Measurement of isotropic variations in the charge radii of europium nuclei by the method of three-stepped laser photoionization of atoms

G. D. Alkhazov, A. E. Barzakh, É. I. Berlovich, V. P. Denisov,
A. G. Dernyatin, V. S. Ivanov, A. N. Zherikhin, O. N. Kompanets,
V. S. Letokhov, V. I. Mishin, and V. N. Fedoseev
Institute of Spectroscopy, Academy of Sciences of the USSR

(Submitted 1 February 1983)
Pis'ma Zh. Eksp. Teor. Fiz. **37**, No. 5, 231–234 (5 March 1983)

The optical isotopic shifts in atomic spectra are measured for the first time using the method of laser multistep photoionization of atoms and the changes in the mean-square charge radii of radioactive nuclei are determined. The measurements were performed for the radioactive isotopes $^{145-149}$Eu in the transition $4f^7\,6s^2\,{}^8S^0_{7/2}$ $-4f^7\,6s\,6p\,{}^6P_{7/2}$, $\lambda = 576.5$ nm.

PACS numbers: 21.10.Ft, 27.90. + b, 32.80.Fb, 32.70.Jz

The high sensitivity and high resolution of the methods of laser spectroscopy permit measuring the characteristics of the ground and isomeric states of short-lived nuclei (spins, magnetic and quadrupole moments), as well as the isotopic variations in the charge radii of nuclei, using the isotopic shifts (IS) and hyperfine structure of optical lines. Such investigations were performed by the method of collinear fluorescent laser spectroscopy[1] and the method of laser-optical magnetic resonance[2] for long isotopic series for some elements.

At the Leningrad Institute of Nuclear Physics and the Institute of Spectroscopy of the Academy of Sciences, a laser-nuclear system using the method developed at the Institute of Spectroscopy[3] for detecting single atoms by means of their stepped photoionization by pulsed dye-laser radiation was built to investigate the properties of radioactive nuclei. The first objects chosen for the study were nuclei of rare-earth elements near a filled shell with neutron number $N = 82$.

It is interesting to study the nuclei in this region for the following reasons. First, the study of the charge radii of a series of isotopes, including magic (with $N = 82$) nuclei, will permit understanding the role of shell effects with increasing distance from the stability band of nuclei with a deficit of neutrons. Second, as N increases from 82 to 90, the shape of the nuclei must change from a spherical to a strongly deformed shape. It is especially interesting to study the nature of this change.[4] Finally, a new region of deformation is predicted for $N < 82$.[5]

In this paper, we present data on measurements of charge radii of europium isotopes ($Z = 63$) with $A = 145$–149, which were obtained by irradiating a tantalum target (120 g) with a beam of 1-GeV protons with intensity 10^{12} s^{-1} on the synchrocyclotron at the Leningrad Institute of Nuclear Physics. The reaction products were separated from the target by heating it to $t \cong 2500$ °C, and the isotopes were separated

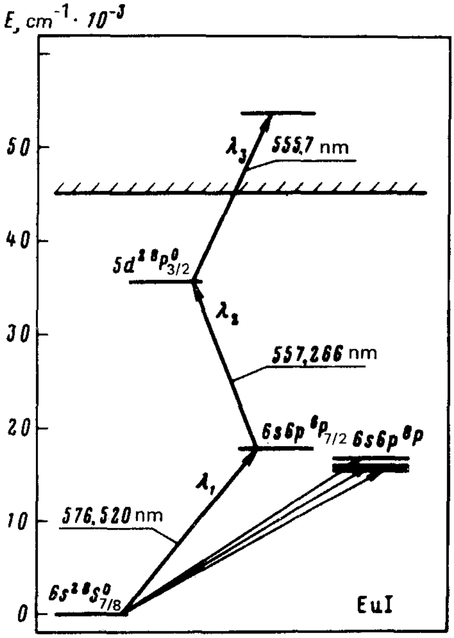

FIG. 1. Diagram of photoionization of Eu atoms by pulsed dye laser radiation (average radiation intensity and generation line width of the laser at the first step $P_1 = 2$ mW, $\Delta\nu_1 = 0.02$ cm^{-1}; for the laser at the second setup $P_2 = 150$ mW, $\Delta\nu_2 = 0.8$ cm^{-1}; and, for laser at the third step $P_3 = 250$ mW, $\Delta\nu_3 = 0.8$ cm^{-1}).

with the help of a mass separator. Eu isotopes, accumulated in annealed tantalum foils in quantities of 10^{10}–10^{12} atoms, were placed in the high-temperature source of the atomic beam. The laser setup consisted of three frequency-tunable dye lasers,[6] pumped by radiation from two pulsed copper vapor lasers, operating synchronously with a pulse repetition frequency of 10 kHz. The radiation frequency of the first dye laser, having a narrow generation line, was tuned in the interval $\Delta\nu = 0.6\ \mathrm{cm}^{-1}$, which ensured selective excitation from the ground state of different europium isotopes. They were subsequently excited and ionized via the autoionization state by the radiation from the other two dye lasers, whose generation frequency was fixed and tuned to resonance with selected transitions. The characteristics of the selected optical transitions in europium and the corresponding parameters of the dye lasers for each transition are presented in Fig. 1.

The laser beams intersected the atomic beam at a right angle. The efficiency of ionization of atoms in the region of interaction with the radiation $\cong 0.01$ was determined primarily by the degree of saturation of the transition to the autoionization state. Since the laser pulse duration was $\tau_i = 17$ ns, approximately 0.02 of the atoms passing through the region of ionization interact with the radiation. The angular size of the ionization region was such that the probability that the atoms leaving the source would strike it was equal to 0.01.

The ions formed by photoionization were detected by a secondary electronic mul-

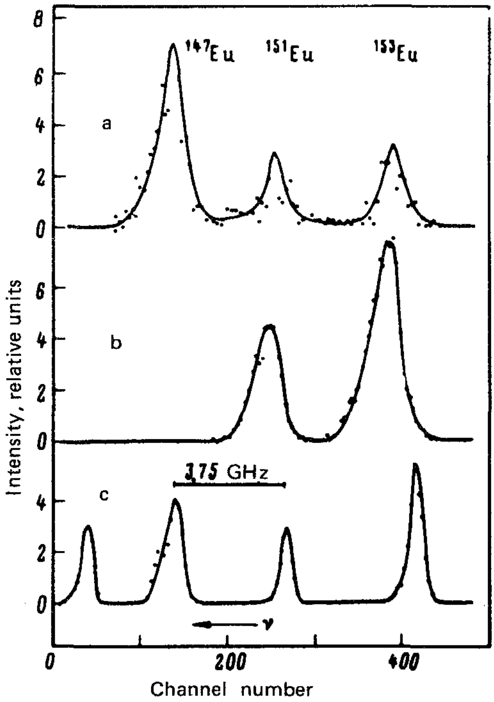

FIG. 2. (a) Photoionization spectrum of specimen with radioactive isotope ^{147}Eu; (b) the same for the isotopes ^{151,153}Eu; (c) transmission bands of confocal interferometer with a base of 2 cm.

TABLE I.

Mass number of isotope, A	149	148	147	146	145
Isotopic shift relative to ^{151}Eu, GHz	– 1.73 (7)	– 3.00 (7)	– 3.25 (7)	– 4.19 (10)	– 5.03 (7)

tiplier (SEM). The change in the wavelength of the tunable laser was controlled by a spherical interferometer with the mirrors separated by a distance of 2 cm. The isotopic shifts were determined at the first resonant transition (576.5 nm), for which the hyperfine splitting is anomalously small (for stable isotopes, about 300 MHz[7]) and less than the generation line width of the scanning laser (600 MHz). To calibrate the interferometer, we also used as references lines of the first transition of the stable isotopes ^{151,153}Eu and, in so doing, the measurements were performed simultaneously with measurements for the isotopes under examination using the reference atomic beam. Signals from the SEM, spherical interferometer, and radiation-intensity sensors entered the measuring-computing complex, which included small Élektronika-60 and SM-3 computers. To decrease the number of background ions created by the sources of atomic beams, an electrostatic shield was placed in their path in the form of a system of diaphragms, and time gates with a duration of 10 μs were introduced into the ion-detection circuits.

Figure 2 shows the results of one frequency scanning cycle for ^{147}Eu. The lines of residues of stable isotopes in the foil, after its annealing, can also be seen in the spectrum (a). The isotopic shifts obtained for the radioactive europium isotopes relative to ^{151}Eu are presented in Table I. The errors in determining the isotopic shifts are

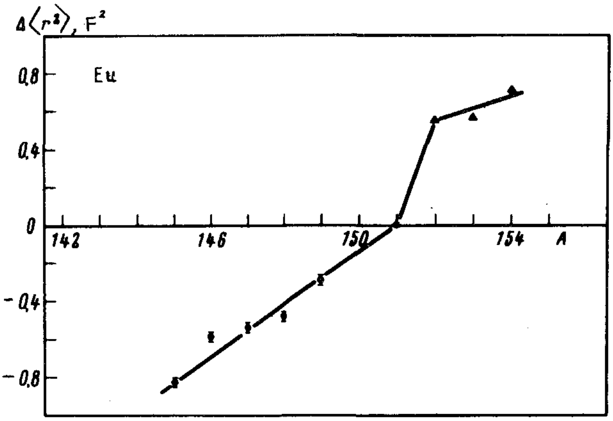

FIG. 3. Variation of the mean-square radii of the charge distribution of the nuclei of uranium isotopes relative to the isotope ^{151}Eu as a function of mass number.

due to the instability of the generation spectrum and the temporal nonuniformity of the frequency scan.

The quantities $\Delta \langle r^2\rangle_{A,151} = \langle r^2\rangle_A - \langle r^2\rangle_{151}$, where $\langle r^2\rangle_A$ is the mean-square radius of the charge distribution in the nucleus of the isotope with mass number A, were calculated from the measured isotopic shifts. The calculations were performed as in Ref. 7. The values of $\Delta \langle r^2\rangle_{A,151}$ are presented in Fig. 3, where the triangles show the results of measurements by others.[8] The jump in the region of $N = 89$ is related to the well-known increase in deformation (the deformation parameter δ varies from 0.14 for ^{151}Eu to 0.28 for ^{153}Eu[4]). The behavior of the values of $\Delta \langle r^2\rangle_{A,151}$ prior to this jump could indicate the small deformation of $^{145-149}$Eu nuclei; however, in order to obtain unambiguous results, it is necessary to measure their quadrupole moments. The variation in the measured values of $\Delta \langle r^2\rangle_{A,151}$ approximately corresponds to the proportionality of the charge radius to the quantity $A^{1/3}$, which agrees with the systematic behavior of the radii indicated near the filled neutron shell for isotopes with a number of neutrons close to the magic number.[9]

[1] E. W. Otten, in: Proceedings of 4-th International Conference on Nuclei Far from Stability; L. O. Skolen, Helsingar (Denmark), Vol. 1, CERN 81-09, 20 July 1981, Geneva, p. 3.
[2] R. Klapish, Atomic Physics 7, Plenum Press, New York, 1981.
[3] V. I. Balykin, G. I. Bekov, V. S. Letokhov, and V. I. Mishin, Usp. Fiz. Nauk **132**, 293 (1980) [Sov. Phys. Usp. **23**, 651 (1980)].
[4] E. E. Berlovich, Izv. Akad, Nauk SSSR, Ser. Fiz., **43**, 2046 (1979).
[5] G. A. Leander and P. Moller, Phys. Lett. B **110**, 17 (1982).
[6] A. N. Zherikhin, V. S. Letokhov, V. I. Mishin, V. P. Belyaev, A. N. Evtyunin, and M. A. Lesnoĭ, Kvant. Elektron. (Moscow) **8**, 1340 (1981) [Sov. J. Quantum Electron. **11**, 806 (1981)].
[7] G. J. Zaal, W. Hogervorst, E. R. Eliel, K. A. H. van Leeuwen, and J. Z. Blok, Physik A **290**, 339 (1979).
[8] K. Heilig and A. Steudel, Atomic Data and Nucl. Data Tables **14**, 613 (1974).
[9] I. Angeli and M. Csatlo's, Nucl. Phys. A **288**, 480 (1977).

Translated by M. E. Alferieff
Edited by S. J. Amoretty