LASER SPECTROSCOPIC STUDIES OF NEUTRON-DEFICIENT EUROPIUM AND GADOLINIUM ISOTOPES

**A.E. Barzakh, D.V. Fedorov, A.M. Ionan, V.S. Ivanov, F.V. Moroz, K.A. Mezilev,
S.Yu. Orlov, V.N. Panteleev, Yu.M. Volkov**

1. Introduction

The region of nuclei near $Z = 64$ and $N < 82$ is of great interest for nuclear physics. It has been established that closed sub-shell $Z = 64$ considerably influences on the regime of the entrance into the deformation region at $N > 82$. Nuclei with Z close to $Z = 64$ keep their spherical form up to $N = 88$. Then the sudden jump of deformation takes place. For nuclei with Z as far from $Z = 64$ as five and more protons, the deformation is changing smoothly and reaches the maximum at $N = 90$–92 [1].

The region of nuclides at $N < 82$ was systematically investigated at the IRIS facility for a long time. Studies of the deformation behavior for Eu ($Z = 63$), Sm ($Z = 62$) and Nd ($Z = 60$) isotope chains point to the smooth change of deformation, growing right after $N = 81$, without any jump-like effects.

In this report the recent development of the laser ion source spectroscopy technique and the results of the very neutron-deficient Eu isotope shift measurements are presented.

To complete these investigations, the isotope change of deformation for Gd ($Z = 64$) isotope chain has to be studied. For Gd the stabilizing influence of the closed sub-shell should be maximal, if it takes place. It is of importance also to extend our knowledge of the deformation behavior in the adjacent isotopic chains (for example, for Eu isotopes) as far as possible.

2. Experimental method

Method of the resonance laser photoionization in the laser ion source proves to be one of the most efficient for isotope shift and hyperfine structure investigations [2]. The essential point of the experimental method is step-by-step resonant laser excitation to autoionization states or continuum. The ionization schemes for Eu and Gd are shown in Fig. 1. The first experimental techniques based on the resonant ionization of the radioactive atoms at the exit of the mass separator enable one to carry out experiments with the isotopes at a production rate down to 10^4–10^5 atoms per second.

To extend the investigations to the more neutron-deficient isotopes, first of all to the region of neutron-deficient isotopes near and below the magic neutron number $N = 82$, the method of photoionization spectroscopy inside the laser ion source has been proposed and applied at the IRIS facility [2]. The experimental setup is presented in Fig. 2. Nuclides under study are produced in the target of the mass-separator by 1 GeV protons of the PNPI synchrocyclotron. The atoms are thermally released from the target to the ion source cavity. Three beams of pulsed dye lasers are introduced to the same cavity to provide the multistep resonance ionization of the atoms under investigation.

The dye lasers are pumped by three copper vapor lasers (repetition rate 10 kHz). The wavelengths of the dye lasers are tuned to the transitions of the chosen ionization scheme. The radiation frequency of the two broadband lasers (bandwidth 30 GHz) are fixed according to the second and the third transitions. The wavelength of the narrowband laser (bandwidth 1 GHz) is scanned across the first transition. The photoion current in the mass-separator collector increases at the resonance. Thus, the experimental spectra represent the dependence of the ion current on the scanned laser frequency. The detection of ion current is provided by α-, β-, or γ-counting. The corresponding detectors are installed on the tape-driving system.

A part of the scanning laser radiation is directed to the Fabry-Perrot interferometer (free spectral range 5 GHz) to produce frequency marks for the frequency scale calibration. Another part of the laser beam is used in a reference chamber to provide a reference spectrum from the sample of stable isotopes for the isotope shifts measurements.

---

[1] G.D. Alkhazov *et al.*, JETP Lett. **37**, 274 (1983).

[2] G.D. Alkhazov *et al.*, Nucl. Instr. Meth. B **69**, 517 (1992); A. E. Barzakh *et al.*, Phys. Rev. C **61**, 034304 (2000).
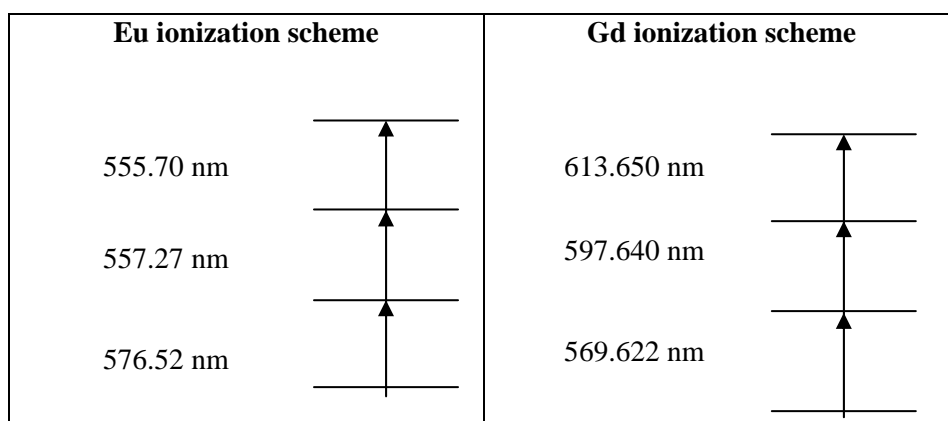
Eu ionization scheme	Gd ionization scheme
555.70 nm	613.650 nm
557.27 nm	597.640 nm
576.52 nm	569.622 nm

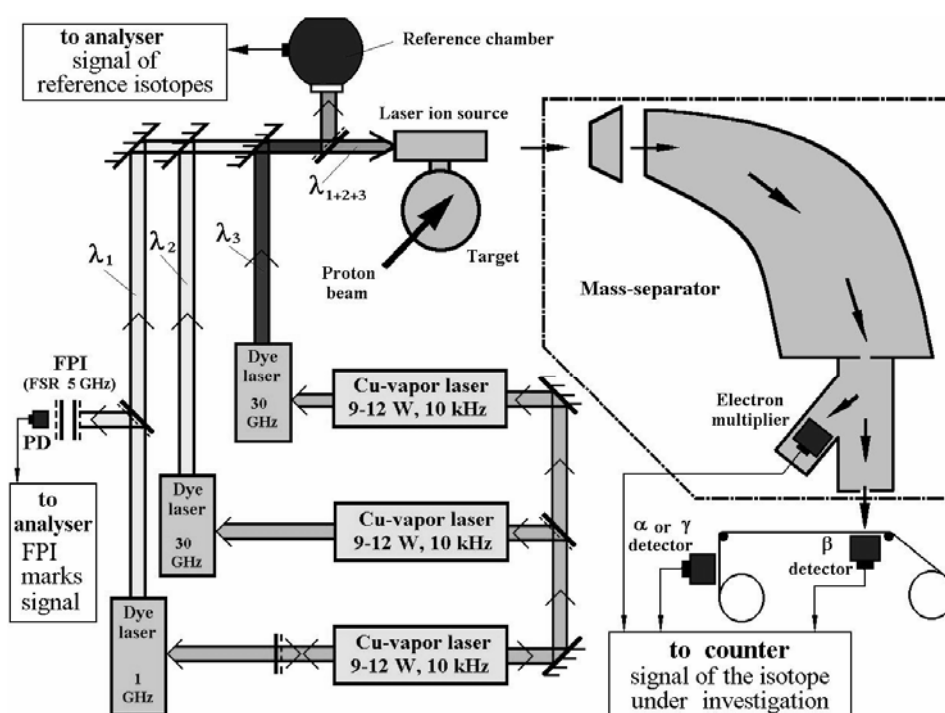**Fig. 1.** Ionization schemes of Eu and Gd

Fig. 2. Experimental setup

Two methods of the multistep resonance ionization at the entrance of the mass-separator have been used in the course of the experiment. The first one is a laser spectroscopy in the laser ion source. This is a traditional for the IRIS facility method, and it was described in details elsewhere [2]. The main point of this method is the multistep resonance ionization of the atoms under investigation directly inside the cavity of the ion source, coupled with the target, irradiated by proton beam. A scheme of this method is presented in Fig. 3 (left).

The second method is based on the resonance ionization directly inside the target, producing the nuclides under study [1]. We call this method as the laser target (LT) in order to emphasize that it differs from the method employing the resonance ionization in the laser ion source (LIS). Schematically this construction is presented in Fig. 3 (right).

For such a hard volatile element as gadolinium (boiling point is 3546°C) an effusion is the main process responsible for the delay of nuclides in the target-ion source system. The newly developed target was specially designed for the production of elements with long sticking time such as Gd to exclude "cold spots" which sometimes exist at the places of the target – transfer tube – ion source connection.
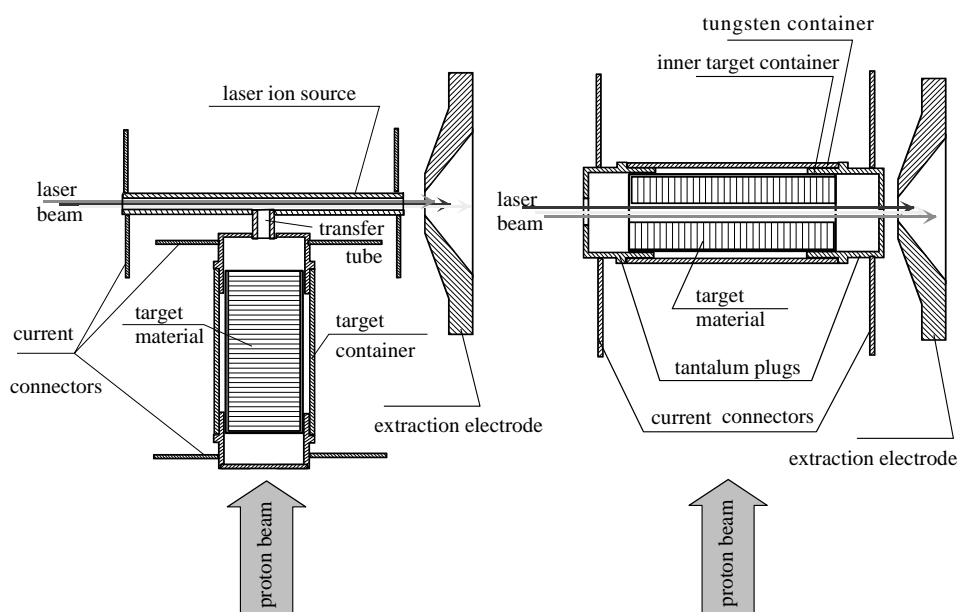

Fig. 3. Scheme of the resonance laser ionization inside the laser ion source LIS used for Eu (left) and the laser high temperature target LT used for Gd (right)

3. Experimental results and discussion

3.1. Europium

Isotope shifts for the chain of europium isotopes have been measured [2]. For ^{142m}Eu, the γ-line with the energy 556.6 keV was used to avoid influence of the short-lived ground state ($T_{1/2} = 2.4$ s). Table 1 presents the experimental results of the isotope shift measurements for neutron-deficient Eu isotopes.

Table 1

Experimental results for isotope shifts of the neutron-deficient Eu isotope chain

Isotope	$\Delta\nu_{145,A}$, MHz	$\Delta\nu_{145,A}$, MHz, (previous meas.)	$\lambda_{145,A}$, fm^2
^{144}Eu	240(160)	340(200)	−0.039(25)
^{143}Eu	150(160)	200(170)	−0.028(25)
^{142}Eu	20(180)	35(150)	−0.010(28)
^{141}Eu	−260(160)	−300(150)	0.032(25)
^{139}Eu	−590(240)	−750(200)	0.079(37)
^{138}Eu	−880(220)	−500(350)	0.114(34)
^{137}Eu	−730(280)	–	0.096(44)

The results previously obtained by the conventional resonance ionization technique [3] are also shown. They are consistent with the new results within the experimental errors. To extract the parameter $\lambda_{145,A}$ which is connected with the changes of the mean square charge radii $\delta\langle r^2\rangle_{145,A}$ the standard procedure [4] was used (with the electronic factor $F = -6.55$ GHz/fm^2). The specific mass shift for this pure s^2-sp transition was neglected. The errors for $\lambda_{145,A}$ in Table 1 are pure statistical; the uncertainty of the electronic factor is assumed to be about 5%.
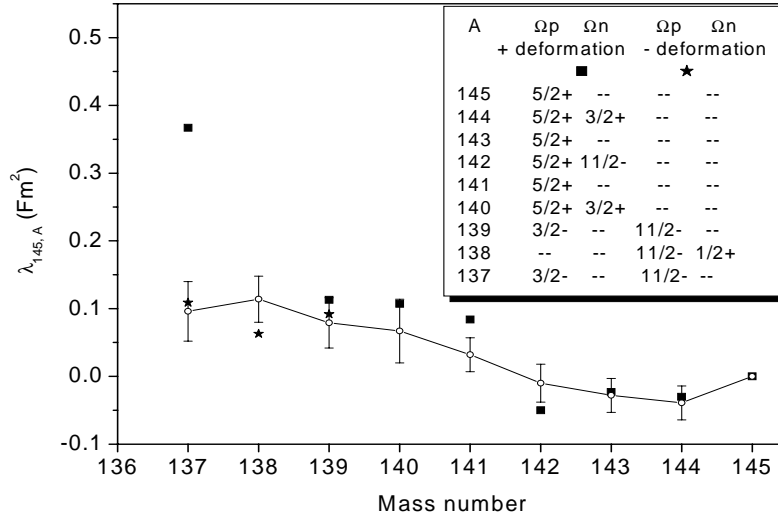

A	Ωp + deformation ■	Ωn	Ωp - deformation ★	Ωn
145	5/2+	--	--	--
144	5/2+	3/2+	--	--
143	5/2+	--	--	--
142	5/2+	11/2-	--	--
141	5/2+	--	--	--
140	5/2+	3/2+	--	--
139	3/2-	--	11/2-	--
138	--	--	11/2-	1/2+
137	3/2-	--	11/2-	--

Fig. 4. Hartree-Fock calculations with SkM′ forces for the neutron-deficient Eu isotopes

Hartree-Fock calculations with SkM′ forces for axially deformed nuclei have been performed for neutron-deficient Eu isotopes (see Fig. 4). The states blocked by the last odd particle were fixed in accordance with the known spin and parity of the corresponding nuclei (see Table in Fig. 4). For ^{137}Eu the agreement of the experimental and theoretical data can be obtained only for the negative deformation minimum on the conditions that the proton state with $\Omega^\pi = 11/2^-$ which lies closest to the Fermi level is blocked by the odd proton. The results of the Hartree-Fock calculations for the very neutron-deficient Eu nuclei are crucially dependent on the odd particle states. It should be noted that for the proper theoretical description of $^{137, 138, 139}$Eu a triaxial deformation should be taken into account instead of the negative quadrupole deformation.

3.2. Gadolinium

The isotope shifts of the optical line 569.622 nm for nuclides ^{145}Gd, ^{145m}Gd and ^{143m}Gd have been measured [3]. For ^{145}Gd ($I = 1/2$) the hyperfine splitting has also been measured. During the data processing, spins for ^{145m}Gd and ^{143m}Gd have been fixed according to known values $I = 11/2$ because the resolution of the method applied is not sufficient to provide hyperfine splitting measurements for the independent determination of the spin values. The optical line width on the measured spectra is taken as a convolution of the laser linewidth and the Doppler broadening in the target-ion source system. Calculated by this way value of the optical line width (of about 2100 MHz) is in agreement with the width of a separate optical line in the experimental spectrum of ^{145}Gd.

We suppose that ^{145m}Gd with its closed proton sub-shell and one neutron vacancy has an electric quadrupole moment with the absolute value not exceeding 1 barn. The systematics for all known nuclei with

[3] V.S. Letokhov *et al.*, J. Phys. G **18**, 1177 (1992).
[4] A.E. Barzakh *et al.*, Eur. Phys. J. A **1**, 3 (1998).

the same neutron configuration and spin (for instance ^{147}Dy: $Z = 66$, $N = 81$, $I = 11/2$, $Q_s = 0.67(10)$ barn) sidewards confirm this estimation.

At this supposition, taking into account the optical linewidth and varying the quadrupole moment in the limits mentioned above, the magnetic moment of ^{145m}Gd can be determined from the broadening of the line in the ^{145m}Gd spectrum. In Table 2 the experimental results on isotope shifts and hyperfine structure constants are shown. For ^{143m}Gd there are no reliable limits for the quadrupole moment. Therefore only the isotope shift for this nuclide has been determined as a distance between the centers of gravity of ^{143m}Gd and ^{160}Gd optical lines.

Table 2

Experimental results for isotope shits $\Delta\nu$ and
hyperfine structure constants a in the 569.622 nm line of Gd isotopes

Isotope	$\Delta\nu_{A,160}$, MHz	a, MHz
^{145m}Gd (I=11/2)	−12350(320)	−7.5(1.5)
^{145}Gd (I=1/2)	−12550(190)	−58.8(3.8)
^{143m}Gd (I=11/2)	−12350(350)	−

Table 3 represents the values of the nuclear parameter $\lambda_{A,A'} \approx \delta\langle r^2\rangle_{A,A'}$ and dipole magnetic moments evaluated according to the standard procedure [5].

Table 3

Changes of mean-square charge radii and dipole magnetic moments of Gd isotopes

Isotope	$\delta\langle r^2\rangle_{A,160}$, fm^2	μ, n.m.
^{145m}Gd (I=11/2)	−1.76(5)	−1.0(0.2)
^{145}Gd (I=1/2)	−1.79(3)	−0.74(5)
^{143m}Gd (I=11/2)	−1.69(5)	−

3.3. Changes of mean-square charge radii $\delta\langle r^2\rangle_{A,146}$ of Gd nuclides with $I = 11/2$ as compared with data for Eu ($Z = 63$) isotopes with the same neutron numbers

In Fig. 5 the data for $\delta\langle r^2\rangle_{A,146}$ of the Gd nuclides with $I = 11/2$ are presented as compared with the data for Eu ($Z = 63$) isotopes with the same neutron numbers. The value of $\delta\langle r^2\rangle_{146,160}$ for Gd has been measured earlier at the IRIS facility [5].
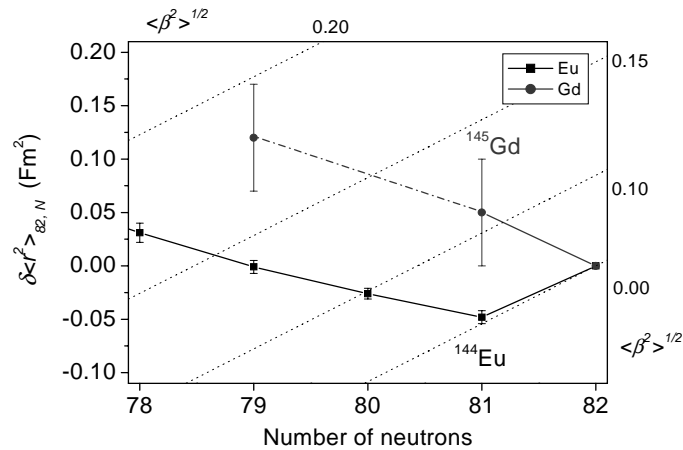

Fig. 5. Changes of mean-square charge radii of Gd nuclides with I =11/2 as compared with data for Eu ($Z = 63$) isotopes

---

[5] G.D. Alkhazov *et al*., JETP Lett. **48**, 373 (1988).

Obviously, the deformation for Gd isotopes rises with the decrease of the neutron number from $N = 82$ to $N = 79$ even faster than for adjacent Eu isotopes with the same neutron number. Therefore there is no indication on the stabilization effect of the proton sub-shell $Z = 64$ near the neutron sub-shell $N = 82$. Values of the dipole magnetic moments measured for [145]Gd and [145m]Gd are close to the values of the dipole magnetic moments for [141, 141m]Sm: [141]Sm, $\mu(I = 1/2) = -0.74(2)$ n.m. and [141m]Sm, $\mu(I = 11/2) = -0.84(2)$ n.m.

4. Conclusion

The laser ion source has been used for the study of the isotope shifts of neutron-deficient Eu and Gd isotopes. The extension of the region of the applicability of the method by using the γ- and β-radiation detection is reported. We have measured the isotope shifts of the Europium optical line 576.520 nm for [137-144]Eu and 569.622 nm for [145, 145m, 143m]Gd. Changes in mean square charge radii for [137]Eu, [145, 145m, 143m]Gd and magnetic moments for [145, 145m]Gd have been determined for the first time.

The resonance ionization directly inside the target (without special ion source unit) was used for producing the Gd nuclides under study. For such a hard volatile element as gadolinium (boiling point is 3546°C) an effusion is the main process responsible for the delay of nuclides in the target–ion source system. The newly developed target was specially designed for the production of elements with long sticking time such as Gd to exclude "cold spots" which sometimes exist at the places of the target – transfer tube – ion source connection. The laser has ensured the resonance count of Gd ions considerably higher than the target system of the usual construction. The most likely explanation of that effect can be a much higher concentration of Gd radioactive neutrals irradiated by the laser beam inside LT than in the volume of the laser ion source.

The gradual transition from the spherical nuclei near the magic neutron number $N = 82$ to the deformed ones near $N = 74$ contrasted with the abrupt increase of deformation on the other side of the same magic neutron number for Eu isotopes at $N = 89$. This different behavior is supposed to be connected with the different influence of the semi-magic number $Z = 64$ on the deformation development for the nuclei with $N > 82$ and $N < 82$.

There is no indication on the stabilization effect of the proton sub-shell $Z = 64$ near the neutron sub-shell $N = 82$ for Gd isotopes as well. Values of the dipole magnetic moments measured for [145]Gd and [145m]Gd are in a good agreement with magnetic moments of other nuclei with the same neutron number.

References

1. V.N. Panteleev *et al*., Rev. Sci. Instr. **75**, 1585 (2004).
2. A.E. Barzakh *et al*., Eur. Phys. J. A **22**, 69 (2004).
3. A.E. Barzakh *et al*., Phys. Rev. C **72**, 017301 (2005).