Resonance photoionization spectroscopy and laser separation of 141Sm and 164Tm nuclear isomers

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RESONANCE PHOTOIONIZATION SPECTROSCOPY AND LASER SEPARATION OF ^{141}Sm AND ^{164}Tm NUCLEAR ISOMERS

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The 141g and 141m samarium and 164g and 164m thulium nuclear isomers have been separated for the first time by the laser selective atomic photoionization technique in on-line experiments with a proton accelerator and a mass separator. The hyperfine structure of the ^{141}Sm isomer lines has been studied and the nuclear parameters μ, Q, and $\delta\langle r^2\rangle$ of the isomers determined.

1. Introduction

Many nuclear investigations require samples with nuclei in a single isomeric state. The selective laser photoionization of atoms with nuclei in the ground and excited states is practically the only means of their separation. Such a possibility was discussed as far back as 1973 in ref. [1] and later, together with the possibility of separating isotopes, in ref. [2] and also in ref. [3]. The selective laser photoionization of Eu isomers was first observed by us in on-line experiments in the studies of the hyperfine structure and isotope shift of the atomic lines of a series of radioactive Eu isotopes [4,5]. The selective photoionization of mercury-137 isomers was reported in ref. [6]. In the experiments which we reported in this paper, the hyperfine and isotope structures of the atomic lines of ^{141}Sm and ^{163}Tm isomers have been analyzed by laser photoionization spectroscopy. The experiments have been conducted using an atomic beam in a manner typical of laser isotope separation experiments described in the literature in sufficient detail [2]. We can therefore say with confidence that in our experiments we have realized separation of ^{141}Sm and ^{164}Tm isomers.

2. Experimental setup and technique

Our experiments were performed at the laser-nuclear facility installed on the proton beamline of the Gatchina synchro-cyclotron. Isotopes in the ground and excited nuclear states accumulated in a hot tantalum target as a result of a spallation reaction induced by bombarding the target with 1 GeV (fig. 1). These isotopes diffused through the tantalum target foils and entered an ionizer where they got ionized on a hot tungsten surface and then were separated according to their masses in a mass separator. A beam of mass-separated fast ions thus obtained and containing isobars and isomers with a kinetic energy of 30 keV was neutralized and thermalized on the bottom of a hot tantalum cylinder installed in its way. The atoms formed from the ions emerged from the cylinder as an atomic beam which was irradiated with three laser beams. The resultant photoions were extracted from the atomic-laser-beam interaction region by means of an electric field acting in a direction normal to the atomic beam (for more detail see refs. [4,5,7]).

The first excitation stage used radiation from a tunable single-frequency cw dye laser that was amplified in a dye cell pumped by a Cu-vapor laser. The bandwidth of the amplified radiation, equal to 50

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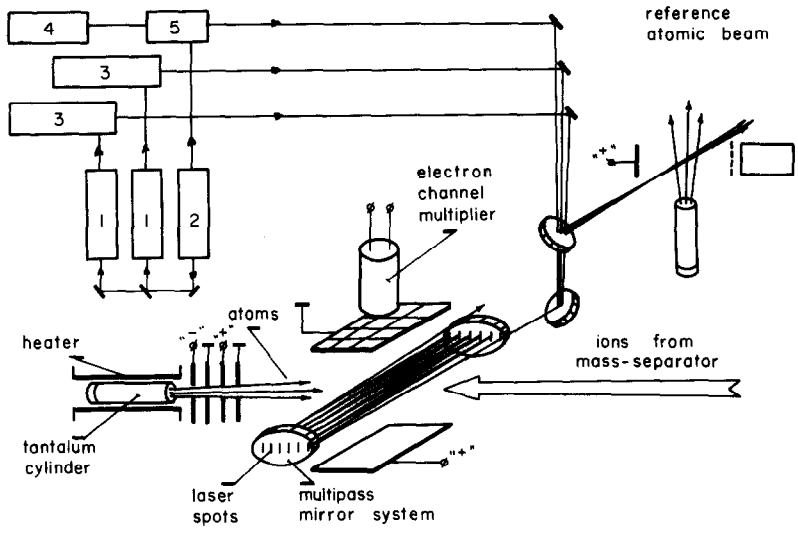

Fig. 1. Diagram of the experimental setup. 1 – Cu-vapor laser amplifiers, 2 – Cu-vapor oscillator, 3 – pulsed dye-lasers, 4 – cw Ar ion laser with cw dye laser, 5 – pulsed dye laser amplifier.

MHz, was inferior to the residual Doppler atomic linewidth (150 MHz). The high pulse power of the amplified radiation made it possible to saturate the atomic transition over the entire width of the inhomogeneously broadened atomic excitation line. The linewidth of the second- and third-state excitation lasers (Cu-vapor laser pumped dye lasers) was equal to 0.8 cm^{-1} and exceeded the hyperfine structure width of these transitions. The average radiation power of these lasers amounted to 0.3–0.6 W.

The photoions produced in the course of the multistep lasers excitation and extracted by the electric field from the interaction region were deposited onto the cathode of a channel multiplier serving to detect them. With the first-stage excitation laser frequency being tuned to resonance with the atomic line, the proportion of photoions relative to the total amount of the mass-separated isotope ions entering the tantalum neutralizer was 10^{-4}.

The photoion spectrum resulting from the photoionization of the isomers from states with different angular momenta was obtained by varying the frequency of the first stage excitation laser.

3. ^{141}Sm isomers

The photoionization of samarium atoms occurred as a result of three successive resonance transitions into an autoionization state induced with pulsed dye lasers. The transition sequence was as follows: $4f^6 6s^2\ {}^7F_2 + \hbar\omega_1(6004.18\text{Å}) \rightarrow 4f^6 6s6p^5 G_2^0 + \hbar\omega_2(6751.52\text{Å}) \rightarrow 32269.8\ cm^{-1} + \hbar\omega_3(6761.9\text{Å})$ → autoionization state.

Fig. 2 presents the photoionization spectrum of a mixture of ^{141}Sm isomers and the result of its deciphering. The hyperfine structure parameters and isomer shift of the $6s^2\ {}^7F_2 \rightarrow 6s6p^5 G_2^0(6004.18\text{Å})$ transition are listed in table 1. The nuclear parameters obtained from these data, such as the magnetic dipole moment ω, electric quadrupole moment Q, difference in mean-square charge radius between nuclei in the ground and excited states, and spin I [8], can be found in table 2.

Similar measurements were also carried out for $^{138-147}$Sm isotopes [9].

It can be seen from fig. 2 that the photoionization spectrum contains well-defined lines belonging to ^{141m}Sm. This means that when the wavelength of the first-stage excitation laser is tuned somewhere in the range 1–4 GHz, there emerges a beam of photoions

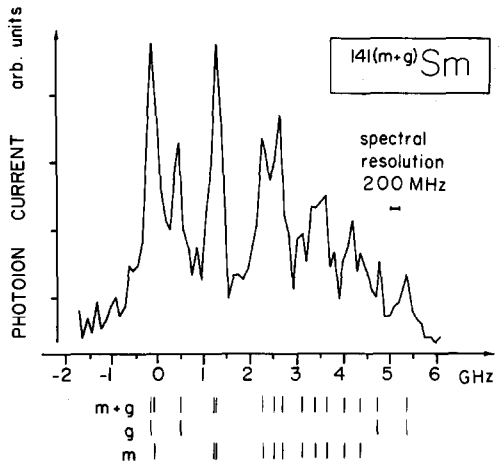

Fig. 2. Spectrum of the $4f^6 6s^2\ {}^7F_2 \rightarrow 4f^6 6s6p\ {}^5G_2^0$ (6004.18Å) transition for the ^{141}Sm isotope in the ground and excited nuclear states, obtained by the three-step atomic photoionization technique. Shown at the bottom are the positions of the lines found when deciphering the spectrum.

with isomeric nuclei in a direction normal to the atomic beam.

4. ^{164}Tm nuclear isomers

The photoionization of thulium atoms also resulted from three successive resonance transitions into an autoionization state. The transition sequence was as follows: $4f^{13}6s^2\ {}^7F_{7/2} + \hbar\omega_1(5896Å) \rightarrow 4f^{12}5d6s^2(6, 7/2)_{7/2} + \hbar\omega_2(5712Å) \rightarrow 4f^{12}\ 5d6s6p + \hbar\omega_3(5755Å)$ $\rightarrow$autoionization state.

Table 1
Hyperfine structure parameters and isomer shift of $6s^2\ {}^7F_2 \rightarrow 6s6p\ {}^5G_2^0$ (6004.18Å) transition of ^{141}Sm

A	a (MHz)	b (MHz)	$\Delta\nu^{A,147}$(MHz)
141	−261(8)	0	2242(100)
141m	−26.9(6)	391(105)	1968(60)

Fig. 3 presents experimental photoionization spectra and the results of their deciphering. The spectrum of fig. 3a was obtained for a mixture of ^{164}Tm isotopes in the ground and excited states. The fluxes of ^{164}Tm emerging from the target in the ground and excited states were practically the same. To identify atomic lines of the hyperfine structure, one needs a spectrum belonging to the isotope either in the ground or in the excited nuclear state. For this purpose, we obtained ^{164}Tm in the ground state as follows. The ion beam at the exit from the mass separator contains a number of isobars, ^{164}Yb in particular. ^{164}Yb ($T_{1/2}=76$ min) decays to yield ^{164}Tm ($T_{1/2}=2$ min) in the ground state, the isomeric thulium state remaining practically unpopulated. Isobars with the mass number $A=164$ accumulated in the cold tantalum cylinder during 1 hour. Then a 15-min time interval was maintained to allow the ^{164m}Tm isomer to decay ($T_{1/2}=5$ min). After that the cylinder was heated. Fig. 3b shows the photoionization spectrum of ^{164}Tm in the ground nuclear state.

Comparing the spectra of figs. 3a and b, it can be concluded that there exist excitation lines belonging to the ^{164}Tm isotope either in the ground or in the excited nuclear state.

5. Discussion and conclusion

An analysis of the photoionization spectra of figs. 2 and 3 shows that for ^{141}Sm and ^{164}Tm there exist frequency regions containing excitation lines belonging only to atoms with isomeric nuclei. Inasmuch as the laser photoionization scheme is such that an isomeric photoion can be detected only after it has been extracted from the atomic beam and deposited onto the multiplier cathode, one can speak of isomer separation in this experiment. The probability that neutral particles from the atomic beam will reach the multiplier (the beam being practically fully freed from ions by the electric protection [4,6,7]) is

Table 2
Nuclear parameter of ^{141}Sm isomers

	A	I	μ(nm)	Q_s(barn)	$\langle r^2\rangle^m - \langle r^2\rangle^g$	$T_{1/2}$(min)
	141	1/2	−0.735(23)	0	0.050(11)	10.2
	141m	11/2	−0.83(2)	1.63(44)		22.6

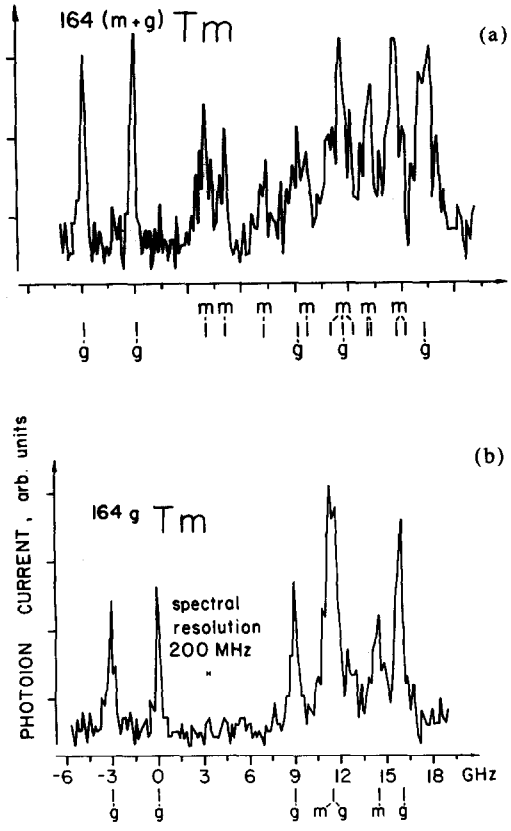

Fig. 3. Photoionization spectrum of the $4f^{13}6s^2\ {}^7F_{7/2} \rightarrow 4f^{12}5d6s^2(6, 7/2)_{7/2}(5896\text{Å})$ transition for the ^{164}Tm isotope in (a) the ground and isomeric nuclear states and (b) the ground nuclear state.

extremely low. The width of the spectral regions containing isomer lines is around 3 GHz, which is greater than the Doppler width of the atomic excitation line in vapors. For this reason, to raise the photoion yield, use can be made of the technique of laser atomic photoionization in a hot cavity [10]. In this latter work, we have experimentally demonstrated that the yield of Sr photoions from the cavity as a result of three-step laser photoionization reached 20%.

Note that our experimental setup consisting of a mass-separator, a laser spectrometer, and a photoionization chamber arranged in line with a proton accelerator allows one to study and separate isomers with a lifetime of the order of the time of their extraction from the target. Typical targets provide for extraction times around 1 s. A similar setup can be built around other sources of isomeric nuclei, such as high-energy ion beams or a nuclear reactor.

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