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MEASUREMENT OF HYPERFINE COUPLING CONSTANTS OF THE EXCITED STATES $4f^7(^8S^0_{7/2})6p_{3/2}(7/2, 3/2)$ IN $^{151,153}Eu^+$ *

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Hyperfine structure spectra of singly ionized europium have been measured by collinear fast-ion-beam laser spectroscopy. All the spectral lines were resolved and the magnetic dipole and electric quadrupole coupling constants of the metastable and excited levels were determined.

Keywords: fast-ion-beam laser spectroscopy, hyperfine structure, magnetic dipole and electronic quadrupole coupling constants
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I. INTRODUCTION

Andrä[1] first introduced the laser excitation of fast ion beams. Bengtson *et al.*[2] used collinear fast-ion-beam laser spectroscopy for hyperfine structure (HFS) measurements in CsII. The collinear geometry technique provided a powerful method of high precision spectroscopy. Because of the kinematic compression when ions are accelerated, sub-Doppler resolution can be obtained with a collinear geometry. The use of an isotope separator permits selective measurements of different isotopes. These two properties make the collinear fast-ion-beam laser spectroscopy method very powerful and accurate.

Hyperfine structure in atomic ions is caused by the electromagnetic interaction between the nucleus and the orbital electrons. Not only the information of nuclear structure but also electronic properties of ions can be obtained through studying the HFS of ions. Höhle *et al.*[3] used collinear ion-beam laser spectroscopy for HFS measurements in LaII. Ginibre[4] has used grating photographic spectrograms and Fourier transform interferograms for the measurement of fine and HFS of singly ionized Pr. Berrah-Mansour *et al.*[5] measured the HFS of ScII by using an rf-laser double resonance method. Kuwamoto *et al.*[6] and Iimura *et al.*[7] have studied HFS in PrI by collinear atomic-beam laser spectroscopy. Ma *et al.*[8] have used collinear fast-ion-beam laser spectroscopy to measure HFS in PrII. Sen *et al.*[9] determined the hyperfine coupling constants of the metastable levels of EuII by using an rf-laser double resonance method. In this paper, the magnetic dipole coupling constant (A) and electric quadrupole coupling constant (b) of the excited levels in EuII were obtained.

II. EXPERIMENT

The experimental set-up is shown in figure 1. A 30kV electronic isotope separator (Danfysik 1080-30) was used to produce a singly charged$^{151,153}Eu^+$ ion beam. An isotopically pure ion beam of $^{151}Eu^+$ or $^{153}Eu^+$ was selected. The ion beam passed through a vacuum tube and entered the chamber. The beam current was typically 1–1.5μA when europium chloride was used as a precursor in the ion source.

A single-mode coherent 899-29 ring dye laser was used to provide light with a bandwidth less than 1 MHz. The laser beam was steered through a Browster window into the chamber and then through a set of apertures that define the ion beam path. In this way, it was possible to obtain a good counter-propagating overlap between the laser and ion beams in the detection region. The frequency of the dye laser was measured by a laser-wavemeter, which was calibrated by use of an iodine absorption spectrum. In order to accurately calibrate the relative frequency of measured resonant spectra, the transmitted light was focused through a 100cm confocal Fabry-Pérot interferometer (FPI with free spectral range (FRS) 146.5MHz). The fluorescence from the laser-excited ion beam and signals from two photodiodes accepting the transmitted light through the FPI and the I_2 cell were simultaneously recorded with three-input multichannel analysers (MCAs).

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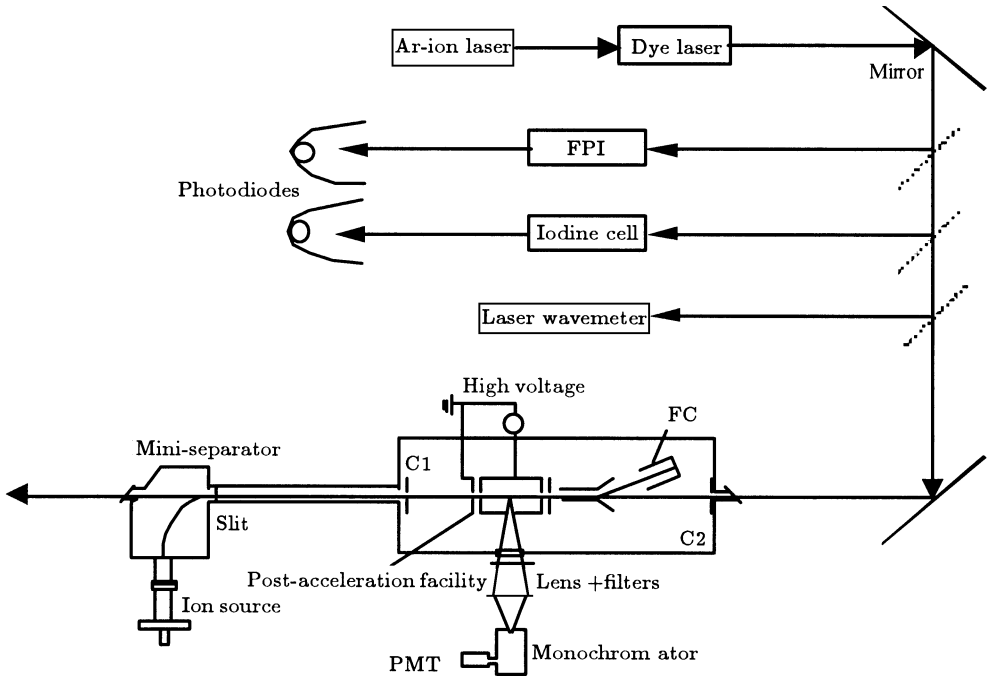


Fig.1. The experimental set-up. The letters PD, HV, PMT, FC, C1 , C2, and FPI represent the photodiode, high-voltage power-supply, photomultiplier tube, Faraday cup, collimators, and Fabry-Pérot interferometer, respectively.

To prevent the depletion of the metastable state by laser light before the ion beam entered the chamber, a three-part post-acceleration electrode structure was placed in the chamber. This allowed us to modulate the ion energy locally. The two outer disks were electrically grounded and the middle one was held at a negative potential of 1000V, where the ions are accelerated locally. Because of the different Doppler shifts, the ions outside the electrode structure are not affected by the laser, and typically they are off resonance by ∼7.5GHz. Keeping the post-acceleration potential fixed, the laser is scanned to bring it into resonance with the ions. By scanning the laser over a frequency region, the entire fluorescence spectrum is obtained. The resonant spectrum is recorded by the fluorescence to the ground state or lower metastable states. The fluorescence light was focused by a set of lens and detected by a photomultiplier (EMI 9789B). A glass filter and a monochromator were used to suppress stray laser light

The laser-excited fluorescence satisfies the Doppler principle. In the ion reference frame, the laser frequency (ν_1) appears as

$$\nu_0 = \nu_1 \frac{1-\beta\cos\theta}{\sqrt{1-\beta^2}}, \qquad (1)$$

where $\beta = v/c$, v and c are the speeds of ions and light respectively, and θ is the angle between the direction of the propagation of the laser and the velocity of ions. For slow ions, β is very small and expanding equation (1) and keeping only the first-order terms in β, we obtain

$$\nu_0(\theta = \pi) = \nu_1(1+\beta), \qquad (2)$$

where $\nu_0(\theta = \pi)$ is the frequency seen by the ions when the laser and ions counter-propagate in the collinear geometry. When $\nu_0(\theta = \pi)$ equals a transition frequency of the ion, the laser photon may be absorbed by the ion resulting in an excitation to a excited level. Subsequently this level decays to lower levels and fluorescence is recorded. From (2) it is easy to see that the laser photon is resonantly absorbed by the ions either by tuning the laser frequency or by changing the post-acceleration voltage to tune the velocity of the ions. We keep the voltage fixed and scan the laser.

Ⅲ. EXPERIMENTAL RESULTS AND DISCUSSION

A partial energy level diagram of Eu^+ investigated is shown in figure 2, where the laser-excited transitions from the metastable levels are indicated by upward arrows. Eu^+ ions were selectively excited from the metastable levels to the excited levels by laser light. In order to get a high signal-to-background ratio, the selectively observed fluorescence wavelength was less than the pump-laser light wavelength by more than one hundred nm. The background was mainly due to the fluorescence light from the collision of ions

with the residual gas molecules.

Europium has two stable isotopes with a mass number 151 and 153, respectively. Their nuclear spins are I=5/2. The conserved quantum number is the total angular momentum F=$I+J$. In first-order perturbation theory, the hyperfine energy splitting ΔE is expressed as the sum of magnetic dipole term $\Delta E_{\rm md}$ and the electric quadrupole term $\Delta E_{\rm eq}$ as follows,

$$\Delta E = \Delta E_{\rm md} + \Delta E_{\rm eq} \tag{3}$$

$$= \frac{1}{2}KA + \frac{\frac{3}{4}K(K+1) - I(I+1)J(J+1)}{2I(2I-1)J(2J-1)}B, \tag{4}$$

where

$$K = F(F+1) - I(I+1) - J(J+1), \tag{5}$$

and A and B are the magnetic dipole and electric quadrupole coupling constants, respectively. The energy shift $\Delta E_{\rm md}$ is caused by the interaction between the internal magnetic field produced at the nucleus by orbital electrons and the nuclear magnetic dipole moment. In the same way, $\Delta E_{\rm eq}$ corresponds to the interaction between the electric field gradient and the nuclear quadrupole moment.

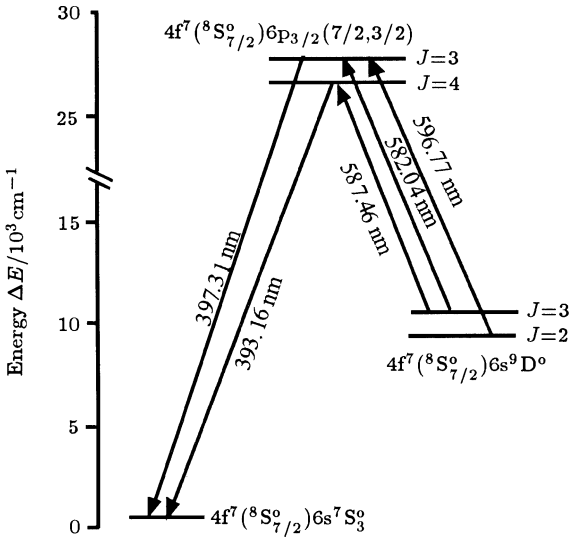


Fig.2. A partial energy-level diagram of Eu^+ investigated. The laser-excited transitions from the metastable levels are indicated by upward arrows.

The typical hyperfine resolved spectra of $^{151}Eu^+$ and $^{153}Eu^+$ in the 582.04nm line are shown in figures 3(a) and 3(b), respectively. Assigned hyperfine transitions are schematically shown in the upper part with the quantum number of upper hyperfine structure levels (F′) and lower hyperfine structure levels (F), respectively. They correspond to the observed peaks of the spectrum in the lower part, respectively. The centre of each fluorescence peak was determined from experimental hyperfine splitting by a least-squares fit to equation (4).

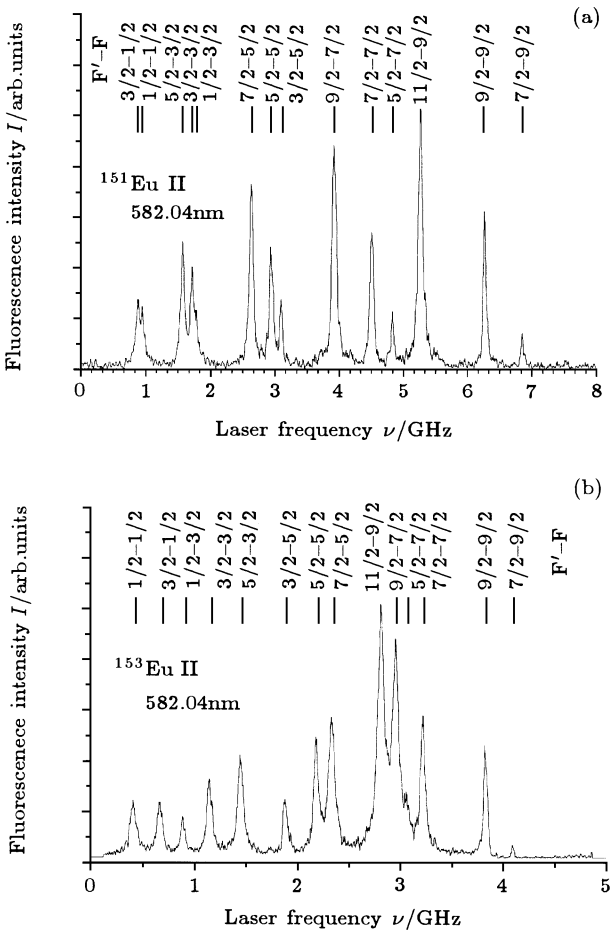


Fig.3. Hyperfine structure spectra in the 582.04nm line of EuII. Lower parts in figures 3(a) and 3(b) show the hyperfine spectrum of $^{151}Eu^+$ and $^{153}Eu^+$, respectively, and assigned hyperfine transitions are shown in the upper parts with the quantum number of upper hyperfine structure levels (F′) and lower hyperfine structure levels (F), respectively.

The analysis of the recorded curves is subject to possible systematic errors caused by experimental uncertainties, such as laser frequency calibration, uncertainties in determining the centres of the peaks in the HFS spectrum, and the ion velocity distribution. The line broadening is partly due to the limited quality of the ion beam. Some additional energy dispersion may arise from plasma ion source instabilities. Such energy fluctuations lead to a spread of the velocity distribution. The measured hyperfine coupling constants A

and B of the excited levels and the metastable levels investigated in $^{151,153}Eu^{+}$ are listed in table 1 together with their errors. For comparison, the results published by Sen *et al.*[9] are also listed in table 1. For the metastable levels, our data are in good agreement with Sen's results. We have also determined the hyperfine coupling constants of the excited levels in EuII.

Table 1. Determined hyperfine coupling constants A and B of the metastable and excited levels in $^{151,153}Eu^{+}$.

Line/nm	Level	Isotope	This work		Sen's results	
			A/MHz	B/MHz	A_S/MHz	B_S/MHz
582.04	$(7/2,3/2)_3$	151	–129.8±1.2	–495.7±6.5		
		153	–55.6±1.1	–1268.1±4.3		
	5d $^9D^o_2$	151	–534.4±1.0	110.7±5.0	–535.103	108.260
		153	–236.4±1.3	286.2±9.5	–237.122	275.291
578.96	$(7/2,3/2)_3$	151	–130.8±0.7	–498.0±6.6		
		153	–57.7±1.0	–1280.4±9.1		
	5d $^9D^o_3$	151	–227.1±1.2	–242.7±3.2		
		153	–100.8±1.1	–624.4±5.2		
596.77	$(7/2,3/2)_4$	151	57.0±1.1	162.4±6.3		
		153	26.9±1.3	385.8±11.0		
	5d $^9D^o_3$	151	–225.9±1.0	–238.2±5.0		
		153	–101.2±1.1	–624.0±8.0		
mean	$(7/2,3/2)_3$	151	–130.3±0.6	–496.8±4.7		
		153	–56.6±0.8	–1274.2±3.9		
	5d $^9D^o_3$	151	–226.5±0.8	–240.3±3.0	–226.307	–244.534
		153	–101.0±0.8	–624.2±3.0	–100.491	–622.627

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