THE IRIN PROJECT AT THE PIK REACTOR

V.N. Panteleev, A.E. Barzakh, D.V. Fedorov, V.S. Ivanov, V.V. Lukashevich,
P.L. Molkanov, F.V. Moroz

NRC "Kurchatov Institute" PNPI Gatchina, Leningrad District, 188300, Russia

Abstract

As it is presently very well understood, the investigation of neutron-deficient and neutron-rich nuclei at the edge of proton and neutron stability with ISOL (Isotope Separator On-Line) methods is of great importance for fundamental nuclear physics studies, for astrophysics, for solid state physics and for modern medicine as well, providing a high purity radionuclides. In PNPI the project IRIN (Investigation of Radioactive Isotopes with Neutrons) of an ISOL facility for the high intensity exotic neutron-rich isotope production at thermal neutrons of a high flux reactor PIK is being developed. The IRIN facility will provide the most intensive beams of neutron rich nuclei in the world. The main directions of studies of neutron rich exotic nuclei at the IRIN facility are the followings:

The studies of the “magic numbers conservation” in the nuclides far from stability are of importance for nuclear physics and also directly connected to astrophysics. Recently obtained data point to change of the magic number values for such nuclei. This leads to considerable revision of the magical number concept itself.

The second very important direction is the measurements of the ground state properties of short-lived nuclei (spins, mean square charge radii, electromagnetic moments etc.), making use the method of resonant laser spectroscopy in a laser ion source. Such a possibility is of great importance for traditional area of the laser-nuclear spectroscopy application – for the isotope shift and hyperfine splitting measurements. Mean square charge radii, spins and electromagnetic moments can be evaluated from these experimental data.

It is planned to build at one beam line of the IRIN mass-separator the system of Penning traps for precise mass measurements of nuclei lying extremely far from the beta-stability line. Making the production efficiency of neutron rich nuclides higher with the IRIN facility we can get a chance to investigate very interesting area of nuclei with anomalous short life times.

Additionally there is a plan of a special ion guide construction at IRIN for a high purity isotope with rather long life-times production and collection. It can be used for the solid-state physics and the nuclear medicine purposes.

1. Introduction

The investigation of neutron-deficient and neutron-rich nuclei at the edge of proton and neutron stability with ISOL methods is of great importance for many goals: for low energy nuclear physics studies, as nearly all information about nuclear structure and nuclear state characteristics has been obtained by experiments at ISOL facilities; for astrophysics when ideas about the creation of chemical elements in the universe and evolution of stars can be tested experimentally by the interaction of RNB (radioactive nuclear beam) with a hydrogen target; for solid state physics where radioactive ion implantation is used to investigate the material properties; and for modern medicine as well, providing a fast and harmless diagnosing diseases.

ISOL installation IRIS (Investigation of Radioactive Isotopes on Synchrocyclotron) has been operating at PNPI since the middle of the 70-s of the last century [1, 2]. Short-Lived Nuclei Laboratory has carrying out the successful systematic investigations of the far from beta-stability nuclei. More than 300 nuclides (17 of them were produced and investigated for the first time) were studied. New approaches and methods of production and investigation of short-lived isotopes were developed and applied at IRIS facility.

Presently there are more than twenty ISOL facilities operating all over the world and about ten more are projected to be built in the following decade. Studies of exotic nuclei far from stability using ISOL facilities on the beams of different bombarding particles (protons, thermal neutrons, heavy ions, and other projectiles) strongly depend on the possibility of producing nuclear beams needed for investigations. The use of the high-flux neutron reactors for these purposes looks very promising in this respect. According to preliminary calculations, the yield of ^{132}Sn (double-magic, far from β-stability) reference nuclide on ISOL facility at the thermal neutron beam of reactor PIK (neutron flux of 3×10^{13} n/cm^2 s, target — 4 g of ^{235}U) can be of about 1×10^{11} particles per second. Presently operating ISOL systems IRIS (PNPI) and ISOLDE (CERN) [3] are able to provide 10^7 and 10^8 of ^{132}Sn nuclides per second correspondingly. The maximum yield of this isotope at the perspective ISOL installation SPIRAL-2 (GANIL, France) [4] will not exceed 109 nuclides per second.

For efficient investigation of the nuclei very close to the neutron stability border, the isobar purity of the isotope under study becomes a decisive factor. To provide the isotope selective ionization of a range of elements, the resonance laser ionization in a hot cavity can be applied [5]. This method has been developed and successfully used at the IRIS facility. Recently, the new laser installation based on this technique has been build and put into operation at the IRIS facility [6]. This is a significant improvement of the laser-ion source device of the IRIS mass-separator, working on-line with proton beam of the PNPI synchrocyclotron. It makes us possible to get the isobarically clean radioactive isotope beams of a great number of chemical elements.

2. The scientific program and IRIN project description

The project IRIN (Investigation of Radioactive Isotopes on Neutrons) is proposed for the high intensity exotic neutron-rich isotope production by the thermal neutrons of reactor PIK. In table 1 the expected production rate of some very neutron-rich isotopes at the IRIN facility is presented.

Data for SPIRAL-2 [4] are given for comparison. As one can see from the table, the production rates of the neutron-rich nuclides at the IRIN facility will be considerably higher than at SPIRAL-2. At the same time one should take into account the additional difficulties in operation with the very thick uranium carbide target (up to 2 kg of ^{238}U) using at SPIRAL-2. This kind of target causes slow release of short-lived isotopes due to the poor target diffusion-effusion properties. The following scientific activities of Short-Lived Nuclei Laboratory are the most interesting and important.

Table 1. Production rate of some very neutron-rich isotopes at IRIN and SPIRAL-2 facilities.

Isotope	Z	$T_{1/2}$ s	Yield (IRIN) at./ s	Yield (SPIRAL2) at./ s
^{74}Ni	28	0,9	4,58E+06	2,75E+05
^{78}Cu	29	0,342	1,09E+07	1,15E+06
^{84}Ga	31	0,085	1,11E+10	1,24E+07
^{127}Ag	47	0,109	1,58E+02	1,71E+01
^{130}Cd	48	0,195	8,78E+10	8,03E+08
^{133}In	49	0,18	1,71E+08	1,06E+08
^{134}Sn	50	1,12	1,77E+10	2,62E+09
^{136}Sb	51	0,82	1,15E+10	3,45E+09

The position of the neutron drip-line is very uncertain, and its experimental determination is a problem of much current interest. The neutron drip-line is only identified up to fluorine (Z=9). The predicted position of the neutron drip-line differs greatly depending on the model used. Beyond its influence on nuclear structure, understanding the behaviour of very neutron-rich nuclei could, for instance, help in elucidating the properties of neutron matter needed for calculations of neutron stars.

Penetrating deeply into unknown area of the nuclear chart is likely to reveal many new phenomena. One of these is the predicted changes in the shell structure. It is probable that the shells which have been identified in the known nuclei are considerably different for very exotic nuclei. Hints that this is indeed the case have already been found in light nuclei, for N=20 and 28, and many other similar cases could occur, which need experimental verification.

A complete description of nucleosynthesis requires a detailed knowledge of the nuclei near the neutron drip-line and of the nuclear reactions in which they are involved. A possible path of the rapid neutron-capture process (or r-process) goes deep into the region of very exotic neutron-rich nuclei, whose lifetimes, binding energies and delayed-neutron emission probabilities, are unknown. Knowledge of these properties is thus a prerequisite for a full understanding of the nucleosynthesis of about half of the heavy elements between iron and uranium.

Experiments with nuclei very far from stability will undoubtedly provide new possibilities to do research with unexpected results. Thus, high priority should be given to systematic investigations of nuclei, covering the whole interval from stability to the neutron drip-line.

Mass measurements of short-lived nuclei have been of great interest for many years. The reason of it is the atomic mass is a nucleus gross property that includes all the effects of the forces that are acting in it. Measurements of masses of a large set of nuclei are required to detect trends in the nuclear binding energy and also to test nuclear models. Masses may reveal the vanishing of shell closures and the appearance of new magic numbers far from stability. Similar arguments can be made for the half-lives of exotic species. When compared to model calculations, they may evidence shell effect and their changes far from stability. In addition, to understand stellar evolution and the production of the elements in the universe, extensive model calculations are used to describe and simulate the different processes occurring in the stars. Especially for violent processes like supernovae explosions or *X*-ray bursts, the properties of unstable nuclei are the most important inputs to the models.

In these investigations the isobaric selectivity becomes more and more important to provide the “purity” of the object under investigation. This area provides the nuclear characteristics of the nuclei very far from stability. 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 order of magnitude higher, than the isotope under study. Hence, the crucial point is to provide the isobarically pure sources of the investigated nuclei to enable the investigation of life-times, decay modes and other nuclear characteristics.

The possibility of the isomer selectivity is also very important point. There is a range of interesting problems when the source of pure isomer could give an excellent opportunity for investigations (isomer-selective measurements of beta-strength functions etc.).

The next very important direction is the measurements of the ground state properties of short-lived nuclei (spins, mean square charge radii, electromagnetic moments etc.). This kind of investigations besides the high isobar and isomer selectivity requires the high production efficiency of the nuclides to be studied. High efficiency could allow penetrating into the region of the more exotic nuclei. Such a possibility is of great importance for traditional area of the laser-nuclear spectroscopy application — for the isotope shift and hyperfine splitting measurements. Changes in the mean square charge radii, spins and electromagnetic moments can be evaluated from these experimental data.

One of the most interesting object of the laser-nuclear spectroscopy is an investigation of shell-closure effect for mean square charge radii of the far from beta-stability nuclides, i.e. sudden jumps in the mean square charge radius course at the magic number region. Change of the shell-closure effect value can be treated as the “change of magicity”.

In this respect, the most interesting nuclei are Sb, Sn, In, Cd, Ag with neutron number close to N=82. The systematic investigations of the mean square charge radii for the long isotopic chain have to be done to discover the general trends and basic properties of the nuclear matter. There is no enough information about the shell-closure effect 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 neighbour closed sub-shells.

Additionally, there is a plan of a special ion guide construction at IRIN for the high purity sources production. It can be used for the solid-state physics and the nuclear medicine purposes.

Schematic view of IRIN setup with the laser ionization complex in the reactor PIK hall of horizontal channels is presented in figure 1. The main part of IRIN is an isotope mass-separator. Target-ion source device of mass-separator is placed inside the reactor channel on the thermal neutron flux of 3×10^{13} n/cm^2 s. This neutron flux irradiates the target material and heats it up to 2000–2400ºC. The power emission as a result of 10^{14} fissions in 4 g of ^{235}U (90% enrichment) target is of 3 kW.

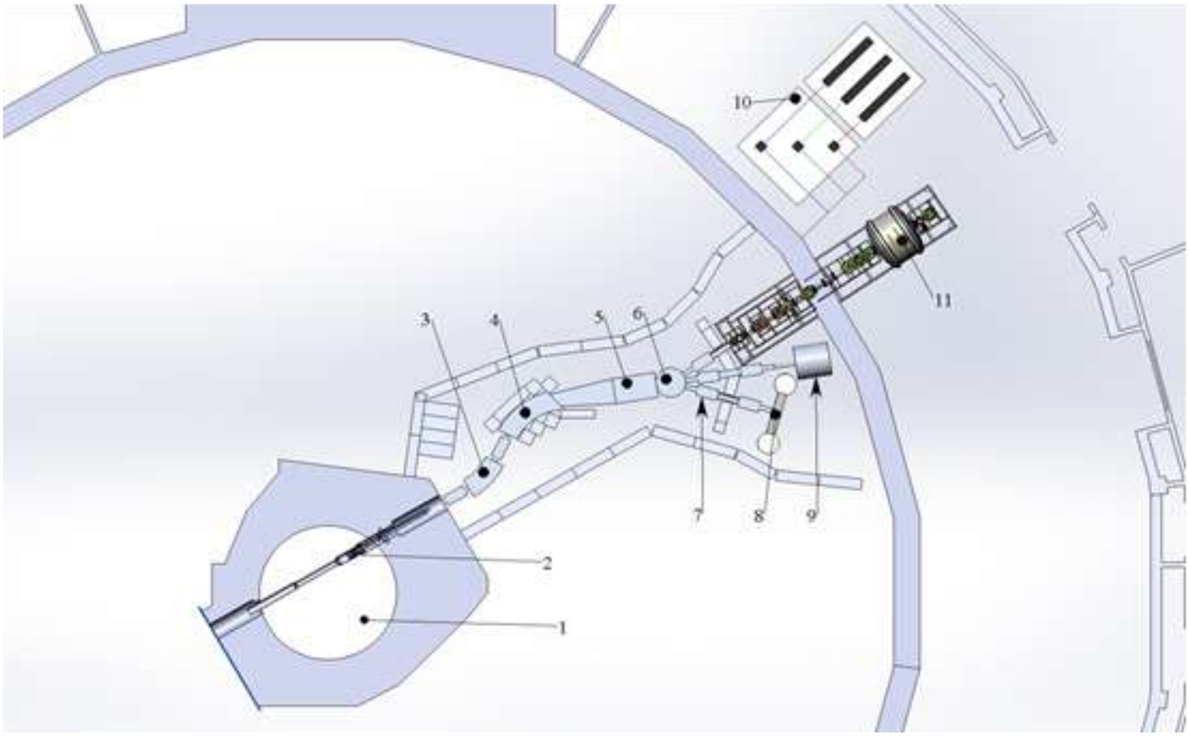

Fig. 1. The layout of IRIN facility at the experimental hall of the PIK reactor. 1- water tank of the reactor; 2- target unit; 3- beam deflecting system; 4- separator magnet; 5- collector chamber; 6- switchyard; 7- ion beam lines; 8- tape moving system; 9- neutron detector; 10- laser installation; 11- system of Penning traps.

Fission products are thermally released from the target material due to diffusion and effusion processes and penetrate into an ion source cavity. Ions from the ion source are formed with extraction electrode into a 30 keV beam (beam divergence is of 2×10^{-2} rad). Ion beam is formed with the focusing lenses (consisting of 3 cylindrical electrodes) into parallel beam. After the beam deflecting device, ion beam goes to the analyzing magnet for mass separation. The ion beam enters into magnet normally to the magnetic field lines and is focused in vertical and horizontal planes. The ion beam cross-section in the focal plane of the mass-separator magnet is of about 1 mm (vertical plane) and 1.5 mm (horizontal plane). The central trajectory curvature in magnetic field is equal to R=1500 mm and provides the distance between neighbor masses equal to $D_{rect}=R/A$, mm (A – mass number). For instance, for

A=150 dispersion $D_{rec}\approx$ 10 mm. The mass range in the focal plane is ±15% of central mass (the mass in the center of focal plane). For example, the mass range in the tin region is the mass numbers from 110 to 150. The mass-separated ion beams are transported from the collector chamber to bending and beam distribution chamber, — the vacuum chamber with two cylindrical capacitors, bending the ion beam in +30 and -30 degrees from the unbending central beam trajectory. The selected ion beams are directed to the experimental hall with the ion guide systems. The focusing triplet electrostatic lenses are installed along the ion beam lines to focus the ion beam to detection posts of experimental set-up. The ion beam cross-sections in the implantation point is of about 2×2 mm^2. Vacuum system should provide the air pressure value of about $(2\text{-}4)\times10^{-6}$ mbar in all parts of mass-separator. The ion beam transmission from ion source to detection posts should be in range of 60-90% (depends on the ion source type and the beam focusing quality).

All ion beam lines are connected to the corresponding experimental set-up. The first ion guide will be supplied with the ion trap for the high precision mass measurements (detection post 2 in fig.1). Using the ion trap, where the Penning trap is used to perform mass measurement, it has already be shown that even for half-lives as short as a few hundred milliseconds it is possible to obtain an accuracy of $\delta m/m\approx 1\times10^{-7}$ [7].

The neutron 4π detector for the delayed neutron registration will be installed on the first ion guide (detection post 1 in fig.1). The fast tape station with α-, β-, and γ-detectors for identification and investigation of rare isotopes will be placed at the second ion guide. All detection posts, tape station and mass-separator will be controlled with the mainframe computer.

3. Conclusion

The project IRIN at the reactor PIK opens the new possibilities for production and investigation of the neutron rich nuclei. It will be able to compete with and in some cases to surpass current and projected ISOL installations. Combination of the mass-separator and the laser resonance ionization facility enables one to overcome the inevitable difficulties in these investigations due to a low production rate of the most exotic nuclei. The Penning trap technique will allow to measure with a very high precision a large survey of the mass surface of extremely neutron rich nuclei far from the beta-stability region.

References

[1] E. Ye. Berlovich et al., Izvestiya Akademii Nauk SSSR, Ser. Fiz., 1976, V.40, P. 2036.
[2] V.N. Panteleev et al., Rev. Sci. Instrum., **73** (2) (2002)738.
[3] V.N. Fedoseyev et al., HyperfineInteractions**, 127** (2000) 409.
[4] A.C.C. Villari, AIP Conf. Proc., **704** (2004) 234.
[5] G.D. Alkhazov et al., Nucl. Instrum. Meth. A **306**, 400 (1991).
[6] A.E. Barzakh et al., Rev. Sci. Instrum. **83**, 02B306 (2012).
[7] F. Herfurth et al., Nuclear Physics, A **701** (2002) 516.