

Shell effect in the isotopic dependence of the mean square charge radii of short-lived europium nuclei measured by laser photoionization detection on line with the accelerator

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The isotopic shifts of the 576.5-nm line of the isotopes ^{141,142,143,144,145}Eu have been measured by laser resonant photoionization of atoms on line with a mass separator and a proton synchrocyclotron. These are the first such measurements. In addition, a selective stepwise ionization of ^{142m}Eu has been achieved for the first time, demonstrating the possibility of a laser separation of isomers.

The isotopic dependence of the mean square charge radii of nuclei changes slope at a magic number of neutrons, N_{mag} , varying more slowly at neutron numbers $N < N_{\text{mag}}$ than at $N > N_{\text{mag}}$.

This shell effect is observed for all sufficiently long isotopic chains (Rb, Ba, and

Cs¹; the chains must be long enough on both sides of N_{mag}). Furthermore, in all cases in which the shell effect has been observed the magic neutron number has been stable or near the stability band. It is thus interesting to examine this shell effect for a magic nucleus at an appreciable distance from the stability band.

We have accordingly measured the isotopic changes $\Delta \langle r^2 \rangle$ in the mean square charge radii of europium isotopes for $N \leq 82$ with $A = 141-145$ (¹⁴⁵Eu is a magic nucleus; the nearest stable nucleus is ¹⁵¹Eu). We have previously² obtained data on $\Delta \langle r^2 \rangle$ of europium isotopes in the region $N \geq 82$. As in Ref. 2, we found the values of $\Delta \langle r^2 \rangle$ from the isotopic shifts of the 576.5-nm line of the Eu atom, measured by laser resonant ionization of atoms.³

The experiments were carried out on a laser-nuclear complex constructed at the Leningrad Institute of Nuclear Physics in collaboration with the Institute of Spectroscopy. The basic parts of the apparatus are the 1-GeV proton synchrocyclotron and the IRIS mass separator. The short half-lives of the isotopes of interest (less than a few minutes) required the development and use of a measurement method different from

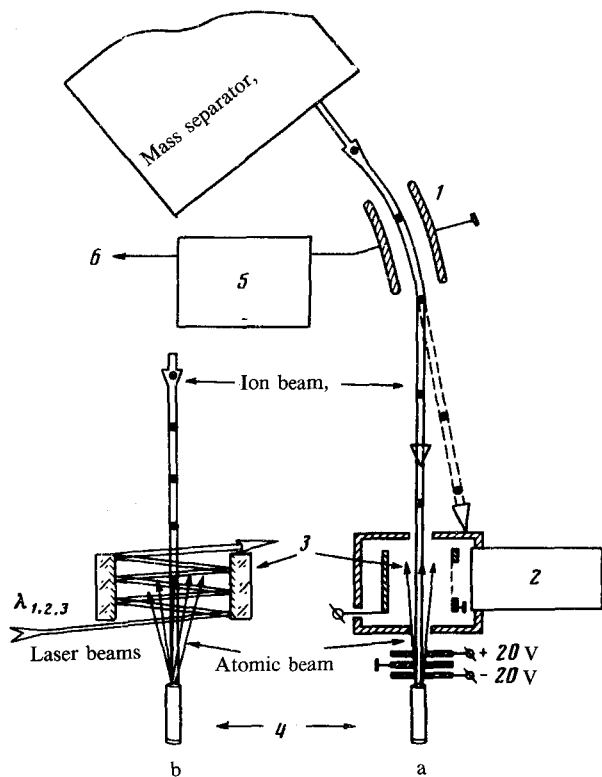


FIG. 1. a, b: Arrangement of the ion, atomic, and laser beams during the photoionization of the radioactive isotopes on line with the proton accelerator. 1—Electrode of the system which blocks the separated ion beam; 2—secondary electron multiplier; 3—mirrors of the multiple-pass optical system; 4—hot tantalum cylinder with a plugged end; 5—pulse voltage generator (50 V, 20 μ s, 10⁴ pulses/s); 6—synchronization with the power supply for the copper-vapor laser.

that used² for long-lived isotopes; the new method involved carrying out measurements on line with the accelerator and the mass separator.

The isotopes were produced for study in a tantalum target (20 g) in the mass separator through bombardment by a proton beam with an intensity of about 10^{12} s^{-1} . A 30-keV ion beam of the separated isotope was directed out of the mass separator into a tantalum tube (50 mm long and 5 mm in diameter) with a plugged end. When this tube was heated (to 1500 °C) the implanted ions emerged in the opposite direction as a collimated beam (Fig. 1). A system of diaphragms held at various potentials blocked thermal ions and electrons. The atoms were excited into an autoionization state by three laser beams which intersected the atomic beam at a right angle. The excitation arrangement, the lasers, and the measurement system are described in Refs. 2 and 4. The photoionization efficiency was raised beyond that in Refs. 2 and 4 by using two plane mirrors to return the laser beams through the atomic beam repeatedly (up to 15 times; Fig. 1b). The average output power of the dye lasers in the first excitation step was 40 mW, that in the second was 200 mW, and that in the third was 300 mW.

Measurements were taken in two modes. Isotopes with a comparatively long decay half-life ($T_{1/2} \gtrsim 1 \text{ min}$) were accumulated in a cold tube for $3 \times T_{1/2}$; then the ion beam of the mass separator was turned off, and the tube was rapidly heated. The evaporation lasted about 20 s. The count rate of background pulses was about 0.1 s^{-1} . In this measurement mode, which was used for $^{141,142,143}\text{Eu}$, the long-lived isomers can be separated from the group of isomers of the given isotopes because the short-lived isotopes have decayed by the time the measurements are taken.

This mode is not appropriate for isotopes with $T_{1/2} \lesssim 30 \text{ s}$. For these isotopes we used a constantly heated tube. The beam leaving the mass separator was interrupted for 20 μs , starting 10 μs before the appearance of the laser pulse (the pulse repetition frequency was 10 kHz, and the pulse length was 17 ns). The effect was to eliminate the ions formed in the residual gas ($5 \times 10^{-6} \text{ torr}$) by the beam from the mass separator by the time at which the measurements are taken, over 5 μs . The resulting background count rate was 1 s^{-1} . Measurements were taken in this mode for ^{144}Eu ($T_{1/2} = 10.2 \text{ s}$) and repeated for ^{143}Eu . Flux intensities of 10^4 s^{-1} were adequate for these measurements. The efficiency at which the europium atoms were detected was 3×10^{-4} (this is the ratio of the flux of photoions detected to the flux of ions leaving the mass separator

TABLE I.

<i>A</i>	<i>N</i>	$T_{1/2}$	$\Delta\nu^{151,A}$ (GHz)	$\lambda^{151,A}$ (fm ²)	β_{LD}	β_{VMI}
145	82	5.94 days	− 5.03 (14)	− 0.835 (23)	0.09	0.09
144	81	10.2 s	− 5.3 (2)	− 0.88 (3)	0.09 (3)	—
132	80	2.6 min	− 5.05 (25)	− 0.84 (4)	0.13 (2)	0.12
142 <i>m</i>	79	1.2 min	− 5.0 (2)	− 0.83 (3)	0.16 (2)	—
141	78	37 s	− 5.2 (3)	− 0.87 (5)	0.16 (2)	0.14

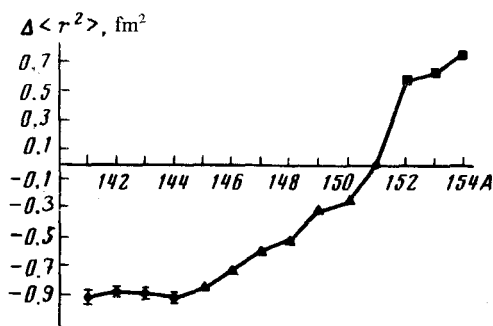


FIG. 2. Mean square charge radii of europium nuclei versus the atomic number A . \circ —Present experiments; \blacktriangle —data of Ref. 2; \blacksquare —data of Ref. 11.

at a fixed frequency of the laser of the first step, tuned to be the center of the atomic line).

Table I shows the measured isotopic shifts (with respect to ^{151}Eu) and the values of $\lambda^{151,A}$ —which are approximately equal to the values of $\Delta \langle r^2 \rangle^{151,A}$ —extracted from these shifts (by a method similar to that used in Ref. 2). Figure 2 shows the behavior of $\Delta \langle r^2 \rangle^{151,A}$. There is a clearly defined shell effect: As N is reduced through the value $N_{\text{mag}} = 82$, the decay of the mean square charge radius abruptly becomes slower. This shell effect can be attributed to the behavior of the effective nuclear deformation, $\beta_{\text{eff}} = \langle \beta^2 \rangle^{1/2}$, which reaches a minimum at $N = N_{\text{mag}}$. We found values of β_{eff} by comparing the expression for $\lambda^{A',A}(\beta_{\text{eff}})$ predicted by the liquid-drop model⁵ with the measured values of $\lambda^{A',A}$ under the assumption $\beta_{\text{eff}}(^{145}\text{Eu}) = \beta_{\text{eff}}(^{144}\text{Sm})$, where the latter quantity was determined from data⁶ on $B(E2)$. The values found for β_{eff} are listed (as β_{LD}) in Table I. It would be interesting to compare these values with independent determinations of β_{eff} .

Unfortunately, the data on $B(E2)$ of the neighboring proton-even Sm and Gd nuclei required for such a determination are not available. On the other hand, the energies of quasirotational levels of these nuclei are well known.⁷ Using these energies and the model of a variable moment of inertia,⁸ we can estimate the values of $B(E2)$ which we need for the even-even Sm and Gd nuclei and extract from them values of β_{eff} ; the values of β_{eff} of the odd-even Eu nuclei are taken to be

$$\beta_{\text{eff}}(^{63}\text{Eu}_N) = \frac{1}{2} \{ \beta_{\text{eff}}(^{62}\text{Sm}_N) + \beta_{\text{eff}}(^{64}\text{Gd}_N) \}.$$

Values found for $\beta_{\text{eff}}(\text{Eu}) \equiv \beta_{\text{VMI}}$ in this manner (Table I) agree well with the values of β_{LD} . This agreement between β_{LD} and β_{VMI} may be taken as evidence that an effective deformation plays a governing role in the shell effect in the isotopic dependence of the mean square charge radius.

The deformation of nuclei in the region under consideration here ($N \leq 82$, near $N_{\text{mag}} = 82$) is assumed to be of a dynamic nature; these nuclei are γ -unstable and possibly nonaxial.⁹

To pursue the study of these questions we would like to see measurements of the electric and magnetic moments of the nuclei. It would also be important to study the isotopic shifts of europium isotopes with $N < 78$, where a significant static deformation is expected.¹⁰

The selective stepwise photoionization of atoms with an excited ^{142m}Eu nucleus (decay half-life of 1.2 min) has been achieved for the first time in these experiments. Ions with these nuclei were accumulated at the cathode of a secondary electron multiplier.

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