Hyperfine-structure of the 8p-2p3/2 and 8p-2p1/2 Levels of In-115

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Published in:
Zeitschrift für Physik A Hadrons and Nuclei

DOI:
10.1007/BF01413400

1982

Citation for published version (APA):
Hyperfine Structure of the $8p^2P_{3/2}$ and $8p^2P_{1/2}$ Levels of $^{115}$In

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Received January 14, 1982

The hyperfine structure of the $8p^2P_{3/2}$ and $2P_{1/2}$ levels of $^{115}$In was measured using high-resolution laser spectroscopy on a collimated indium atomic beam. Step-wise excitations from the metastable $5^2P_{3/2}$ state via the short-lived $6s^2S_{1/2}$ state were employed. For the magnetic-dipole and electric-quadrupole interaction constants $a$ and $b$, respectively, the following results were obtained: $a(8p^2P_{3/2}) = 16.3 (3)$ MHz, $b(8p^2P_{3/2}) = 11 (3)$ MHz and $a(8p^2P_{1/2}) = 44.0 (5)$ MHz. The magnetic hyperfine structure is shown to be strongly influenced by core polarization. For the electric-quadrupole moment of $^{115}$In the value $Q = 0.79 (20)$ barn is deduced.

1. Introduction

The ground configuration of indium has three electrons outside closed shells: $5s^25p$. As the two $s$ electrons form a closed subshell the residual electron gives rise to an alkali-like spectrum, where, however, the lowest term is a $^2P$. Thus $5p^2P_{1/2}$ is the ground state whereas the other member of the doublet, $5^2P_{3/2}$, is a metastable state situated about 0.27 eV above the ground state. The hyperfine structure of the two stable indium isotopes, $^{115}$In (96%) and $^{113}$In (4%), both with nuclear spin $I=9/2$, has been measured for these states with high precision using atomic-beam magnetic-resonance [1, 2]. The hyperfine structure in the two lowest $S$ states, 6 and $7^2S_{1/2}$ has recently been measured by laser spectroscopy [3, 4]. The lowest $^2D$ states were measured more than 10 years ago by level-crossing spectroscopy [5, 6]. The hyperfine structure of these $^2D$ states is quite anomalous which can be explained by configuration interaction, e.g. by the $5s5p^2$ configuration. Already the ground configuration hyperfine structures strongly deviate from the alkali-like values. For example, the ratio of the magnetic-dipole interaction constants $\frac{a_{1/2}}{a_{3/2}}$ is 9.42 rather than close to 5. It is quite interesting to experimentally determine the hyperfine structure for higher lying $^2P$ states. The first measurements of this kind are reported in the present paper, where the $8p^2P_{3/2}$ and $2P_{1/2}$ levels were investigated using high-resolution laser fluorescence spectroscopy.

The $8p^2P_{3/2,1/2}$ levels were reached by step-wise laser excitations from the thermally populated metastable $5p^2P_{3/2}$ level using the $6s^2S_{1/2}$ state as the intermediate level. In order to obtain a high spectral resolution, a collimated atomic beam was used, which was excited at right angles employing a single-mode dye laser for the second excitation step. A limit for the obtainable resolution is set by the short lifetime of the intermediate level, 7 ns [7], resulting in a natural radiative width of 23 MHz.

2. Experimental Arrangement

The experimental arrangement used in the hyperfine-structure measurements for indium is similar to the one employed in a recent investigation of high-lying levels of barium [8]. A molybdenum oven, resistively heated, was used to produce an atomic beam in a vacuum system. Using aperture stops the atomic beam was collimated in order to achieve a high spectral resolution. The beam was terminated on a liquid-nitrogen cool trap and an additional cool trap in the oven section was used for helping to attain a vacuum of about $2 \times 10^{-6}$ torr. In order to produce the indium beam the oven was kept at
about 1200 K. At this temperature about 13% of the atoms are in the metastable $6p^2P_{3/2}$ state. The transition at 451.1 nm from this state to the $6s^2S_{1/2}$ state was induced by a commercial multi-mode dye laser operating with the dye Stilbene 3. One of the laser mirrors was piezo-electrically vibrated in order to sweep the laser modes quickly back and forth resulting in an effectively white excitation of the hyperfine transitions of the line. High resolution experiments on this line have been performed by Zaal et al. [3] and in initial experiments on In we also repeated such measurements.

For the second laser excitation step we used a stabilized, single-mode dye laser (CR-599-21) operating with the dye Rhodamine 110. The transitions occur at 571.0 nm and 572.8 nm to the $8p^2P_{3/2}$ and $8p^2P_{1/2}$ states, respectively. Fluorescence light from the atomic beam, released after the step-wise excitations, was monitored in the UV region in the decay of the $7s^2S_{1/2}$ state, which was populated in the cascade decay of the highly excited $2p$ states. By isolating the light with suitable filters it was possible to completely suppress straylight from the lasers as well as the intense blue fluorescence light from the first excited $6s^2S_{1/2}$ state. A Peltier-cooled 9558 BQ photomultiplier tube was used to record the faint signals obtained in the present experiments. The fluorescence-light spectra were recorded together with fringes from a 50 MHz free-spectral-range multi-pass interferometer.

3. Measurements

In the measurements the blue laser was first set to the $5p^2P_{3/2} - 6s^2S_{1/2}$ transition by observing the strong fluorescence light in the decay of the $S$ state. The yellow single-mode laser was then tuned to the proper wavelength using a digital wavelength meter. The wavelengths derived from [9] were found to be reliable. Wavelengths for higher-lying states can be obtained from the recent work of Neijzen and Dönszelmann [10]. The laser was tuned repetitively through the signal structures which were recorded together with Fabry-Pérot fringes. In Fig. 1 a recording of the $6s^2S_{1/2} - 8p^2P_{3/2}$ transition is shown, displaying the large $S$ state splitting and the small $P$ state splittings. The experimental linewidths were found to be 30-60 MHz. A scan with a higher resolution is shown inserted for one of the small-splitting groups. In Fig. 2 the splitting of the $8p^2P_{1/2}$ state is shown. The observed signals are all due to $^{115}$In. The less abundant $^{113}$In isotope could not be studied in the present experiments. In the measure-

![Fig. 1](image1.png)

**Fig. 1.** Recording of the $6s^2S_{1/2} - 8p^2P_{3/2}$ transition in In. The hyperfine structure for the $^2P_{3/2}$ state is shown enlarged for clarity. Also included are transition diagrams. Only the dominant indium isotope, $^{115}$In, is observed.

![Fig. 2](image2.png)

**Fig. 2.** Recording of the $6s^2S_{1/2} - 8p^2P_{1/2}$ transition.
ments the laser powers in the individual beams were attenuated so that no power broadening or light-shifts influenced the results. For the \( ^2P_{3/2} \) state structures a computer program calculating a resulting partly overlapping structure for given values of the \( a \) and \( b \) factors and the linewidth, facilitated the data analysis. From a large number of recordings we obtained the following results:

\[
\begin{align*}
 a(8p \; ^2P_{3/2}) &= 16.3 (3) \text{ MHz} \\
 b(8p \; ^2P_{1/2}) &= 11 (3) \text{ MHz} \\
 a(8p \; ^2P_{1/2}) &= 44.0 (5) \text{ MHz}
\end{align*}
\]

There errors are mainly determined by the statistical spread in the data. Calibration errors and systematic effects are estimated to be much less.

4. Discussion

In a simplified picture of an atom with one electron outside closed shells the magnetic-dipole interaction in a \( P \) state can be calculated using a semi-empirical formula [11]. This formula contains an expectation value \( \langle r^{-3} \rangle \) which, evaluated from the experimental \( a \)-factor, can be used to determine the nuclear-quadrupole moment from the \( b \)-factor. In a more general theory the Hamiltonian for the magnetic-dipole interaction contains three operators, describing the orbital, spin-dipole and contact interaction [12]. This leads to three different \( \langle r^{-3} \rangle \) parameters. For \( P \) states in alkali atoms, however, the \( \langle r^{-3} \rangle \) parameters for the orbital and spin-dipole interaction are often almost equal and the contact interaction is usually small. One approach in a semi-empirical treatment is to correct the experimental \( a \)-factors for the contact interaction and assume the orbital and the spin-dipole \( \langle r^{-3} \rangle \) parameters to be equal [13]. The contact interaction is due to a polarization of closed shells caused by the \( p \)-electron and is of the same size but with different signs in the \( ^2P_{1/2} \) and the \( ^2P_{3/2} \) states. The corrected \( a \)-factors, referring to the \( p \)-electron alone, should then, apart from relativistic correction factors [14], have a ratio of 5, which follows from the angular parts of the spin-dipole and orbital interactions. This method to extract \( \langle r^{-3} \rangle \) values has been applied on \( P \) states in rubidium and a good agreement with \( \langle r^{-3} \rangle \) values obtained from fine-structure splittings was found [15]. When the same method is applied to the \( 8^2P \) states in indium the correction due to polarization effects is much larger but the agreement between \( \langle r^{-3} \rangle \) values obtained from hyperfine- and fine-structure splittings is still very good as can be seen in Table 1. A similar calculation was performed for the ground state. The correction is here of the opposite sign but the \( b/a \) ratios, which are proportional to the quadrupole moment, are still very close as seen in the last column. If the Sternheimer shielding [16] is neglected we obtain a mean value of 0.91 barn for the quadrupole moment of \(^{115}\text{In}\). If a Sternheimer correction factor of 0.87 is applied, as suggested from calculations for the similar element gallium [16], a value for the quadrupole moment \( Q = 0.79 \) (20) barn is obtained.

The semi-empirical treatment seems to work very well for the \( P \) states of indium and this was also the case for the \( P \) states in the alkali atoms. The \( a \)-factors in the lowest \( D \) states of indium were found to be inverted for the \( J = 3/2 \) states, which was suggested to be due to configuration-interaction effects [5, 6]. Anomalous negative \( a \)-factors were also found for alkali \( ^2D_{5/2} \) states. Many-body perturbation calculations were able to explain this behaviour in terms of strong core-polarization effects [17]. It would be very interesting to perform the same type of calculations for the hyperfine structure in the \( P \) and \( D \) states of indium. Further experiments on the hyperfine structure in elements of the third group are in progress.

This work was supported by the Swedish Natural Science Research Council.

Table 1. Calculation of \( \langle r^{-3} \rangle \) parameters from corrected \( a \)-factors and fine-structure splittings. The following correction factors in the formulas of [11] were used: \( F_1(\Omega) = 1.394 \), \( F_2(\Omega) = 0.980 \) [14], \( H_r = 1.0502 \), \( Z_r = 45 \) [11] and \( R_r = 1.918 \) [14].

<table>
<thead>
<tr>
<th>State</th>
<th>( a_{3/2} \text{ MHz} )</th>
<th>( a_{1/2 \text{ corr}} \text{ MHz} )</th>
<th>( \langle a_{3/2}^2/r^3 \rangle ) from ( a_{3/2 \text{ corr}} \text{ MHz} )</th>
<th>( \langle a_{1/2}^2/r^3 \rangle ) from ( \delta W )</th>
</tr>
</thead>
<tbody>
<tr>
<td>( 8^2P )</td>
<td>16.3</td>
<td>7.43</td>
<td>0.122</td>
<td>0.131</td>
</tr>
<tr>
<td>( 5^2P^o )</td>
<td>242.165057</td>
<td>311.15</td>
<td>5.097</td>
<td>5.338</td>
</tr>
</tbody>
</table>

* Experimental values from [1, 2]

References

2. Eck, T.G., Kusch, P.: Rev. 106, 958 (1957)
Note Added in Proof

A further investigation, previously overlooked by us, was brought to our attention after the submission of the present paper. Neijzen and Dönzelmann (Physica 96C, 143 (1979)) have, using the quantum-beat technique, determined the hyperfine coupling constants of the \( ^{8}P_{3/2,1/2} \) states with the results: \( a(8^2P_{3/2}) = 16.3(1) \text{ MHz} \), \( b(8^2P_{3/2}) = 11.4(3) \text{ MHz} \) and \( a(8^2P_{1/2}) = 44.2(4) \text{ MHz} \). Our values, determined by a completely independent technique, are in excellent agreement with these published values. Further, our measurements confirm the assumption of positive interaction constants made by Neijzen and Dönzelmann.