MEASUREMENTS OF CHARGE RADII AND ELECTROMAGNETIC MOMENTS OF NUCLEI FAR FROM STABILITY BY PHOTOIONIZATION SPECTROSCOPY IN A LASER ION SOURCE

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1. Introduction

During the last decades many nuclei far from stability have been investigated using laser based spectroscopic techniques. The study of atomic isotope shifts and hyperfine structures provides evaluation of nuclear spins, electromagnetic moments and changes in mean square charge radii $\delta\langle r^2\rangle$.

At the IRIS mass-separator at the PNPI synchrocyclotron laser investigations have previously been performed using resonance photoionization spectroscopy in an atomic beam [1]. This experimental technique enables successful experiments with the isotopes at a production rate down to 10^4 atoms per second. To extend the investigations to the more neutron deficient isotopes (first of all to the region of neutron deficient Yb and Tm isotopes near magic neutron number $N = 82$) photoionization spectroscopy in a laser ion source has been applied.

In this region a deviation from the established systematic behaviour of the isotope shifts for the Yb isotopes with $N = 82$–84 has been recently reported (see G.D.Sprouse *et al*., Phys. Rev. Lett. **63**, 1463 (1989)). The measurements indicate that the charge radii of Yb isotopes, between $N = 82$ and $N = 84$, increase far more rapidly than those in the other isotopic chains in this region. A strong deformation jump at $N = 84$ (^{154}Yb) was supposed to cause this surprising effect (G.D.Sprouse *et al*). It is of interest to measure the isotope shifts and hyperfine structures of the adjacent odd isotopes, $^{153, 155}$Yb, in order to estimate the deformation value of the Yb isotopes with $N = 82$–86. Besides, it is of importance to investigate the isotopes of the neighbouring elements with the same neutron number.

2. Experimental method

In this work we have used the method of photoionization spectroscopy in a laser ion source [2]. Atoms are ionized by step-by-step resonant laser excitation to autoionizing states or continuum. The following ionization schemes were used:

– for Yb atoms:

$$6s^2\,{}^1S_0 \xrightarrow{555.6\ \text{nm}} 6s6p\,{}^3P_1 \xrightarrow{581.1\ \text{nm}} 4f^{13}(^2F_{7/2})6s^2 6p_{3/2} \xrightarrow{581.1\ \text{nm}} \textit{autoionizing state (or continuum),}$$

– for Tm atoms:

$$4f^{13}6s^2\,{}^2F_0 \xrightarrow{597.1\ \text{nm}} 4f^{13}6s6p\ (7/2,0)_{7/2} \xrightarrow{600.3\ \text{nm}} 4f^{13}5d6s \xrightarrow{552.4\ \text{nm}} \textit{autoionizing state.}$$

The experimental set-up is presented in Fig. 1. Nuclides under study were produced in the tantalum target (12 g/cm^2) of the mass-separator by 1 GeV protons. The atoms were thermally released from the target to the ionizer tube (1.5–2.5 mm in diameter, 60 mm in length) made of Nb or W, where they were ionized by the beams of three pulsed dye lasers merged into a single beam. The dye lasers (of average power ~ 300 mW) were pumped by three copper vapour lasers at a repetition rate of 9 kHz. The frequencies of the dye lasers were tuned to the resonance transitions of the chosen excitation scheme. The radiation frequency of the two broadband lasers (bandwidth 30 GHz) were fixed in accordance with the second and the third step excitation frequencies. In the experiments with ^{153}Yb the radiation of the broadband laser was amplified in a dye cell amplifier pumped by copper vapour laser. Average power of the laser+amplifier system was 900 mW. The wavelength of the narrow band laser (bandwidth 1 GHz) was scanned. On resonance the photoion current in

the mass-separator collector increases. Thus, the experimental spectra represent the dependence of ion current on the scanned laser frequency.

The high efficiency of the method provided by the following factors. Multiple intersection of the laser beam by the atoms in the laser ion source cavity considerably increases the probability of photoionization. At the same time electron emission from the heated tube wall creates an electric potential near the wall, which traps photoions near the central axis and prevents their recombination on the wall surface. The electric field created by the heating DC drives photoions towards the extraction electrode of the mass-separator. A portion of the scanning laser radiation was directed to the Fabry-Perot interferometer (free spectral range 5 GHz) to produce the frequency marks for frequency scale calibration. Another part of the laser beam was used in a reference chamber to provide a reference spectrum from the sample of stable isotopes. Two modes of photoion detection have been used:

(1) direct registration of the ion current by the channel electron multiplier (when selectivity was high enough), and

(2) registration of the α-particles from the decay of the isotopes under investigation.

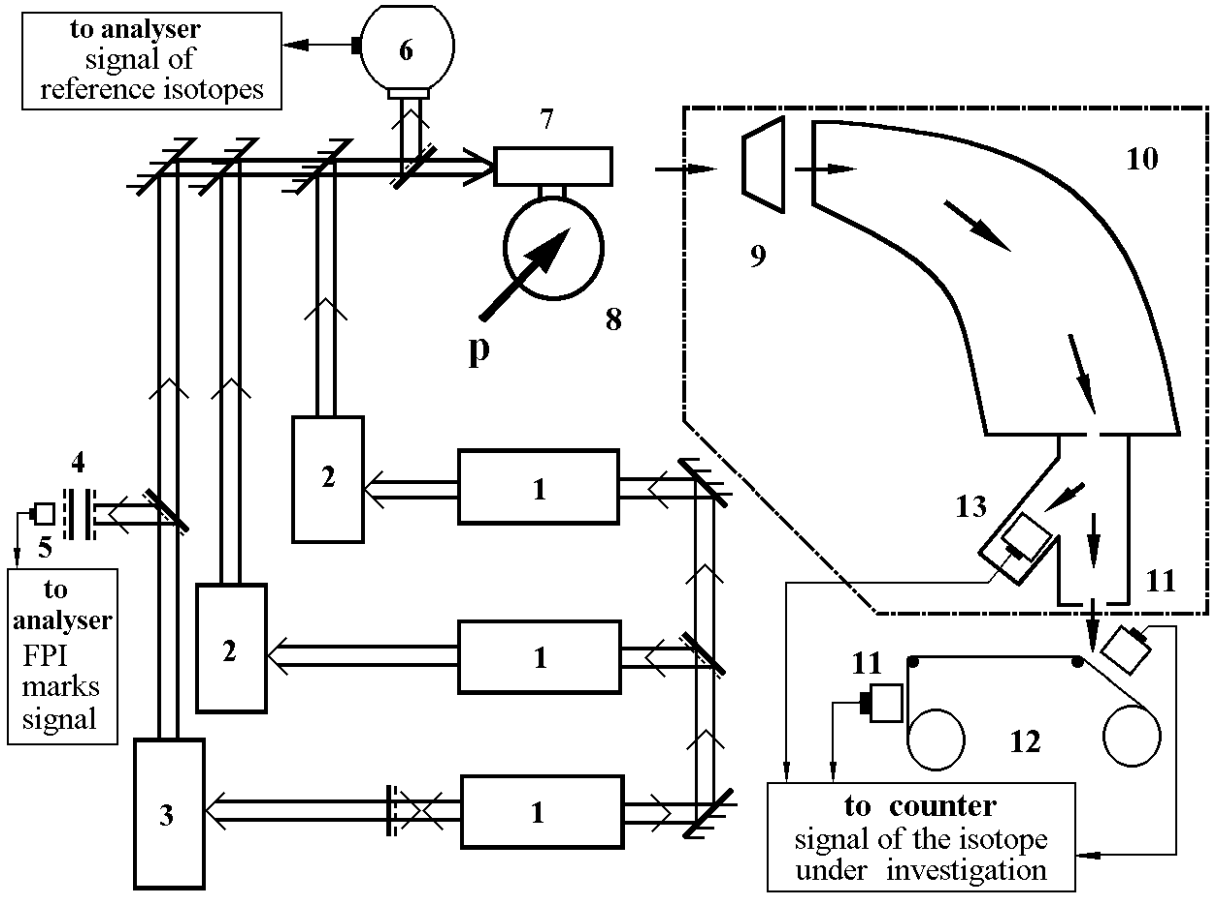

Fig. 1. Experimental setup

1 – Cu-vapour lasers; 2 –broadband dye laser; 3 – narrowband scanning dye laser; 4 – Fabry-Perot interferometer; 5 – photodiode; 6 – reference chamber; 7 – laser ion source; 8 – target; 9 – extraction electrode; 10 – mass-separator; 11 – α-detector, 12 – tape-driving device; 13 – channel electron multiplier

Background ions are produced by the surface ionization inside the ion source and the target as well. If the production rate of isobars is significantly higher than that of isotope under study, the background ion current can make the direct ion counting by the electron multiplier impossible. In such case an isotope selective method of registration is required.

In our experiments a high temperature target ($T \geq 2500$°C) has been used. In this case the main part of the background current comes from the target itself. In order to extend the applicability of the RIS/LIS technique a new method of isobar suppression has been developed [3] and applied. In this method suppression is provided by the locking of the background thermoions inside the high temperature target by a potential of the heating direct current flowing through the target container. The background current was reduced by a factor of 20 using this technique. The application of this method of background suppression has provided an opportunity to perform measurements of isotope shifts and hyperfine structures for radioactive Tm isotopes when isobaric contamination is severe.

3. Experimental results

In experiments with $^{158-164}$Yb and $^{158-163}$Tm photoions were detected with the channel electron multiplier. The experimental spectra obtained in this experiments are shown in Figs. 2, 3. The measured IS are presented in Tables 1, 2 and compared with reference data. In the experiments with $^{153, 155, 156}$Yb and $^{153, 154}$Tm a selective photoion detection by registration of the α-particles from the decay of the isotopes under study was applied. For ^{153}Yb the registration of the α-particles from the decay of its daughter nucleus (^{153}Tm) was applied. The experimental spectra obtained in this experiments are shown in Figs. 4, 5. The measured values of the isotope shifts and the hyperfine structure constants and the corresponding values of $\delta\langle r^2\rangle$, μ, and Q_S, calculated with the aid of the well-known scaling relations are given in Table 3. The measured value of isotope shift of ^{156}Yb ($\Delta\nu_{174,156}$ = 17610(120) MHz) is in agreement with that measured by Sprouse *et al.* ($\Delta\nu_{174,156}$ = 17514(21) MHz). The total ionization efficiency calculated as the ratio of the experimentally observed ion beam intensity and calculated production rate of ^{156}Yb is about 10%. The estimated minimal production rate of ^{153}Yb or ^{153}Tm yet sufficient for measurement of isotope shifts is equal to 10^2 nuclides per sec.

The data for the Tm isotopes can be compared with the analogous data for the Ho isotopes with the same neutron numbers and spins [4]. The magnetic moments of the Tm isotopes are very close to the corresponding single particle values and practically coincide with the magnetic moments of the isotonic isotopes with the same spin: $\mu_{sp}(11/2)$ = 6.9 n.m., $\mu(^{151}\text{Ho}, I = 11/2)$ = 6.93(2) n.m., $\mu(^{152}\text{Ho}, I = 9)$ = 5.92(2) n.m., $\mu(^{152}\text{Ho}, I = 2)$ = –1.02(2) n.m. The slope for the isotopic dependency of $\delta\langle r^2\rangle$ is very close to the corresponding values for Ho and Er. Thus the characteristics of the Tm isotopes with N = 84–86 do not noticeably deviate from the systematic trends in this region of the nuclide chart.

Table 1

Isotope shifts of Yb isotopes, measured with the direct registration of the ion current by the electron multiplier

Isotope	$\Delta\nu_{174,A}$, MHz	$\Delta\nu_{174,A}$, MHz [2]
^{166}Yb	5327(100)	5290(4)
^{164}Yb	7368(100)	7331(6)
^{162}Yb	9703(100)	9710(8)
^{160}Yb	12278(100)	12257(10)

Table 2

Isotope shifts of Tm isotopes, measured with the direct registration of the ion current by the electron multiplier

Isotope	$\Delta\nu_{169,A}$, MHz	$\Delta\nu_{169,A}$, MHz [5]
^{163}Tm	4140(80)	4101(20)
^{162}Tm	5425(100)	5460(50)
^{160}Tm	7590(190)	7538(40)
^{158}Tm	10145(180)	10205(80)

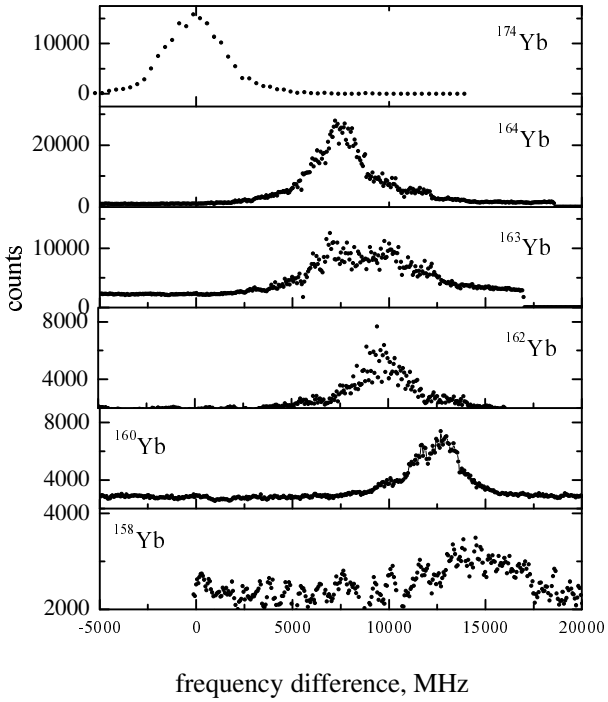

Fig. 2. Experimental spectra of $^{158\text{-}164}$Yb

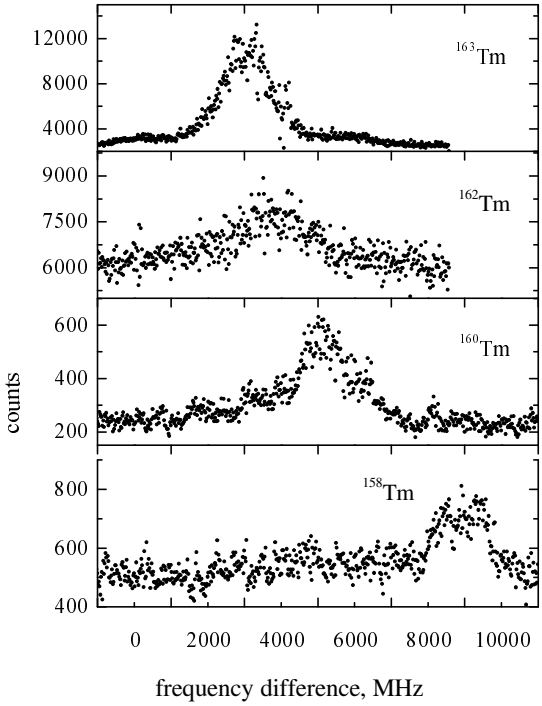

Fig. 3. Experimental spectra of $^{158\text{-}163}$Tm

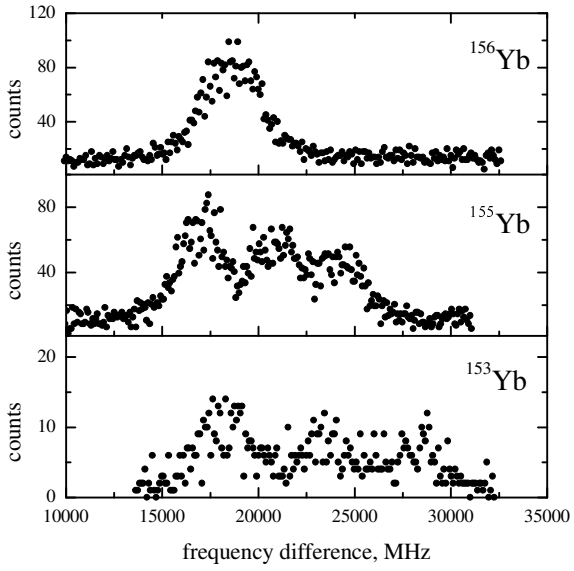

Fig. 4. Experimental spectra of ^{153,155,156}Yb

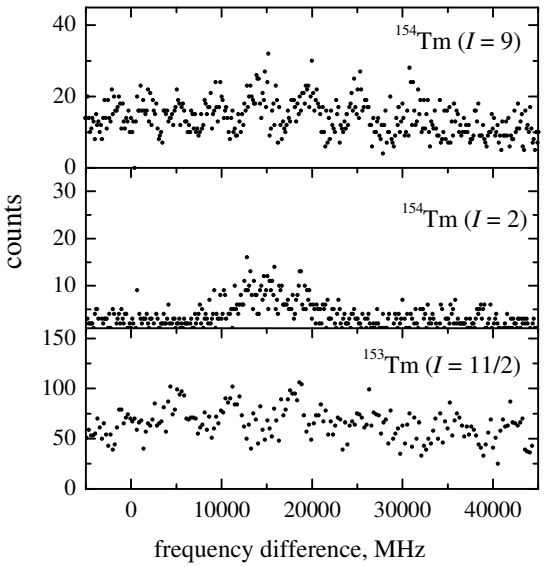

Fig. 5. Experimental spectra of ^{153,154}Tm

The isotopic changes of mean square charge radii for Yb isotopes with N = 82–86 are presented in Fig. 6. Corresponding data (Otten, E.W., "Nuclear Radii and Moments of Unstable Isotopes," in *Treatise on heavy-ion science*, Vol. 8, edited by D.A. Bromley, Plenum, New York, 1989, pp. 517–638) for Dy (Z = 66) and Sm (Z = 62) isotopes are also shown for comparison. The IS data for $^{152–154}$Yb point to the inverse odd-even

staggering effect (see Fig. 6). Usually this effect corresponds to the development of static octupole deformation (Ra, Fr isotopes). In the case of near magic Yb isotopes the similar description seems to be doubtful. The small negative values of the spectroscopic quadrupole moment of ^{153,155}Yb make also doubtful the explanation of the unusual $\delta\langle r^2\rangle$ behaviour by static quadrupole deformation.

Table 3

Ground state characteristics of ^{153}Yb, ^{155}Yb, ^{153}Tm (I = 11/2), ^{154}Tm (I = 2) and ^{154}Tm (I = 9)

Isotope	$\delta\nu_{174,A}$, MHz	A, MHz	B, MHz	$\delta\langle r^2\rangle_{174,A}$, fm^2	μ, n.m.	Q_S, b
^{155}Yb	19115(80)	-1050(25)	160(80)	–1.623(8)	-0.913(22)	-0.5(3)
^{153}Yb	21695(150)	-1210(30)	490(20)	–1.843(12)	-1.052(25)	-1.5(6)

Isotope	$\delta\nu_{169,A}$, MHz	A, MHz	B, MHz	$\delta\langle r^2\rangle_{169,A}$, fm^2	μ, n.m.	Q_S, b
$^{154,I=9}$Tm.	15520(150)	532(3)	200(500)	–1.522(15)	5.91(5)	-0.2(4)
$^{154,\ I=2}$Tm	15150(200)	-460(10)	-600(1200)	–1.486(19)	-1.14(2)	0.4(9)
$^{153\ I=11/2}$Tm	16470(320)	1020(16)	-700(1300)	–1.615(31)	6.93(11)	0.5(10)

The errors shown in Table 3 are purely experimental. Systematic uncertainty for $\delta\langle r^2\rangle$ is determined by the uncertainty in the semiempirical calculation of the F and M values (Yb: F = –11.9 GHz/fm^2, M = 296 GHz/a.m.u.; Tm: F = –10.3 GHz/fm^2, M = 268 GHz/a.m.u.). It is supposed to be about 5% (according to Otten).

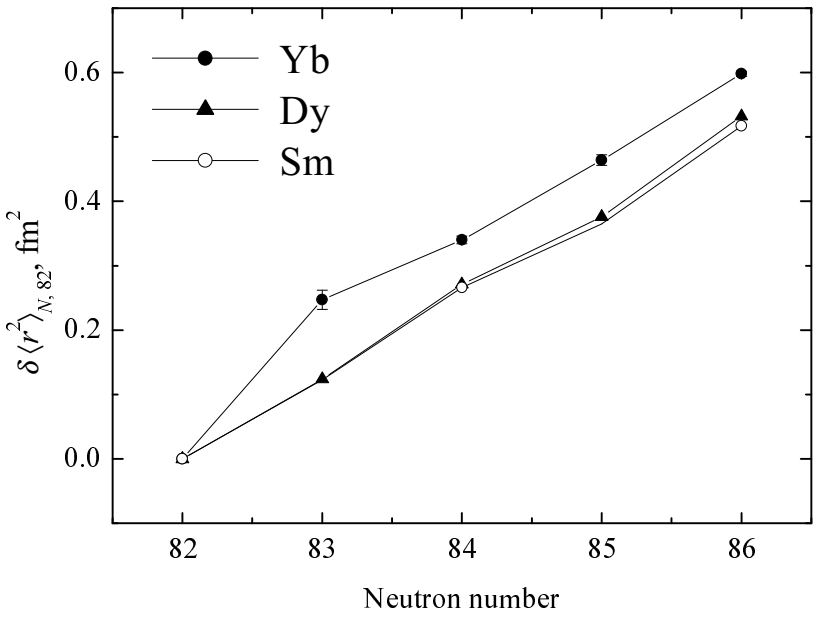

Fig. 6. Change in mean square charge radii of Yb, Dy and Sm isotopes relative to N = 82

4. Conclusion and outlook

The on-line experiments with neutron deficient Yb and Tm isotopes have shown a high sensitivity of the method of resonant photoionization in a laser ion source. The further development of this experimental method – enhanced Target-Ion Source system aimed to suppress thermoionic background – essentially widens the range of the applicability of the RIS/LIS method. Application of the other modes of registration, for example, by *X*-ray or γ-detection enables the further extension of the region of applicability of this method of laser spectroscopy.

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