^{-1}, which has been chosen as reference level (see e.g. [1]).

2. Theoretical background

The theory of IS is well known and was thoroughly described e.g. in the monograph by King [13]. We limit therefore ourselves to the definitions and formulae which are used in this work.

Isotope shift is the small difference in the transition energy of electrons for different isotopes. It is the sum of three effects: normal mass shift (NMS), specific mass shift (SMS) and field shift (FS):

$$\mathrm{IS} = \mathrm{NMS} + \mathrm{SMS} + \mathrm{FS}. \tag{1}$$

The normal mass shift is given by the formula:

$$\mathrm{NMS}_{A_1,A_2} = \frac{1}{1822.9}\frac{A_1 - A_2}{A_1 A_2} v, \tag{2}$$

where A_1 and A_2 denote the mass numbers of the isotopes ($A_1 > A_2$) and v is the transition frequency.

The field shift can be written as follows:

$$\begin{aligned}\mathrm{FS}_{A_1,A_2} &= -\pi\Delta|\psi(0)|^2 \frac{a_0^3}{Z} f(Z)\delta\langle r^2\rangle_{A_1,A_2} \\ &= F_i \delta\langle r^2\rangle_{A_1,A_2},\end{aligned} \tag{3}$$

with i: the transition, a_0: the Bohr radius, $\delta\langle r^2\rangle$: the change of the mean square charge radius between the isotopes and $f(Z)$: the relativistic correction factor (in the case of Nd II $f(60)$=17.13 GHz/fm^2 [14]). $\Delta|\psi(0)|^2$ is the difference of electron density at the nucleus between the lower and the upper level of the transition [13]. From the FS and $\Delta|\psi(0)|^2$ values conclusions can be drawn about the electronic states involved in the transition. This approach neglects the contributions of higher nuclear moments. They amount to about 4.4% for neodymium (see Fig. 6.3 in [15]).

The SMS effect describes the correlation of motion between the electrons in the electronic shells of the atom. This can not be as easily calculated as the NMS. It can, however, be determined from a King plot [13], when the FS is known.

Furthermore a so-called residual isotope shift (RIS) is used:

$$\mathrm{RIS} = \mathrm{IS} - \mathrm{NMS} = F_i \delta\langle r^2\rangle_{A_1,A_2} + M_i \frac{A_1 - A_2}{A_1 A_2} \tag{4}$$

In a King plot the RIS is used, multiplied by a modifying factor

$$\mu_{A_1,A_2} = \frac{(A_{s1} - A_{s2})}{(A_1 - A_2)} \frac{A_1 A_2}{A_{s1} A_{s2}} \tag{5}$$

where A_{s1} and A_{s2} are from an arbitrary chosen pair of isotopes, the standard isotope pair (in neodymium the isotopes 146 and 144). In the case that the $\delta\langle r^2\rangle$ values are known (from calculations or other experiments) the modified RIS (μRIS) are plotted versus modified $\delta\langle r^2\rangle$ for all investigated isotope pairs. Then the FS and the SMS values can easily be determined from a linear regression.

The value of the energy term isotope shift for a particular level ($^{A_1 A_2}\Delta T$) can easily be calculated from the IS of the line if the value ΔT for the other level involved in this transition is known, or when the other level is the reference level. The ΔT values are e.g. helpful for the determination of the dominant configuration of a particular level, but in the case of levels which show particularly strong configuration mixing they are not sufficient for the determination of the configuration of this level.

3. Experiment

In this work our investigations of the IS of the Nd II spectrum using the laser induced fluorescence method in a HC discharge are presented. The scheme of the experimental setup is shown in Fig. 1.

The Nd II target ions for LIF are produced in a HC. It consists of a copper cylinder with an axial bore. Neodymium is placed inside the cathode in the form of a rod (a sample with natural abundance of isotopes), with an axial bore of 7 mm diameter. The cathode is then screwed in the centre of a metal tube. On both sides of the HC two ring shaped aluminium anodes are mounted. The anodes are electrically insulated from the metal tube (and cathode) by ceramic pieces. The metal tube is sealed on both sides to glass tubes, which are closed with glass windows. All parts of the source are cooled by liquid nitrogen. The whole device is connected to a simple liquid nitrogen-cooled sorption pump, backed by a rotary vacuum pump. Ultimate pressure of this system is better than 10^{-4} mbar. The HC is filled with argon as a buffer gas at a pressure of 0.5 mbar. The discharge current used in the present experiment ranged from 10 to 100 mA.

The laser beam for the excitation of the ions was generated by a modified tunable ring dye laser (Coherent CR 699-21), operating with Stilbene 3 and optically pumped by an argon ion laser (Spectra Physics 2085-3.0). The value of the output power of the laser was limited by two factors: the position of the wavelength of the transition on the gain curve of the dye and the degree of degradation of the dye solution. The laser power used ranged from 10 to 100 mW. The laser beam, intensity-modulated at a frequency of ca.