INVESTIGATION OF SPINS, ELECTROMAGNETIC MOMENTS AND CHARGE RADII OF RADIOACTIVE NUCLEI BY LASER SPECTROSCOPY

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One of the most important problems in nuclear physics is the proper description of the nuclear ground states. To solve this problem, one needs experimental information on the ground states characteristics. The significance of this information rises greatly when one can trace the changes of these characteristics with the changes of the nucleon numbers N and Z within sufficiently wide limits which lie far from the stability line. The task of the nuclear theory is twofold: firstly we have to describe the general trends of the observed isotopic and isobaric dependencies; then, it is of importance to explain the sudden changes of some nuclear parameters near some peculiar points on the chart of nuclides. Of special interest are the data on the nuclei near nucleon drip lines, since it is for these nuclei that the validity of up-to-date theoretical approaches could be questioned first of all.

The laser spectroscopy plays the leading role in the creation of the two-dimensional picture of the ground state properties. It enables one to determine spins I, magnetic dipole moments μ, electric quadrupole moments Q_s and also variations of the mean square charge radii $\delta < r^2 >_{AA'} = < r^2 >_A - < r^2 >_{A'}$ for isotopes with atomic numbers A and A' for nuclei very far from the stability line with the lifetime less than tens of milliseconds. Values of I, μ, Q_s are extracted from the hyperfine splitting of the optical atomic lines, and $\delta < r^2 >$ – from the isotopic shifts of these lines.

There are many spectroscopic methods which were applied for nuclear ground state investigation in different laboratories: observation of atomic fluorescence in the cooled atomic vapour or in the collimated atomic beams, optical pumping in the atomic vapour with the subsequent detection of asymmetry of β-decay, collinear laser spectroscopy in the fast atomic or ionic beams, etc.

In the middle of 70s the mass separator facility IRIS based on the 1 GeV proton synchrocyclotron was launched at PNPI under the supervision of late Prof. E.Ye.Berlovich. Due to his initiative, in 1979 the construction of a high-sensitive laser installation for hyperfine structure and isotopic shifts studies was also started. The first experimental results – isotopic changes of charge radii for long-lived Eu isotopes – were obtained in 1983 [1].

Experiments on the new laser installation were carried out in collaboration with Institute of Spectroscopy RAS (Troitsk). The method of resonance multistep ionization of atoms was used. This method was proposed earlier at Institute of Spectroscopy for solving the problem of single atom detection. At PNPI, this method was applied for the first time for investigation of radioactive atoms. The essence of the method is as follows. Photoionization takes place after stepwise (level by level) excitation of the atom in question to an autoionization state or immediately to the continuum. The photoions are detected with a channel electron multiplier. For atom excitation, dye lasers tuned to resonance with the frequencies of the corresponding atomic transitions are used. The dye lasers are pumped by synchronized Cu-vapour lasers. The scheme of the experimental setup is given in Fig. 1.

The isotopes under study were produced in a tantalum or uranium target by 1 GeV protons. After mass separation, the ions of the isotope to be investigated were implanted into a tantalum tube collector. The collector was heated and atoms of the isotope emerged as a well collimated

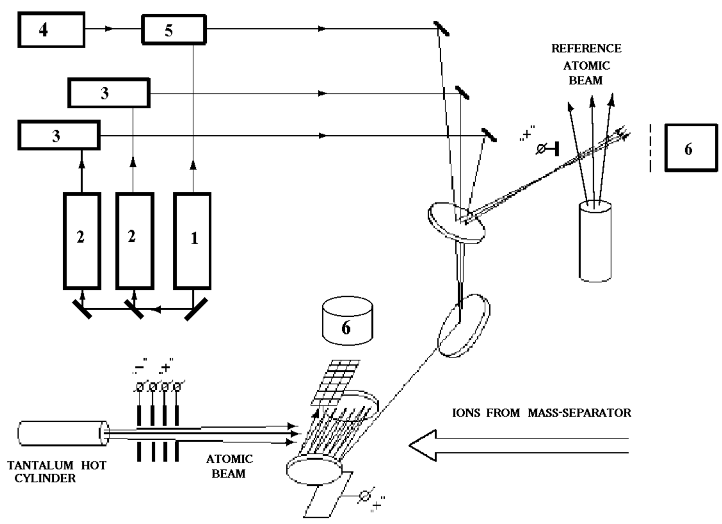

Fig. 1. Scheme of the experimental setup. 1 – Cu-vapour laser (oscillator); 2 – Cu-vapour lasers (amplifiers); 3 – dye lasers; 4 – system: Ar-ion laser and CW dye laser; 5 – pulsed dye-laser amplifier; 6 – channel electron multiplier.

beam which was intersected at a right angle by three laser beams merged into one. The laser radiation frequencies for the second and third excitation steps were kept in resonance with the atomic transitions chosen, while the first step excitation laser frequency was scanned. The optical spectra represented a number of photoions versus the scanned frequency.

The first-step excitation radiation was generated by a pulsed dye laser operated as an amplifier and a CW dye laser (Spectra Physic Mod. 380), pumped by Ar-ion laser (Spectra Physics Mod. 2020), as an oscillator. The linewidth of the amplified radiation was less than 30 MHz. The width of the lines in the measured spectra was 100–200 MHz, which was mainly due to residual Doppler broadening. The linewidth (about 30 GHz) of the dye laser radiation in the second and third steps of atom excitation overlapped both the isotope shifts (IS) and hyperfine splitting (HFS) of the corresponding transitions. The high sensitivity of the installation allows to carry out measurements with such a small intensity of the mass separated beam as 10^4 s^{-1}. For comparison, in the standard collinear spectroscopy method the minimum ion flux must exceed 10^6 s^{-1}.

At the IRIS mass separator, another technique for IS and HFS investigation was applied too – the high resolution collinear laser spectroscopy of ions in metastable states. The method was proposed at Marburg University (Germany) and was utilized for on-line measurements at PNPI in collaboration with physicists from this University. The high resolution (down to the natural linewidth) of this method is due to the Doppler broadening reduction as the result of the compression of the velocity distribution occurring in the accelerated particle beam. The experimental setup is presented in Fig. 2.

Two ion beams of different mass – one serving as a reference beam – were used in these experiments. The frequency of CW dye laser was stabilized by keeping it in resonance with the strongest HFS component of the reference isotope, the HFS of the isotope under study

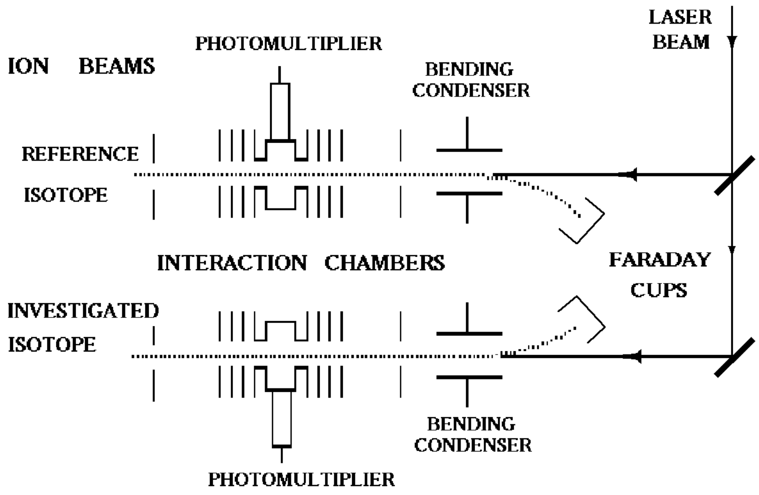

Fig. 2. Scheme of the experimental setup for the high resolution collinear laser spectroscopy.

being measured in the second beam line against the reference HFS component. The tuning to resonance was ensured by means of voltage scanning in the second interaction chamber. The laser light absorption in both beam lines was monitored via the fluorescence light which was detected by photomultipliers.

Since the ionic resonance lines lie usually in the UV region, it is convenient to use transitions from low-lying ionic metastable states. These transitions are well accessible for conventional CW dye lasers. Ionic metastable states are populated in a hot ion source [2].

The rare-earth nuclides were chosen as objects for investigation. The shape of these isotopes is rapidly changed on the both sides of the magic neutron number $N = 82$, and the character of this changing depends strongly on the proton number Z. Resonance ionization spectroscopy was used for investigation of Yb, Tm, Ho, Tb, Gd, Eu, Sm and Nd isotopes. Collinear ion beam spectroscopy was applied in accurate measurements for stable and long-lived Eu and Sm isotopes and isomers, as well as for radioactive ^{145}Pm and ^{147}Pm. The isotopes studied at PNPI with the aid of the laser spectroscopy are marked with black in Fig. 3. Their mean square charge radii determined in our experiments are displayed in Fig. 4, the known values of $< r^2 >$ for stable isotopes being taken into account.

The character of the isotopic dependence of $< r^2 >$ is due to the deformation of nucleus. As one can see from Fig. 4, there is a marked difference in a deformation behaviour on the both sides of $N = 82$. The isotopic dependences demonstrate the abrupt change of deformation near $N = 88$–90, this jump being bigger the nearer the proton to semimagic $Z = 64$. For nuclei with $N < 82$, deformation varies smoothly and reveals a strong Z-dependences. Such a difference in the deformation behaviour is considered to be connected with different character of the np interaction in the corresponding regions. A strong np interaction, which tends to destroy the subshell gap, takes place in nuclei with $N > 82$ only near $N = 88$–90, when a noticeable amount of neutrons appears in the $h_{9/2}$ shell which is a spin-orbit partner of the

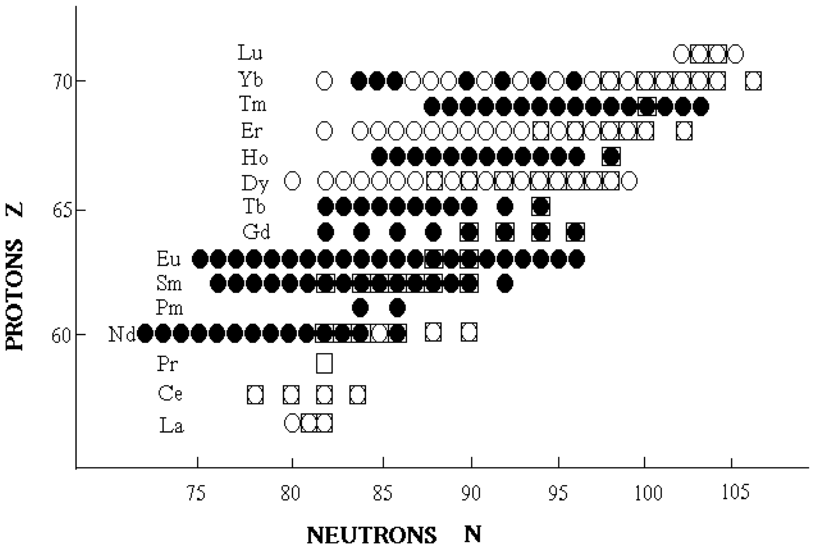

Fig. 3. Fragment of a chart of the nuclides. Squares – stable nuclides; circles – unstable nuclides.

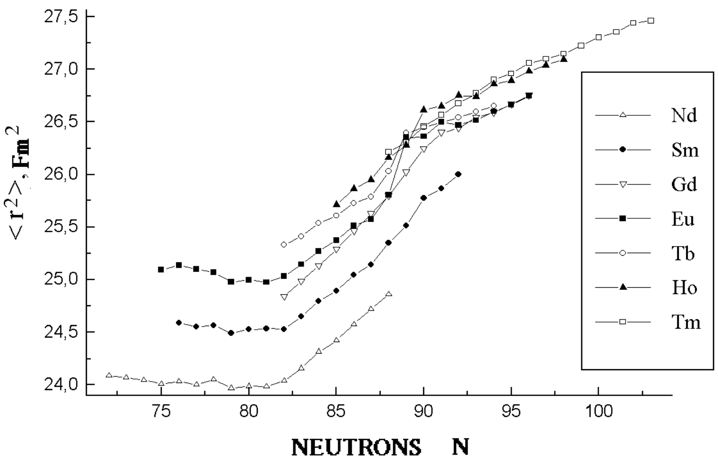

Fig. 4. Mean square charge radii $< r^2 >$.

proton $h_{11/2}$ shell. For the nuclei with $N < 82$, a strong np interaction of the $h_{11/2}$ protons and $h_{9/2}$ neutrons occurs immediately after crossing $N = 82$ [3].

There is a marked odd-even staggering in the charge radii: the radius of the odd-neutron isotopes, as a rule, is smaller than the mean of the radii of the adjacent even-neutron isotopes. In the vicinity of ^{154}Eu the odd-even effect changes the sign. The inverted staggering is supposed to be an evidence for the stable octupole deformation on the border of stable quadrupole deformation region.

A systematic study of the charge radii in the rare-earth region gives the opportunity to reveal the isobaric and isotopic dependencies of $< r^2 >$ in this region. The most remarkable feature of the isotonic curves for N = 82–90 is the absence of any visible discontinuity at $Z = 64$, unlike the case of the "true" magic number $Z = 50$ (for isotonic curve at $N = 66$).

The theoretical analysis of the experimental data was performed in our work on the base of both microscopic-macroscopic approach (with the Strutinsky's shell correction method) and Hartree-Fock (HF) calculations. Different versions of the Skyrme forces were tested. The general tendency of the calculated isotopic dependence of $< r^2 >$ turned out to be rather sensitive to the chosen force. Hence, comparison with the experimental results allows the choice of more realistic force to be made. It is obvious from Figs. 5,6 that the description of experimental

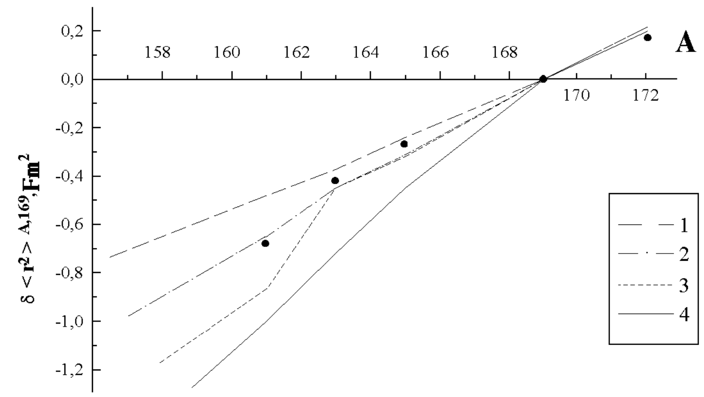

Fig. 5. The isotopic dependence of the Tm mean square charge radii. Experimental results are shown by solid circles, results of Hartree-Fock calculations – by curves: 1 – spherical nuclei, 2 – deformed nuclei (SkM' force), 3 – deformed nuclei ($S3$ force), 4 – drop model.

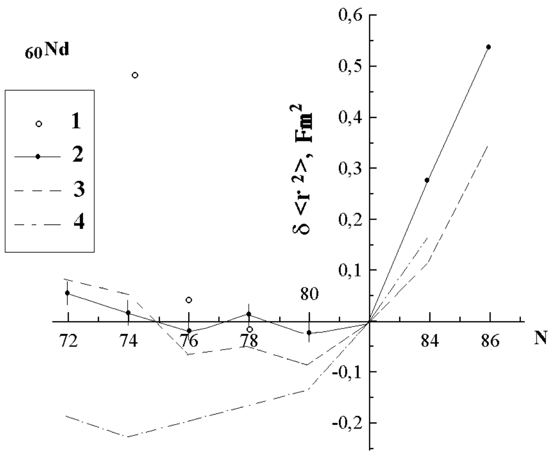

Fig. 6. The isotopic dependence of the Nd mean square charge radii. Hartree-Fock calculations: 1 – HF–BCS taking into account bound one-particle states only (SkM' force); 2 – experimental values; 3 – HF–BCS taking into account continuum (SkM' force); 4 – the same with $S3$ force.

radii with $S3$ force is worse than with SkM' force. Nevertheless, in the region of strong deformation even the "best" forces (SkM' and G_σ) do not reproduce radii well enough. The observed discrepancy may occur due to incorrect prediction for the volume changes of the radii, which are not related to the deformation. When spherical HF predictions (the spherical part of HF-values accounts for volume effects only) agree with standard droplet model calculations – it is the case of nuclei near N= 82, the total HF-values describe well the experimental data. A special significance of the data for isotopes near nuclear drip lines is confirmed by the comparison of the theoretical and experimental values on Fig. 6. When only negative energy single particle states are used in the BCS approximation, strong disagreement with experiment is found for nuclei very far from stability. Even a schematic consideration of continuum states changes the situation radically [4].

Optical spectroscopy of long isotope chains requires a high sensitivity, because isotope production yields drop when one goes out of the stability region. To increase the sensitivity, the use of a laser ion source was proposed and realized in PNPI. The experimental setup for IS measurements is presented in Fig. 7.

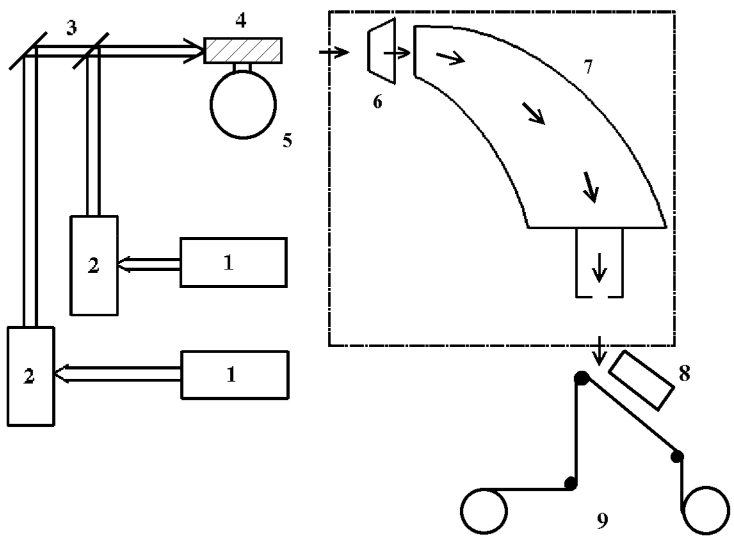

Fig. 7. Scheme for resonance photoionization spectroscopy of $^{154-156}$Yb in a laser ion source. 1 – Cu-vapour lasers; 2 – dye lasers; 3 – optics; 4 – laser ion source; 5 – target; 6 – extraction electrode; 7 – magnet of the mass-separator; 8 – α-detector; 9 – tape-driving device.

The laser ion source is a hot tube connected with a target. Laser radiation passes through the tube where radioactive atoms from target appear. Atoms in the tube, before their photoionization, can cross the laser beam many times. This repeated crossing leads to a significant enhancement of photoionization probability (up to 30%). It is essential that the photoions are not neutralized on the wall, since there exists a repulsive electric field near the wall as a result of a thermoelectron emission. The electric field, caused by direct current flowing through the tube to heat it, makes the ions to drift to the tube exit, where they are extracted by the accelerating electric field of the mass separator. This approach was tested by the IS and HFS measurements for $^{154-156}$Yb. To get rid of the background from surface ionization, a selective detection of photoions of a given isotope was used by counting α-particles of characteristic lines in the isotopic decay spectra. In this case, optical spectra represent the numbers of α-particles of the certain α-line plotted against the scanned frequency [5]. The experiment performed shows that the new method permits us to carry out spectroscopic measurements when the isotope production rate is as low as 1–10 atoms per second. Unfortunately, the resolution in this kind of experiments cannot be better than the Doppler width value. However, this drawback might be eliminated if one takes advantage of the saturation spectroscopy. In this method the laser radiation, after passing through a cell with atoms, is reflected backward, and the laser beam again crosses the cell. When the intensity of the incident radiation is sufficient to saturate the first step of multistep atomic excitation, in the centre of the photoion yield dependence on saturating radiation frequency a narrow dip occurs. The width of the dip corresponds to the bandwidth of the saturating narrow-band dye laser (near 30 MHz in the standard configuration). The combination of the saturation and resonance spectroscopy in a laser ion source promises to bring the sensitivity in the measurements with a good resolution of hyperfine splitting and isotope shifts to the value corresponding to the production rate in a target down to 10^2–10^3 atoms per second. This is quite sufficient for the determination of charge radius of ^{11}Li, this experiment would be very important in view of unusual and intriguing structure of this exotic nucleus.

In summary, laser spectroscopic studies of more than a hundred nuclides have been carried out at IRIS. Spins, electromagnetic moments and isotopic changes of mean square charge radii for these nuclei have been determined. Theoretical analysis of experimental data has shown the significance of the obtained results for the understanding of the nuclear structure. New approaches toward the refinement of the experimental method are proposed.

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