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Lande g_J factors for even-parity electronic levels in the holmium atom

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ABSTRACT

In this work the hyperfine structure of the Zeeman splitting for 18 even-parity levels in the holmium atom was investigated. The experimental method applied was laser induced fluorescence in a hollow cathode discharge lamp. 20 spectral lines were investigated involving odd-parity levels from the ground multiplet, for which Lande g_J factors are known with high precision, as the lower levels; this greatly facilitated the evaluation of g_J factors for the upper levels. The g_J values for the even-parity levels considered are reported for the first time. They proved to compare fairly well with the values obtained recently in a semi-empirical analysis for the even-parity level system of Ho I.

1. Introduction

Holmium - an element located in the right-hand part of the lanthanides series - possesses only one stable isotope $^{165}_{67}$Ho, but nevertheless, due to its relatively high nuclear spin value $I = 7/2$ its hyperfine structure (*hfs*) is very rich. The first *hfs* investigations of holmium were performed with Fourier spectroscopy [1]; later the *hfs* constants were determined with very high precision on an atomic beam for four levels of the ground multiplet: by magnetic resonance (ABMR) for the ground state [2], and by laser-rf double resonance (ABMR-LIRF) for the remaining metastable levels [3,4]. A comprehensive literature survey on the electronic levels' structure in the holmium atom was given in our two recent works [5,6], where we reported extensive studies of the hyperfine structure for the odd- and even-parity level systems in Ho I; in the latter case, apart from experimental investigations, also semi-empirical analysis of both the fine- and the hyperfine structure was performed.

Holmium atom has been recently attracting some attention due to its quantum engineering applications: e.g. due to its rich *hfs* with the magnetic field splitting (Zeeman effect) overlapped, it was proposed for collective coding of quantum registers [7], and its laser cooling in MOT was already demonstrated [8].

Strangely enough, the explicit Zeeman data on Ho I are extremely scarce, and there are only a few electronic levels that have their Lande g_J factors determined. These obviously include the very precisely measured g_J values in the ground multiplet [3]. However, the only other attempt of Zeeman effect analysis in holmium that can be found in the literature resulted in determination of g_J factors of a few excited levels [9]. Lande g_J factors (like the *hfs* constants) belong to the characteristic features of the electronic levels and can greatly facilitate their assignment to particular configurations.

For the even-parity level system in the holmium atom there are, however, some theoretical estimates of the Lande factors available [10].

In this work we embarked on the task of determination of g_J factors for some even-parity levels in the holmium atom. The work is the outcome of the recently established collaboration between two research groups - from Poznan University of Technology (so far specializing in investigations of the hyperfine structure, including laser spectroscopy in a hollow cathode discharge) and from University of Gdansk (with many years tradition in Zeeman studies for various elements). Preliminary results were already used to confirm the assignment of some levels to configurations in the semi-empirical fit of the even-parity level system fine structure, reported in [6].

2. Experimental details

All the experimental investigations were performed in Poznan University of Technology. The experimental method and setup were mostly the same as described in more details in our recent works concerning the holmium atom [5,6], and below only a brief overview is given. The most important modification consisted in

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providing the sufficiently strong external magnetic field and the control of polarization of light, in order to allow independent observation of the σ and π components in the *hfs* patterns of the spectral lines investigated. These aspects are described below in more detail.

The method applied was laser induced fluorescence (LIF) in a hollow cathode discharge. The sources of exciting radiation were single-mode tunable dye lasers routinely used in our *hfs* investigations, operated on the following laser dyes: Rhodamin 6G (yellow-orange region, ca. 565–620 nm) and Coumarine 498 (blue-green region, ca. 485–520 nm, optically pumped by a diode laser [11]). The resulting fluorescence was recorded, spectrally resolved by a monochromator. Along with the LIF signal, a frequency marker transmission signal (FP interferometer, FSR = 1500 MHz, wavelength-corrected) was recorded; this facilitated construction of the relative frequency scale for the spectra. The transitions wavenumbers were measured with the use of a wavemeter; no deviations from the values calculated as the differences of both levels' energies [12] were observed.

In order to observe the Zeeman patterns in the hyperfine structure of the holmium spectral lines our experimental setup was modified to apply the method routinely used by the research group from University of Gdansk (in collaboration mainly with Technical University of Graz) [13–18]. The external magnetic field was generated by a permanent neodymium magnet mounted directly above the hollow cathode discharge tube (as described in [14,15]). The magnetic flux was measured in the vicinity of the magnet, along the line at an estimated constant distance where the laser beam propagates through the discharge. The field was found only moderately uniform and the flux amounted to ca. 500 Gs. This order of the magnitude of the magnetic field strength results in the Zeeman splitting of the hyperfine structure for the fine structure levels.

This approximate magnetic flux value was later confirmed by the Zeeman effect measurements performed on the reference spectral line of Ar (the buffer gas used in the discharge), involving the levels with the known g_J factors.

The permanent magnet setup rearrangement is currently in progress in order to improve the uniformity of the magnetic field and thus to increase the attainable precision of the g_J factors.

Distinction between the Zeeman σ and π components required a careful control of the polarization of the exciting laser light. The degree of linear polarization of the laser beams exiting the dye laser used was found quite high (exceeding 99.8 %), but it was further improved by a polarizing prism. In order to select σ and π components, linear polarization perpendicular or parallel to the magnetic field direction is required, respectively. With the use of a broad-band polarization rotator we were able to achieve both polarization states.

As routinely practiced in our *hfs* investigations, typically up to several tens of individual frequency scans were recorded for each polarization setup, which were then divided into groups and averaged in order to increase the signal-to-noise ratio.

3. Results

In this work altogether 20 spectral lines in the holmium atom were investigated (11 in the yellow-orange region and 9 in the blue-green region); all of the lines involved the odd-parity levels belonging to the ground multiplet as the lower levels. For all the lines the hyperfine structure without the magnetic field was previously studied; the respective results were reported in our most recent work [6]. The magnetic field strength applied yielded sufficient splitting of the spectra observed. The magnetic flux was calibrated by recording of the Zeeman structure of the Ar line $\lambda = 586.0310$ nm, which corresponds to the transition between the levels with known Lande g_J factors: 104 102.0990 cm^{-1}, $J = 1$ ($g_J = 1.985$) $\rightarrow$ 121 161.3135 cm^{-1}, $J = 1$ ($g_J = 1.271$) [12].

The Zeeman patterns of individual spectral lines were typically evaluated for 10–15 independent averaged groups of scans for each of two polarization setups. In the analysis, the software initially developed in the research group of University of Gdansk [19], later updated and described in detail in [20,21], was applied. This software was successfully applied in the analysis of the *hfs*-Zeeman spectra in various elements (e.g. neodymium [13], praseodymium [16], lanthanum [17,18] or thallium [22]).

The program uses atomic structure constants of two levels involved, i.e. quantum numbers I and J, hyperfine structure constants A and B, and Lande g_J factors as input parameters. For a given magnetic field flux value B, consecutive program procedures calculate relative frequencies and intensities of the *hfs*-Zeeman transitions, and based on them creates Doppler-broadened spectrum applying a line shape profile:

$$I(\nu) = I_{bc} + \sum_i \frac{I_{0,i}[1 + (\chi/\alpha_1)(\nu - \nu_{0,i} - \widetilde{\nu})]}{1 + [(2/\delta_1)(\nu - \nu_{0,i} - \widetilde{\nu})]^2 + [(2/\delta_2)(\nu - \nu_{0,i} - \widetilde{\nu})]^4} \quad (1)$$

where $I_{0,i}$ and $\nu_{0,i}$ are the intensity and position of a single *hfs*-Zeeman component, $\widetilde{\nu}$ denotes a shift of the whole spectrum with respect to the frequency scale (the relative frequency detuning is measured from the start value for the scan), $\delta_{1,2}$ are the line shape parameters, where δ_1 is full linewidth at half maximum. The χ parameter describes the asymmetry of the line profile. In case of present studies in holmium with the hollow cathode as the atom source we didn't observe any asymmetry in the profiles of the lines. A least-squares procedure compares simulated and experimental profiles, adjusting the fitted parameters (like Lande g_J factors and line shape or background parameters) step-by-step until the best agreement is obtained. The experimental linewidths varied in the range of (550–1100) MHz.

In case of laser spectroscopy experiments the saturation effects are very common and we noticed significant deviations of the relative intensities of the observed transitions from the calculated ones. Reduction of the laser light did not always improve the results. Due to a very large number of *hfs*-Zeeman components, this issue could not be solved by adjusting independently intensities of each component. Nevertheless, we found a simple solution to the issue of saturation by introducing additional parameter (denoted by γ) in the fitting procedure. This parameter alters intensity of each component given by equation (30) from [20] by raising it to a power of γ,

$$\widetilde{a}^{Saturated}_{M'_F,M_F} = \left[\widetilde{a}^{Total}_{M'_F,M_F}\right]^{\gamma}. \quad (2)$$

We can assume that the intensity of each component is proportional to the transition probability of the line. This approach yielded surprisingly good results for all lines where saturation effects were present. In case of lines of holmium reported here, the γ parameter applied varied from 1.0 (no saturation) down to 0.4, where strong saturation effects have been observed.

Fortunately, an mentioned in *Introduction*, for the levels in the ground multiplet very precise Lande g_J factors are available [3]. In the fitting procedure we used these data for the lower energy levels and treated them as fixed parameters; this restriction improved the consistency of the results of the fitting procedure for different polarization setups and reduced possible systematic errors due to some unwanted fluctuations in the magnetic field strength or saturation effects.

Although the double resonance method is much superior from the point of view of precision as compared with the Doppler-reduced method used by us, its application in nevertheless limited to the lowest-lying levels only. The hollow cathode source,