HYPERFINE STRUCTURE INVESTIGATION OF THE $4f^76s^2\,{}^8\mathrm{S}_{7/2}$ and $4f^76s6p\,{}^6\mathrm{P}_{5/2}$ STATES OF UNSTABLE EUROPIUM ISOTOPE ^{155}Eu*

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The method of laser induced resonance fluorescence on an atomic beam has been used in order to measure hyperfine structure splittings of the $4f^76s^2\ {}^8\mathrm{S}_{7/2}$ and $4f^76s6p\ {}^6\mathrm{P}_{5/2}$ levels of the unstable isotope ^{155}Eu. Experimental values of magnetic-dipole A- and electric-quadrupole B-constants of ^{155}Eu have been determined for the first time; $A_{\mathrm{exp}}(^{155}\mathrm{Eu}^8\mathrm{S}_{7/2}) = -8.87(22)$ MHz, $A_{\mathrm{exp}}(^{155}\mathrm{Eu}^6\mathrm{P}_{5/2}) = -261(1.2)$ MHz and $B_{\mathrm{exp}}(^{155}\mathrm{Eu}^6\mathrm{P}_{5/2}) = -957(12)$ MHz. After corrections for second-order hyperfine structure perturbations the values: $A_{\mathrm{corr}}(^{155}\mathrm{Eu}^6\mathrm{P}_{5/2}) = -260.9(1.2)$ MHz and $B_{\mathrm{corr}}(^{155}\mathrm{Eu}^6\mathrm{P}_{5/2}) = -958(12)$ MHz have been obtained and the values of nuclear moments of 155Eu have been estimated: $\mu(^{155}\mathrm{Eu}) = 1.519(10)$ n.m. and $Q_s(^{155}\mathrm{Eu}) = 2.512(62)$ b.

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1. Introduction

High resolution laser spectroscopy has been extensively developed during the past several years. Measurements of hyperfine structure (hfs) splittings in optical spectra of atoms or ions by means of this method make it possible to determine the multipole nuclear moments (magnetic-dipole μ and

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electric-quadrupole Q_s) or the mean square charge radii differences between various isotopes $\delta\langle r^2\rangle$. The magnetic-dipole interaction constants A, which are obtained from hfs measurements performed for several isotopes, supply information for the study of the hyperfine magnetic anomaly along the chain of isotopes.

Europium is an element which offers a long chain of radioactive isotopes with long lifetimes. There are 11 various isotopes with the lifetimes ranging from a few days to a few years: from ^{145}Eu($\tau = 5d$) to ^{155}Eu($\tau = 5a$). Therefore, from the spectroscopic point of view this makes them candidates for systematic hfs investigations in a long isotopic chain. The isotope ^{155}Eu is particularly interesting since it is known to have a strongly deformed nucleus, as observed by collinear laser–ion–beam spectroscopy [1]. The present experiment has been aimed at a more precise measurement of the nuclear moments of this isotope. This experiment is simultaneously the first one concerning the hfs of the atomic 155Eu.

In this paper the hyperfine splitting measurements in the $4f^76s^2\,{}^8\mathrm{S}_{7/2}$ ground state and in the $4f^76s6p\,{}^6\mathrm{P}_{5/2}$ excited state are reported. The importance of correcting the experimental results for the second-order hyperfine interactions is demonstrated. From the corrected hfs intervals the values of magnetic-dipole A_{corr}- and electric-quadrupole B_{corr}-constants have been determined and the values of nuclear moments μ and Q_s of ^{155}Eu have been obtained.

2. Experiment

In our experiment the well-known method of laser induced resonance fluorescence on a collimated atomic beam has been used. A detailed description of the experimental setup is given elsewhere [2]. The atomic beam has been produced by heating of the sample in a Ta crucible. Europium atoms were excited from the $4f^76s^{2\,8}\mathrm{S}_{7/2}$ ground state to the $4f^76s6p^6\mathrm{P}_{5/2}$ state Fig. 1 by the radiation of a cw tunable dye laser. The laser-excited resonance fluorescence was detected by a photomultiplier operating in a single photon counting mode. The spectrum was recorded by a multichannel analyser synchronized with the laser frequency tuning. Fig. 2 shows laser induced fluorescence of the optical transition at $\lambda = 564.58$ nm in ^{155}Eu and ^{153}Eu atoms. The spectrum of ^{155}Eu has been identified and 3 hfs intervals between various F-sublevels in the $4f^76s6p^6\mathrm{P}_{5/2}$ state of ^{155}Eu have been measured;

$$F=5 \leftrightarrow F=4 \quad 1880.13(55)\,\mathrm{MHz}\,,$$
$$F=4 \leftrightarrow F=3 \quad 980.82(68)\,\mathrm{MHz}\,,$$
$$F=3 \leftrightarrow F=2 \quad 443.91(76)\,\mathrm{MHz}\,.$$

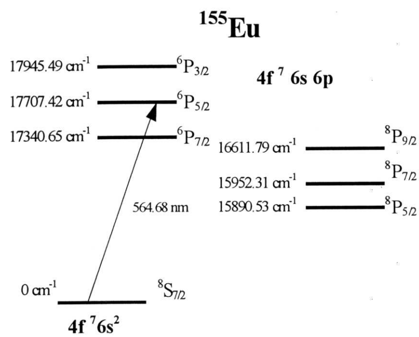

Fig. 1. Partial energy level diagram of 155Eu showing the ground state and a few excited states of the atom.

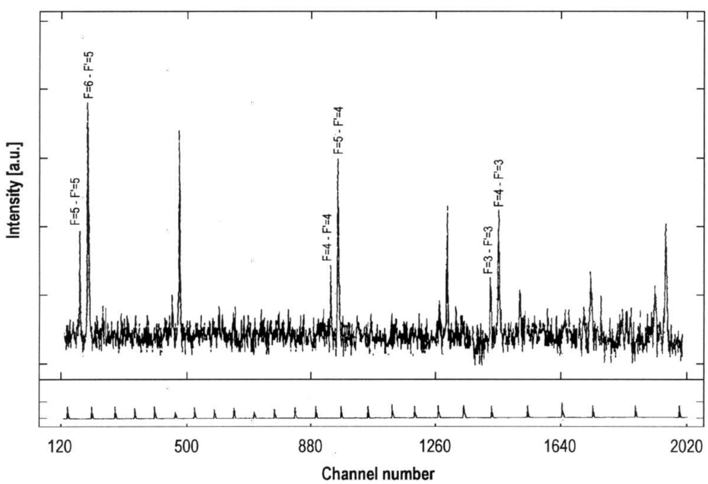

Fig. 2. Laser-induced fluorescence observed for the optical transition at $\lambda = 564.58$ nm in ^{155}Eu and ^{153}Eu atoms; upper trace — fluorescence signal, lower trace — reference marker signal. Only the hfs components of the isotope ^{155}Eu are marked.

Moreover, 4 hfs intervals in the ground state of ^{155}Eu have been determined:

$$
\begin{aligned}
F = 6 \ &\leftrightarrow F = 5 \quad 52.72(48)\,\text{MHz}\,,\\
F = 5 \ &\leftrightarrow F = 4 \quad 44.58(61)\,\text{MHz}\,,\\
F = 4 \ &\leftrightarrow F = 3 \quad 34.50(60)\,\text{MHz}\,,\\
F = 3 \ &\leftrightarrow F = 2 \quad 30.67(109)\,\text{MHz}\,.
\end{aligned}
$$

They are, however, much smaller than those for the excited state and therefore their relative accuracy is worse in our measurements.

3. Results and discussion

The hyperfine intervals are expressed in terms of the magnetic dipole and electric quadrupole hfs constants $A_{\rm exp}$ and $B_{\rm exp}$; their values have been evaluated in a least-squares fitting procedure using the expression: (1)

$$\Delta E_{\rm hfs} = \frac{K}{2A} + \frac{\frac{3}{2}K(K+1) - 2I(I+1)J(J+1)}{2I(2I-1)2J(2J-1)}B\,, \qquad (1)$$

where $K = F(F+1) - I(I+1) - J(J+1)$ and J, I and F are the quantum numbers of the electronic angular momentum, nuclear spin and the total atomic angular momentum, respectively. The experimental values $A_{\rm exp}$ and $B_{\rm exp}$ are listed in Table I. More accurate determination of $A_{\rm exp}(^8{\rm S}_{7/2})$ and $B_{\rm exp}(^8{\rm S}_{7/2})$ will be possible if all hfs intervals of the ground level could be measured precisely.

TABLE I

Experimental values of hfs constants A (magnetic-dipole interaction) and B (electric-quadrupole interaction) for the $4f^76s^2\,{}^8{\rm S}_{7/2}$ and $4f^76s6p\,{}^6{\rm P}_{5/2}$ levels of ^{155}Eu. The errors quoted are the statistical ones.

Level	$A_{\rm exp}$ [MHz]	$B_{\rm exp}$ [MHz]
$4f^76s^2\,{}^8{\rm S}_{7/2}$	−8.87(22)	1(3)
$4f^76s6p\,{}^6{\rm P}_{5/2}$	−261.0(1.2)	−957(12)

From earlier investigations of the hyperfine structure of europium isotopes [3–6] it is known that hfs interactions that mix electronic states with different J quantum numbers play an important role and cannot be neglected in the interpretation of hfs measurements in most cases. To take this into account the "repulsion effect" between hfs sublevels with the same quantum number F, belonging to different levels, has been calculated using second-order perturbation theory. In order to correct the hfs constants for the J off-diagonal hfs perturbations we have used the procedure described in [4–6]. The measured transition frequencies have been corrected by second-order perturbation theory and the shift of each of the energy levels

$$\delta W_F = \frac{|\langle \Psi, JIFm_F|H_{\rm hfs}|\Psi', J'IFm_F\rangle|^2}{E(\Psi,JF) - E(\Psi',JF)} \qquad (2)$$

has been evaluated. Only the dipole-dipole, dipole-quadrupole and quadrupole-quadrupole contributions to δW_F are of importance and have been calculated. The matrix element in the numerator of Eq. (2) can be expressed as a function of hfs radial parameters and $a_{nl}^{\kappa k}$ $b_{nl}^{\kappa k}$ $nl = 4f, 6s, 6p, 5d$ and $\kappa k = 01, 12, 10, 02, 11, 13$). To obtain preliminary values of the corrections we assumed that

$$\frac{A_{\rm exp}(^6{\rm P}_{5/2}(^{155}{\rm Eu}))}{A_{\rm exp}(^6{\rm P}_{5/2}(^{153}{\rm Eu}))} = \frac{a_{nl}^{\kappa k}(^{155}{\rm Eu})}{a_{nl}^{\kappa k}(^{153}{\rm Eu})}$$

and

$$\frac{B_{\rm exp}(^6{\rm P}_{5/2}(^{155}{\rm Eu}))}{B_{\rm exp}(^6{\rm P}_{5/2}(^{153}{\rm Eu}))} = \frac{b_{nl}^{\kappa k}(^{155}{\rm Eu})}{b_{nl}^{\kappa k}(^{153}{\rm Eu})}, \qquad (3)$$

where $A_{\rm exp}(^6{\rm P}_{5/2}(^{155}{\rm Eu}))$ and $B_{\rm exp}(^6{\rm P}_{5/2}(^{155}{\rm Eu}))$ are the experimental values from Table I. The values of $A_{\rm exp}(^6{\rm P}_{5/2}(^{153}{\rm Eu}))$, $B_{\rm exp}(^6{\rm P}_{5/2}(^{153}{\rm Eu}))$, $a_{nl}^{\kappa k}(^{153}{\rm Eu})$ and $b_{nl}^{\kappa k}(^{153}{\rm Eu})$ were taken from [3,7]. With the intermediate-coupling electronic wavefunctions in many-configurations approximation $[4f^7 6snp + 4f^7 5d6p + 4f^7 6s5f + 4f^7 6s6f + 4f^6 5d6s^2 + 4f^6 5d^2 6s (n = 6-13)]$ the matrix elements in Eq. (2) have been evaluated. The amplitudes of leading components in linear combination of the eigenvector of the $4f^7 6s6p\,^6{\rm P}_{5/2}$ state are:

- $4f^7(^8{\rm S})6s6p(^3{\rm P});\ ^6{\rm P}_{5/2}$ 0.888284,
- $4f^7(^8{\rm S})6s6p(^3{\rm P});\ ^8{\rm P}_{5/2}$ 0.351590,
- $4f^7(^6{\rm P})6s6p(^3{\rm P});\ ^4{\rm P}_{5/2}$ 0.133819,
- $4f^7(^8{\rm S})5d6p(^3{\rm P});\ ^6{\rm P}_{5/2}$ 0.172869.

The $4f^7 6s6p\,^6{\rm P}_{5/2}$ level exhibits only a slight amount of configuration interaction. This simplified greatly our hfs calculations for this level.

As the shift of the $4f^7 6s6p\,^6{\rm P}_{5/2}$ sublevels is mainly determined by the "repulsion" of the neighbouring $4f^7 6s6p\,^6{\rm P}_{3/2,\,7/2}$ levels, the eigenvector compositions of these levels have been also analysed [8].

The non-linear corrections cannot be implemented in a linear fitting procedure used for the solution of the linear expansion of hfs interactions. Therefore, the energy shifts were first used to correct the measured hfs intervals. Then the hfs constants $A_{\rm corr}$ and $B_{\rm corr}$ were calculated by fitting to the corrected hfs intervals. Finally, the corrected hfs constants of $4f^7 6s6p\,^6{\rm P}_{5/2}$ level are: $A_{\rm corr}(^6{\rm P}_{5/2}) = -260.9(1.2)$ MHz and $B_{\rm corr}(^6{\rm P}_{5/2}) = -958(12)$

MHz. They differ very little from the experimental ones, which shows that hfs second-order effects do not influence strongly the $4f^76s6p\,^6\mathrm{P}_{5/2}$ level.

From the corrected hfs constants the values of nuclear moments can be estimated: $\mu(^{155}\mathrm{Eu}) = 1.519(10)$ n.m. and $Q_s(^{155}\mathrm{Eu}) = 2.512(62)$ b. Our results are in a good agreement with the first estimate of μ and Q_s [1], they are, however, more precise than the earlier ones.

4. Conclusions

In this work hfs of the $4f^76s^2\,^8\mathrm{S}_{7/2}$ and $4f^76s6p\,^6\mathrm{P}_{5/2}$ levels of the unstable isotope ^{155}Eu have been investigated for the first time. The hfs constants of these levels have been determined. The values of nuclear moments $\mu(^{155}\mathrm{Eu})$ and $Q_s(^{155}\mathrm{Eu})$ determined here confirm the results obtained for singly ionized ^{155}Eu [1]. They indicate that the nucleus of this isotope is strongly deformed. Moreover, the hfs constants $A_{\mathrm{corr}}(^{155}\mathrm{Eu})$ supply information necessary for the study of hyperfine magnetic anomaly along the chain of Eu isotopes.

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