PROJECT OF NEW UNIVERSAL LASER COMPLEX OF IRIS FACILITY FOR ATOMIC AND NUCLEAR INVESTIGATIONS

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1. Introduction

The Short-Lived Nuclei Laboratory based at the IRIS (Investigation of Radioactive Isotopes on Synchrocyclotron) facility has been carrying out successful systematic investigations of the far from stability nuclei with the aid of laser technique since the beginning of 1980-es. More than 120 nuclides were studied, new approaches and methods of production and investigation of short-lived isotopes were developed and applied during this period.

In the near future the following directions of the scientific activity seem to be the most promising and important:

1. Nuclear spectroscopy.

a. The nuclear characteristics of the nuclei very far from stability (lifetime, decay modes, their branching ratios, *etc.*) are of great importance for the models of astrophysical processes (*r*- and *rp*-processes *etc.*). Due to the extremely low production rate in proton-nucleon collisions, the investigation of these nuclides has to be done at the background of isobars with production rates of some orders of magnitude higher than the isotope under study. Hence, the availability of the isobaric pure sources of the investigated nuclei becomes the key point for the investigation of the basic nuclear characteristics of these exotic nuclei.

b. The problem of "the magic numbers conservation" for the far from stability nuclides has the fundamental importance and also is connected directly with astrophysics. Recently obtained data point to the change of the magic numbers for very far from stability nuclei (the vicinity of ^{78}Ni, ^{65}Mn). This may lead to a revision of the magic number concept itself. Detailed nuclear-spectroscopic investigations of this areas and the search for other similar areas require the pronounced isotope and isobar selectivity also.

c. There is a number of interesting problems when the source of pure isomer could give an excellent opportunity for new investigations (isomer-selective measurements of beta-strength functions *etc.*). To this end the isomer selectivity is very important point.

2. Laser spectroscopy.

The traditional area of the laser spectroscopy application for the nuclear physics research is the isotope shift and hyperfine splitting measurements. Differences in mean square charge radii, spins and electromagnetic moments can be evaluated from these experimental data.

One of the most interesting objects for this laser-nuclear spectroscopy is an investigation of the so called shell effect in the mean square charge radii, *i.e.* the marked kink in the isotopic mean square charge radius dependence on the magic number. A disappearance of this kink may point to the change of the magic number.

In this respect the most interesting nuclei are Sb, Sn, In, Cd, Ag with the neutron number N close to 82. It is worth noting that it is the systematic investigation of mean square charge radii for the long isotopic chains that has to be done to discover the general trends and basic properties of the nuclear matter.

There is no enough information about the shell effect in the region near $N = 50$. Here the most interesting isotope chains are the chains of Ge, Ga, Zn, Cu, and Ni isotopes. These isotopes attract additional interest as unique objects to test the mean square charge radius trend between the two neighbor closed sub-shells.

Very special case is a vicinity of $N = 126$. The three orders of magnitude drop of the half-life values takes place for the isotopes of Ac, Ra, Fr, Rn, and At at the $N = 126$ (see Fig. 1, for example: $T_{1/2}(^{212}\text{Rn}) = 24$ min, $T_{1/2}(^{213}\text{Rn}) = 20$ ms). This leads to a fast drop of the production rates of the very short-lived nuclei, and the usual laser-nuclear spectroscopy method cannot be applied because of lack of sensitivity. Making the production efficiency of such nuclides higher we can get a chance to investigate this very interesting area of anomalous short lifetimes.

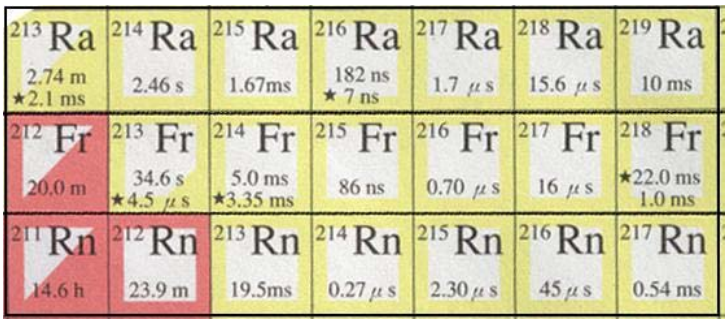

Fig. 1. Half-life drop in a vicinity of N =126

Obviously the anomalous half-life decrease in this region is connected with the enormous acceleration of alpha-decay. Besides the shell effect investigations, the systematic studies in this exotic region could clarify the influence of the alpha-particle binding energy on the shape and dimension of the nuclei.

The Hg isotope chain deserves a special attention. Investigations of these isotopes started the laser-nuclear direction in nuclear physics. Here the well known "jump" in the course of mean square charge radii and the "staggering effect" (unusually wide fluctuations of mean square charge radii at the transition from even to odd isotopes) were found. It would be very interesting to find whether the stabilization of this staggering effect takes place and, if yes, at which N it happens (see Fig. 2). For this purpose the investigations of the isotopes with $N < 181$ are necessary.

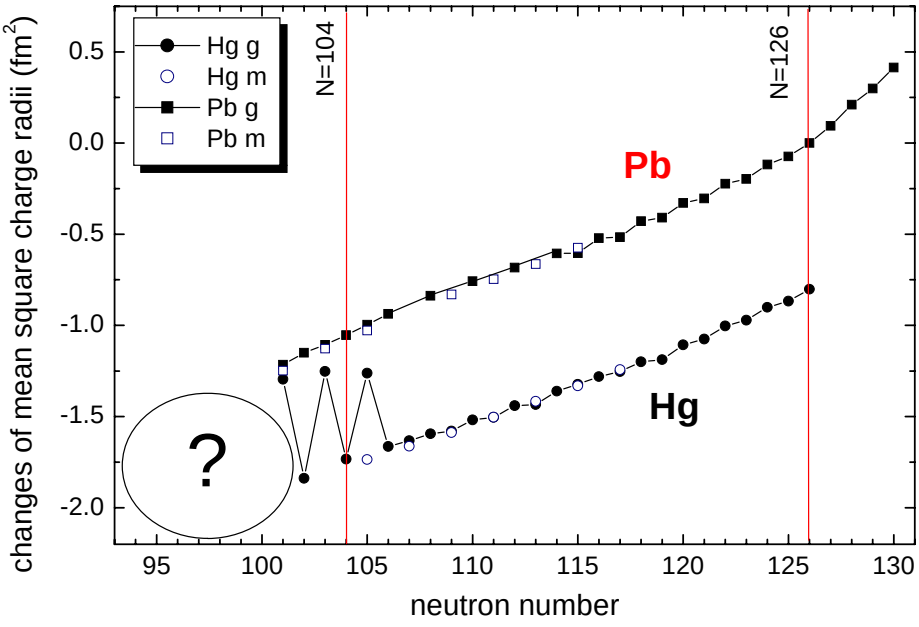

Fig. 2. Staggering effect in the course of mean square charge radii at N = 104 for Hg (Z = 80) and the smooth its behavior for Pb (Z = 82)

As we can see, the high production efficiency of the nuclei under investigation and the high isobar and isomer selectivity of the ionization method are the crucial conditions for the successful study.

2. Target-ion source system for efficient production of isotopes under investigation

In the course of the IRIS facility work at the proton beam of PNPI synchrocyclotron, the Short-Lived Nuclei Laboratory has accumulated a big experience in development and construction of target systems for on-line application. For more than thirty years uranium carbide targets [1,2] have been explored for production of a large variety of neutron-rich (fission reaction) and neutron-deficient (spallation reaction) nuclei. The main problem of uranium carbide target development was the creation of the target material with a high dispersivity and porosity in order to decrease the release time of the species produced by different reactions in the target material. On the other hand, for a more efficient use of a neutron beam after the primary beam converter in future ISOL facilities the uranium density of the target material should be as high as possible. Additionally, the target material with a higher density has a higher thermal conductivity that would allow dissipating a higher power introduced into the target by the primary beam, when the target is used for exotic nuclei production in the direct reaction. Hence, for more effective production of short-lived isotopes of the element chosen for investigation a special selection of a metal carbide target material is required, concerning not only the target material structure, but also its density. Recent developments at Short-Lived Nuclei Laboratory make it possible to produce a wide range of short-lived isotopes of different elements with good efficiency (*i.e.* production rates are enough to carry out physical experiments). In Fig. 3 the construction of a new high density thick uranium carbide target is presented [1].

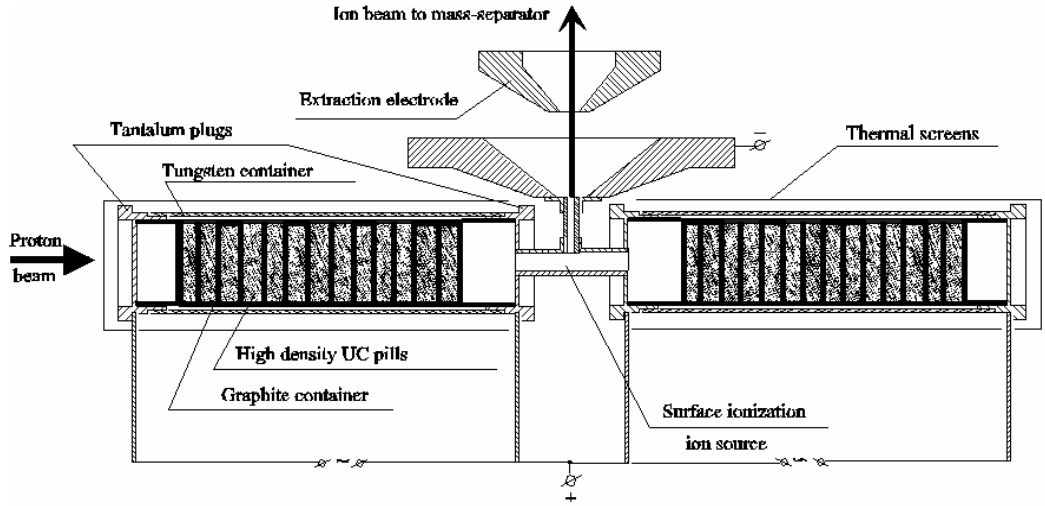

Fig. 3. High density thick uranium carbide target (91 g/cm^2)

Table 1 represents the normalized production rates of some isotopes of elements listed above as objects for investigations.

Table 1

Isotope	Half-life	Normalized production rate, 1/s (0.1 μA proton beam, target thickness 1 g/cm^2)
$^{219}Fr_{132}$	20 ms	$8.4(1.8)\times10^2$
$^{121}Ag_{74}$	0.78 s	$9.6(2.1)\times10^2$
$^{134}Sn_{84}$	1.12 s	$3.5(1.1)\times10^3$
$^{58}Mn_{33}$	65 s	$4.2(4)\times10^3$
$^{119}Cd_{71}$	2 min	$1.2(2)\times10^5$

[1] H.L. Ravn, Nucl. Instr. Meth. B **70**, 197 (1992).
[2] A.M. Evensen *et al.*, Nucl. Instr. Meth. B **126**, 107 (1997).

In Table 2 the production rates of the same isotopes extrapolated to the 91 g/cm^2 thickness of uranium carbide target and to the 0.2 μA proton beam intensity are shown.

Table 2

Isotope	Half-life	Production rate, 1/s
$^{219}Fr_{132}$	20 ms	$1.5(0.3)\times10^5$
$^{121}Ag_{74}$	0.78 s	$1.7(0.4)\times10^5$
$^{134}Sn_{84}$	1.12 s	$6.4(2)\times10^5$
$^{58}Mn_{33}$	65 s	$7.6(7)\times10^5$
$^{119}Cd_{71}$	2 min	$2.2(4)\times10^7$

3. LIS method of nuclear investigations

Method of the laser resonance ionization inside the cavity of the laser ion source (LIS), developed and firstly applied at the Short-Lived Nuclei Laboratory, meets the requirements of the efficient production of the isobaric and isomeric selective sources.

The idea of the laser photoionization is demonstrated in Fig. 4. The essential point of the method is step-by-step resonant laser excitation of atom from the ground state – through intermediate states – to the autoionization state or the continuum. Lasers tuned to the fixed wavelengths according to the specific atomic transitions provide the selective ionization of the investigated element [3] . The produced ions can be extracted from the ion source, mass-separated and delivered to the detector stations.

At the same time the method of resonance laser photoionization in the laser ion source proves to be one of the most efficient tools for isotope shift and hyperfine structure investigations [4].

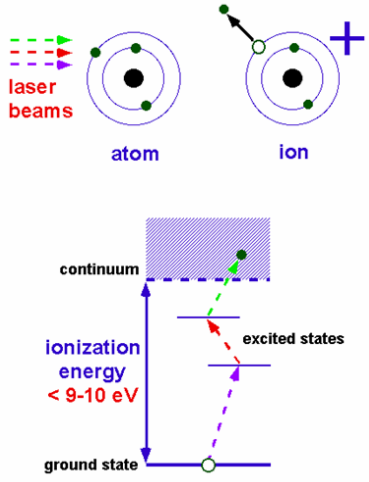

Fig. 4. Scheme of resonance ionization

The scheme of the experimental setup built at the IRIS facility of the Short-Lived Nuclei Laboratory at the beginning of 1980-es is presented in Fig. 5.

A description of the setup and experimental details can be found in Ref. [2]. The main points which should be mentioned here are as follows:

1. Now copper-vapor laser (CVL) pump system can provide three resonance wavelength channels with average laser power of 100–500 mW each.
2. Values of the available wavelength are in the region of 530–800 nm.

[3] V.S. Letokhov *et al.*, Optics Comm. **7**, 59 (1973).
[4] G.D. Alkhazov *et al.*, Nucl. Instr. Meth. B **69**, 517 (1992).

These restrictions mean that we are able to ionize the atoms with the ionization potentials lower than 6.5 eV. These are atoms of alkalis, alkali-earths, rare-earths and some other elements. Additionally, due to the lack of power, we can not saturate the third transitions of the ionization scheme (see Fig. 4). This considerably decreases the ionization efficiency.

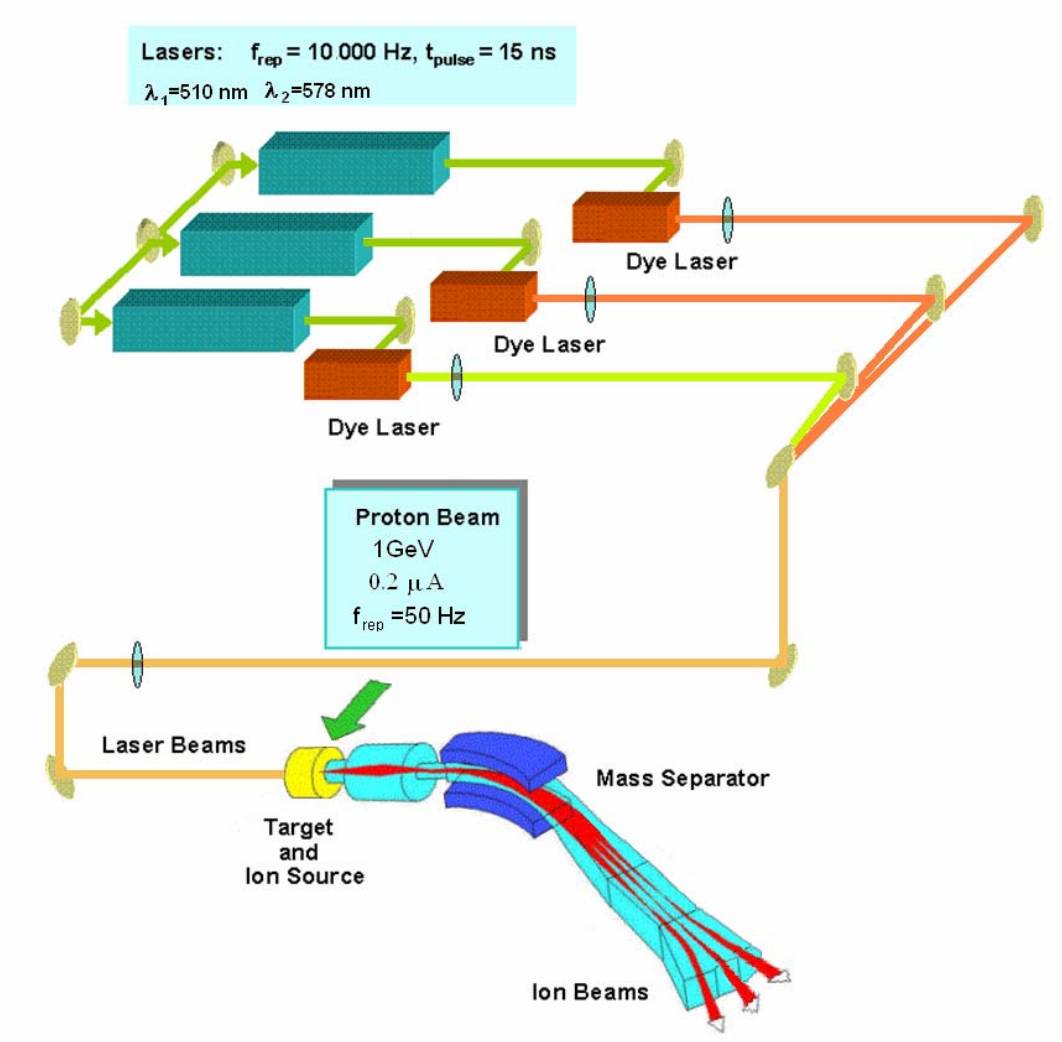

Fig. 5. Scheme of the laser-nuclear experimental setup used at the IRIS on-line facility for studies of Yb isotopes

To overcome these restrictions it is necessary to increase the pump power of the copper-vapor lasers and to produce the resonance wavelengths in higher energy ultraviolet diapason that allows to ionize the atoms with ionization potentials up to 10 eV (*i.e.* almost all elements of the Periodic Table). To meet these requirements a completely different, more sophisticated laser installation has to be built.

The scheme of a new laser-nuclear experimental setup to be constructed at the IRIS facility is presented in Fig. 6. A master oscillator – power amplifier system of copper vapor lasers (CVL) provides two output laser beams in the form of 15 ns pulses at a repetition rate of 9–11 kHz, each with an average power of typically 30–40 W. The lasers rely on stimulated emission from two copper spectral lines, resulting in laser light comprising of green (511 nm) and yellow (578 nm) components.

After separation of these components, four beams are available for the pumping of dye lasers and, where applicable, non-resonant ionization of atoms brought to a highly excited state by one or more resonant photon absorption steps. The LIS setup includes three dye lasers and, therefore, ionization schemes employing up to three resonant transitions can be used. The wavelength range of the dye lasers is 530–850 nm.

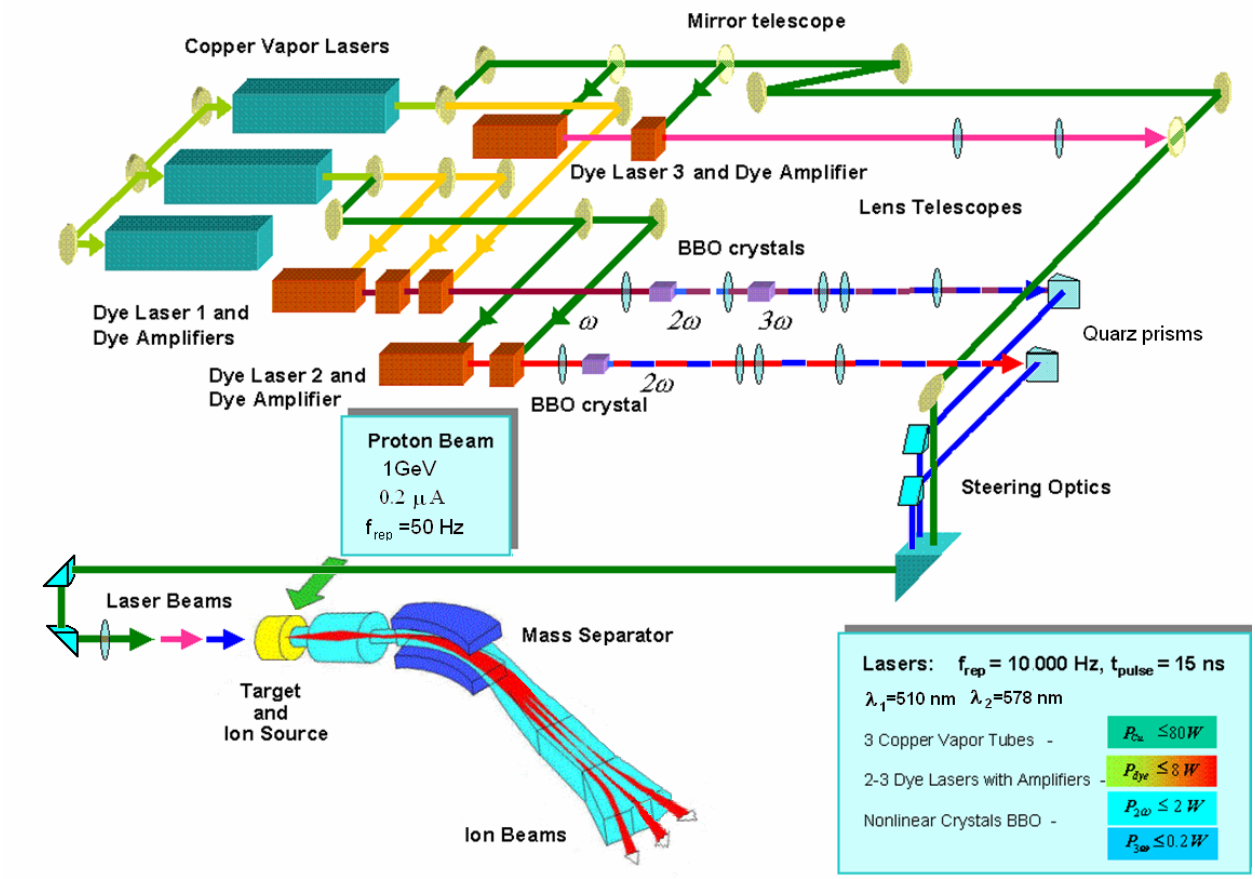

Fig. 6. Scheme of a new universal laser-nuclear experimental set-up which is under construction at IRIS facility

Tuning is achieved by rotation of the diffraction grating in the laser resonator cavity and, depending on the diffraction grating used, the spectral width of the laser line is between 9 and 30 GHz. Frequency doubling and summation (tripling) is carried out using non-linear BBO (beta-barium borate) crystals to generate second or third harmonics of the fundamental beam, extending the wavelength range to include 214–415 nm. This enables high lying first excited atomic states to be accessed and is crucial for elements with a high ionization potential. Schemes using one, two or three resonant transitions can be used. Most commonly, the last step is a transition to the continuum using an available CVL beam. Alternatively, the final step can be a resonant transition to an autoionizing state. A transition to the autoionizing state usually has a higher cross section than a non-resonant transition into continuum; this improves both the ionization efficiency and the stability of the ion current.

The ionization takes place in a hot cavity connected to the target. Reaction products enter this cavity as an atomic vapor at a high temperature (near 2300°C). The role of the cavity is to preserve the atoms for a certain time within a volume where they can be irradiated by the laser light and to confine the ions during their drift towards the extraction region. The ionization cavities are refractory metal (W, Ta or Nb) tubes. They are resistively heated to a temperature up to 3000°C (in the case of W ionizator) with a DC current of 200–350 A. After leaving the source, ions are accelerated to 30 kV, separated in a magnetic field and guided to the user by electrostatic ion-optical elements. Operating in narrow band mode where the laser bandwidth is reduced to 1 GHz, *i.e.* becomes close to that of the Doppler broadening of the atomic transitions (~ 1–3 GHz), the LIS can be used as a precise spectroscopic tool for the isotope shift and hyperfine structure study.

4. Conclusion

As one can see from the above consideration, the application of the laser ion source method opens wide possibilities for very different investigations with the chemically, isobar and isomer pure radioactive beams. The new universal laser complex at IRIS facility should provide these beams of exotic nuclides that is of great importance for many scientific areas. Presently, the first stage of the universal laser ionization spectroscopy system (new advanced pump copper-vapor lasers with their power supplies) has been built and delivered to the IRIS experimental hall. It will be put into operation in 2007. The following new developments in the region of the laser resonance ionization and the efficient target-ion source units will make it possible to enlarge considerably the areas of scientific applicability of the IRIS facility. Besides the studies of structure and properties of exotic nuclei, the new applications can be developed. As it has been demonstrated by the world leading ISOL facilities such as ISOLDE (CERN) and ISAC (TRIUMF, Canada), the high intensive and selective isotope and isomer beams can be used also in solid state physics to investigate the properties of new semiconductors and other materials. Another important application of ISOL facilities can be a radioisotope production for medical investigations. Short-lived isotopes can be used for non-invasive methods of internal organ and metabolism studies. It is of great importance for early and precise diagnostics.

References

1. V.N. Panteleev, in *Materials of the EURISOL town meeting*, CERN, Geneva, 26 – 29 November 2006.
2. A.E. Barzakh *et al*., Phys. Rev. C **61**, 034304 (2000).