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Hyperfine Structure of the $7p^2P_{1/2,3/2}$ Levels of $^{115}$In and the $5p^2P_{1/2}$ Level of $^{27}$Al

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The hyperfine structure of the $7p^2P_{1/2,3/2}$ levels of $^{115}$In and the $5p^2P_{1/2}$ level of $^{27}$Al has been measured using high-resolution laser spectroscopy on atomic beams. For the magnetic-dipole and electric-quadrupole interaction constants, $a$ and $b$, the following values were obtained:

- $a(7p^2P_{1/2}) = 90.7(10)$ MHz,
- $a(7p^2P_{3/2}) = 32.3(2)$ MHz, and
- $b(7p^2P_{3/2}) = 24.5(1.5)$ MHz for $^{115}$In and $a(5p^2P_{1/2}) = 20(2)$ MHz for $^{27}$Al.

Many-body calculations on $2p$ states in aluminum, gallium and indium have also been performed.

1. Introduction

Recently, the hyperfine structure (hfs) in the $5s^28p^2P_{1/2,3/2}$ states of $^{115}$In was investigated and the magnetic-dipole and electric-quadrupole coupling constants, $a$ and $b$, for these states as well as for those of the ground configuration were analysed using a semiempirical method [1]. These configurations are alkali-like, since there is only one electron outside closed subshells but the $a$ factors were found to deviate strongly from alkali-like values. In this paper we report on hfs measurements in the $5s^27p^2P_{1/2,3/2}$ states of $^{115}$In and in the $3s^25p^2P_{1/2}$ state of the lighter group III element $^{27}$Al. Theoretical calculations including polarization effects [2] have been performed in the $^2P_{1/2,3/2}$ sequences of Al, Ga and In.

The measurements were performed on collimated atomic beams and the investigated states were reached using two-step laser excitation. In the second step a single-mode dye-laser was employed. Using the same technique, hfs has previously been studied in the $4s^22S_{1/2}$ state of aluminum [3] and in $^2P_{1/2,3/2}$ states of gallium and indium [4, 1]. The $^2P_{3/2}$ sequence in aluminum is now being investigated using quantum-beat spectroscopy [5]. This method has earlier been applied in gallium and indium [6]. The hfs in the ground configuration of aluminum, gallium and indium has been measured with high precision using atomic-beam magnetic resonance [7–9]. For gallium the importance of polarization and relativistic effects was demonstrated in a theoretical analysis [10]. The lowest excited $^2D$ states in aluminum and gallium were investigated using the level-crossing technique and were found to be affected by configuration interaction [11, 12]. This was also found for lifetime values in the entire $^2D$ sequences of aluminum and indium [13]. For aluminum the interaction between the doubly excited $3s^3p^2$ configuration and the $^2D$ sequence has been studied theoretically [14].

2. Experimental Set-Up and Measurements

Measurements were made on the hfs of the $5p^2P_{1/2}$-level in Al and the $7p^2P_{1/2,3/2}$ levels in In using stepwise excitations from the metastable $^2P_{3/2}$-level of the ground configurations.

The first excitation step $5p^2P_{3/2} - 6s^2S_{1/2}$ at 4,513 Å in In and $3p^2P_{3/2} - 4s^2S_{1/2}$ at 3,963 Å in Al was induced by a commercial multimode dye laser working with the dyes Coumarine 41 (In) or Stilbenc 1 (Al). A PZT mounted folding mirror made the laser modes sweep back and forth which resulted in a white excitation of the intermediate level. The wavelengths of the first steps were set to the respective transition by observing the fluorescence light from the atomic beam. We used the dye Rhodamine 101 to induce the second step transitions $6s^2S_{1/2} - 7p^2P_{1/2}$ at 6,902 Å and $6s^2S_{1/2} - 7p^2P_{3/2}$ at 6,849 Å in In and $3s^2S_{1/2} - 5p^2P_{1/2}$ at 6,100 Å in Al. The wavelengths
of the second step were set using a digital wavelength meter. The two laser beams were superimposed using a dichroic mirror and crossed the atomic beam perpendicularly. Neutral density filters were used to attenuate the laser power to avoid power broadening and light shifts. The atomic beams consisting of either free In or Al atoms were produced from a resistively heated boron-nitride oven inside a vacuum system. To diminish the Doppler broadening, the atomic beam was well collimated. The atomic beam was terminated on a liquid-nitrogen cool trap. During the experiment the pressure was about $10^{-6}$ torr inside the vacuum system.

Detection of the fluorescence light of the second step was made with a Peltier cooled photomultiplier tube (EMI 9558 BQ). In order to decrease the background due to scattered laser light, long entrance and exit tubes with apertures were used. In addition, suitable interference and coloured-glass filters suppressed unwanted fluorescence light. The transitions were recorded on a strip-chart recorder together with fringes from a 50 MHz FSR multipass interferometer. The linewidths were about 50-60 MHz. The signal to noise ratio allowed only the more common isotope $^{115}$In (96%) to be studied in the indium experiment. From the evaluation of a large number of measurement curves we find $a(7p^2P_{1/2}) = 90.7(10)$ MHz, $a(7p^2P_{3/2}) = 32.3(2)$ MHz and $b(7p^2P_{3/2}) = 24.5(1.5)$ MHz for $^{115}$In and $a(5p^2P_{1/2}) = 20(2)$ MHz for $^{27}$Al. The error bars include the statistical uncertainty as well as estimated possible systematic effects.

3. Analysis

In this section we will give the results from semi-empirical and many-body calculations of hfs for all
Table 1. Calculation of radial parameters and quadrupole moments from corrected $a$ factors and fine-structure splittings using the formulae of [15, 16]

<table>
<thead>
<tr>
<th>Atom</th>
<th>State</th>
<th>$a_{3/2,a}$ [MHz]</th>
<th>$a_{3/2,m}$ [MHz]</th>
<th>$\langle a_0^2/r^3 \rangle$ from $a_{3/2,m}$</th>
<th>$\langle a_0^2/r^3 \rangle$ from $\delta W$</th>
<th>$b/a_{3/2,m}$</th>
<th>$Q$ [barn]</th>
</tr>
</thead>
<tbody>
<tr>
<td>$^{27}$Al</td>
<td>$3p,^2P$</td>
<td>94.25$^7$</td>
<td>98.30</td>
<td>1.322</td>
<td>1.414</td>
<td>0.191</td>
<td>0.14</td>
</tr>
<tr>
<td>$^{69}$Ga</td>
<td>$4p,^2P$</td>
<td>190.79428$^8$</td>
<td>242.9</td>
<td>3.33</td>
<td>3.43</td>
<td>0.26</td>
<td></td>
</tr>
<tr>
<td></td>
<td>$6p,^2P$</td>
<td>22.4$^6$</td>
<td>12.0</td>
<td>0.164</td>
<td>0.171</td>
<td>0.27</td>
<td></td>
</tr>
<tr>
<td>$^{115}$In</td>
<td>$5p,^2P$</td>
<td>242.165057$^9$</td>
<td>311.15</td>
<td>5.10</td>
<td>5.34</td>
<td>1.44</td>
<td></td>
</tr>
<tr>
<td></td>
<td>$7p,^2P$</td>
<td>32.3</td>
<td>15.17</td>
<td>0.248</td>
<td>0.269</td>
<td>1.62</td>
<td></td>
</tr>
<tr>
<td></td>
<td>$8p,^2P$</td>
<td>16.3$^1$</td>
<td>7.43</td>
<td>0.122</td>
<td>0.131</td>
<td>1.48</td>
<td></td>
</tr>
</tbody>
</table>

Table 2. Theoretical values for the magnetic-dipole interaction constant $a$ from many-body theory. Experimental values are included (MHz)

<table>
<thead>
<tr>
<th>Atom</th>
<th>State</th>
<th>Experimental</th>
<th>Semiempirically corrected exp. values</th>
<th>Theory</th>
</tr>
</thead>
<tbody>
<tr>
<td>$^{27}$Al</td>
<td>$3p,^2P_{1/2}$</td>
<td>502.05$^7$</td>
<td>498.00</td>
<td>HF: 400.0</td>
</tr>
<tr>
<td></td>
<td>$3p,^2P_{3/2}$</td>
<td>94.25$^7$</td>
<td>98.30</td>
<td>RHF: 80.0</td>
</tr>
<tr>
<td></td>
<td>$5p,^2P_{1/2}$</td>
<td>20(2)</td>
<td>18.9</td>
<td>HF: 19.1</td>
</tr>
<tr>
<td>$^{69}$Ga</td>
<td>$4p,^2P_{1/2}$</td>
<td>1,338.9938$^8$</td>
<td>1,286.7</td>
<td>RHF: 195.1</td>
</tr>
<tr>
<td></td>
<td>$4p,^2P_{3/2}$</td>
<td>190.79428$^8$</td>
<td>242.9</td>
<td>HF: 975.5</td>
</tr>
<tr>
<td></td>
<td>$6p,^2P_{1/2}$</td>
<td>53.3(7)$^6$</td>
<td>63.7</td>
<td>RHF: 44.9</td>
</tr>
<tr>
<td></td>
<td>$6p,^2P_{3/2}$</td>
<td>22.4(2)$^6$</td>
<td>12.0</td>
<td>HF: 9.0</td>
</tr>
<tr>
<td>$^{115}$In</td>
<td>$5p,^2P_{1/2}$</td>
<td>2,281.95536$^9$</td>
<td>2,213.0</td>
<td>HF: 9.3</td>
</tr>
<tr>
<td></td>
<td>$5p,^2P_{3/2}$</td>
<td>242.165057$^9$</td>
<td>311.15</td>
<td>HF: 14.7</td>
</tr>
<tr>
<td></td>
<td>$7p,^2P_{1/2}$</td>
<td>90.7(10)</td>
<td>107.8</td>
<td>HF: 276.4</td>
</tr>
<tr>
<td></td>
<td>$7p,^2P_{3/2}$</td>
<td>32.3(2)</td>
<td>15.17</td>
<td>HF: 365.3</td>
</tr>
<tr>
<td></td>
<td>$8p,^2P_{1/2}$</td>
<td>44.0(5)$^1$</td>
<td>52.9</td>
<td>HF: 31.9</td>
</tr>
<tr>
<td></td>
<td>$8p,^2P_{3/2}$</td>
<td>16.3(3)$^1$</td>
<td>7.43</td>
<td>HF: 6.4</td>
</tr>
</tbody>
</table>

$P$-states in aluminum, gallium and indium measured so far. In the semi-empirical approach [15] it is assumed that the radial parameters for the orbital and spin-dipole interactions are equal. The $a$ factors are corrected for the contact interaction, which is of the same size but with different signs in the $^2P_{1/2}$ and $^2P_{3/2}$ states. The corrected $a$ factors, referring to the $p$-electron alone, can then be used to evaluate an experimental radial parameter which together with the $b$ factor gives the quadrupole moment [16]. As can be seen in Table 1 the correction is very large in gallium and in indium but still the agreement between radial parameters obtained from corrected $a$ factors and fine structure splitting is good. The $b/a$ ratios for different states, proportional to the quadrupole moment, are also close. In the last column mean values for the quadrupole moments are given. Sternheimer correction factors of 0.94, 0.89 and 0.87 for aluminum, gallium and indium, respectively, have been applied [17].

The many-body calculations are based on a diagrammatic perturbation expansion of effective operators, as described in, for instance, Refs. [2, 18]. The starting point in the calculation is the Hartree-Fock model for the closed-shell ions Al$^+$, Ga$^+$ and In$^+$. Beyond this model the most important perturbations are the core-polarization and pair-correlation effects. The former are due to distortions of the closed shells caused by the electrostatic interactions with the valence $p$-electron. By means of an iterative procedure [18] this effect has been included to all orders in the present calculation. The remaining effects – particularly the pair correlation – has not been considered. The calculations are non-relativistic, but in order to estimate the relativistic effects we have performed relativistic Hartree-Fock (Dirac-Fock) calculations for the atoms and compared the results with the corresponding non-relativistic results.

The results for the different calculations are given in Table 2 (column 4–6). The third column gives the experimental values corrected for the effective contact interaction, as described above (see Table 1). Since most of the core-polarization effects are here eliminated, these values should be compared with the Har-
tree-Fock results in column 4 – or the relativistic Hartree-Fock results in column 5. The original experimental data in the second column, on the other hand, should be compared with the polarization results (HF + pol) in the last column.

The overall agreement between the experiments and theoretical results is not particularly good, but some interesting observations can be made. Firstly, the sign of the effective contact interaction (i.e. the difference between the values in column 3 and column 2) is different in the ground configuration on one side and in the excited configuration on the other. This effect is reproduced in the theoretical calculation, and therefore we can conclude that this effect is mainly due to spin-polarization. Furthermore, the agreement is reasonably good between the corrected experimental results (col. 3) and the Hartree-Fock results (col. 4, 5), while it is quite poor between the uncorrected experimental results (col. 2) and the polarization results (col. 6), particularly for the ground configuration. This indicates that all effects, except the effective contact interaction, are reasonably well reproduced in the present calculation. The conclusion that can be drawn from this observation is that the electron correlation – which is strongest in the ground configuration with three strongly overlapping outer electron orbitals – has a large influence on the effective contact interaction. Preliminary calculations of the correlation effect for the $3^2 P$ configuration of Al supports this conclusion [19]. As a matter of fact, the inclusion of the electron correlation almost exactly cancels the contact interaction caused by the spin polarization. Evidently, there are many interesting observations to be made in this type of elements, and further theoretical calculations are in progress.

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5. Jönsson, G., Kröll, S., Lundberg, H., Svanberg, S.: (to be published)

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