Eurasian Journal of Physics and Functional Materials

2019, 3(1), 63-70

Exotic nuclides at the reactor pik: pitrap project

Yu.N. Novikov[1,2*], Yu.I. Gusev[1], S.V. Chenmarev[1], S.A. Eliseev[1], P.E. Filyanin[1], T.V. Koneva[1], D.A. Nesterenko[1], A.W. Popov[1], D. Simonovski[2], O.I. Bezrodnova[1,2], N.S. Martynova[1,2], Yu.V. Nechiporenko[1,2]

[1]Petersburg Nuclear Physics Institute, Research National Center "Kurchatov Institute", Russia

[2]St. Petersburg State University, St. Petersburg, Russia

E-mail: novikov_yn@pnpi.nrcki.ru

DOI: **10.29317/ejpfm.2019030109**
Received: 17.03.2019 - after revision

The PITRAP-project for mass measurements of exotic nuclides is based on the use of high flux-reactor PIK and a high precision Penning trap mass spectrometry. This combination gives a synergy in exploration of different problems of fundamental physics: from astrophysics to neutrino physics.

Keywords: exotic nuclides, astrophysical r-process, mass landscape in neutron-rich nuclides, high flux reactor, penning trap mass spectrometry.

Introduction

A nuclear reactor is the unique installation for production of neutron-rich nuclides and among them of very exotic ones in the fission region of the Nuclear Chart. Nearly all of these nuclides that can exist as such participate in different astrophysical processes, unfolded as a result of stellar explosions. The exact number of these nuclides is unknown and masses (total binding energies) covering the energetics of these processes are mostly also unknown. The information on them is provided presently only by the theoretical predictions. However, they are not exact and considerably scattered for very neutron-rich nuclides. Figure 1

shows how different are the predictions of the neutron drip-line that frames the area of nucleon-stable nuclides participating in the stellar processes.It is obvious that any experimental information on the mass values towards the drip-line is of paramount importance.

Success in experiments with nuclides of an exotic proton/neutron composition depends on the intensity of the producing primary beam as well as the sensitivity of the measuring setup. The new PIK reactor which is under commissioning at the PNPI NRC "Kurchatov institute" is expected to be a high-flux facility [1, 2], with a powerful production of such exotic nuclides. A Penning ion trap is an ultra sensitive apparatus capable of operating with a single ion. This combination provides synergy and a unique possibility for studying exotic nuclei. Penning ion traps are widely used to solve different physical problems [3]. The Penning ion-trap systems ISOL TRAP (CERN), SHIP TRAP (Germany), JYFL TRAP (Finland), LEBIT (USA), and TITAN (Canada) operate in combination with particle accelerators and are intended for the on-line direct mass measurements.

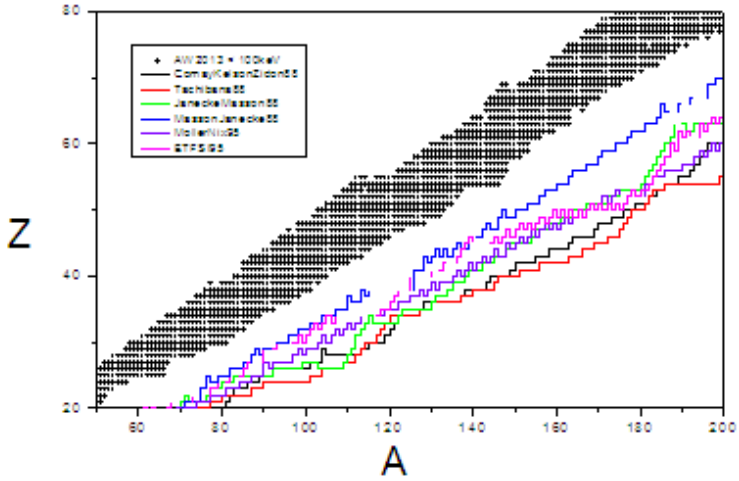

Figure 1. Nuclear chart with the indicated neutron-drip-lines (in color) obtained by different mass formulae listed in the inset.

The PITRAP-project proposed at the St. Petersburg Nuclear Physics Institute in corporate many years of experience gained by the authors on some of the facilities listed above.

Physical Problems

High productivity with high sensitivity of PITRAP will make it possible to cover wide regions of the Nuclear Chart and obtain unique information with nuclear-physical and astrophysical content.

We will focus here on the astrophysical aspect of the problem. For fast neutron capture (r-process) caused by explosion or neutron stars merge, the density distribution of isotopes relates [4] the astrophysical parameters (neutron density and temperature of the stellar medium) with the nuclear parameter – the separation energy of a neutron in nuclei, which depends on the mass difference of the nuclei. The latter quantity determines the path of the process under prescribed

astrophysical conditions. For this reason nuclide mass becomes the key quantity that sets the path of the r-process. It is important to know the true 'nuclide path' of this process in order to determine the parameters characterizing the explosion of a star. The mass of nuclides in the initial and middle regions of the r-process at N = 50 and N = 82, which are important for determining and studying the starting path of this astrophysical process, can be just measured at the PIK reactor with the Penning Trap Mass Spectrometry (PTMS).

The mass of a nucleus, which is directly related with the nuclear total binding energy, is one of the fundamental characteristics reflecting the sum of all nucleonic interactions in nucleus. The measurement of mass in long isotopic and isotonic chains makes it possible to study the fine structure of the mass landscape. An important question in direct measurements is the possibility to resolve the isomeric and ground states. In [5] the mass doublet ^{164}Er-^{164}Dy with the small mass difference Q = 25.07(12) keV was resolved by the method of octupolar excitation in a Penning trap; the resolution attained was about 2×10^{-7}. A new method of phase determination of the cyclotron frequency making high resolution possible was also adopted in the SHIPTRAP setup [6]. Both these methods can be used at PITRAP to study the energy of isomeric states of nuclides. A large volume of new information on the mass of nuclides that can be obtained with PITRAP will improve the parameterization of the empirical mass formulae with the further possibility of using them directly to predict even more exotic regions of nuclides.

Another block of problems is associated with the high-precision off-line measurements of long-lived radionuclides. They can be produced by irradiating targets in the PIK reactor. The measurements can be performed after this irradiation in a trap independently of the reactor operation. High-precision measurements of the masses of long-lived nuclides can open up an entire strata of problems in fundamental physics ranging from neutrino physics to cosmo chronology [7, 8].

Production and Transportation of Exotic Nuclides

Nuclides formed during the irradiation of external targets in the PIK reactor [1, 2] (Figure 2) can be extracted by several methods:

1. Transporting fission products in a gas stream outside of the reactor core by means of aerosols (so called He-Jet transportation) followed by ionization and delivery of ions into a Penning trap,

2. or by use of a "cold target" in the area of the reactor core in combination with the IGISOL-type mass separation [9];

3. or employing a 'hot target' together with the IRINA electromagnetic mass separator [10].

Two variants (1) and (3) are examined in the present work. The planned arrangement of a PITRAP at the PIK reactor complex is shown in Figure 2. In the first method a capillary with the carrier gas and aerosols delivering the reaction products is connected to a chamber, where as kimmer, an ion source, and extracting electrodes are located. A magnet (3) that turns the ion beam towards the PITRAP channel (4) and performs selection by mass numbers is located farther.

The fission products in the "cold" chamber containing a target in the form of an approximately 10 μm thick ^{235}U metal foil with an area of 150 cm^2 coated with nickel will be thermalized in a buffer gas, e.g., in helium at pressure of $0.2 \div 0.3$ MPa. After this they are secured to aerosol particles and delivered by means of a capillary with inner diameter equal to about 1 mm and length of several meters towards the ion source. Then the ions are extracted and accelerated by the electric field created with a set of electrodes. The expected efficiency of the removal of nuclides through the capillary up to the ion source equals $50 \div 70$ %. The ionization efficiency depends on the type of ion source as well as the particular isotope and can vary from 0.1 to 10 %. The power release in the target is approximately 1.5 kW. The target is cooled by water circulating in a closed loop. The details of this method can be found in [11].

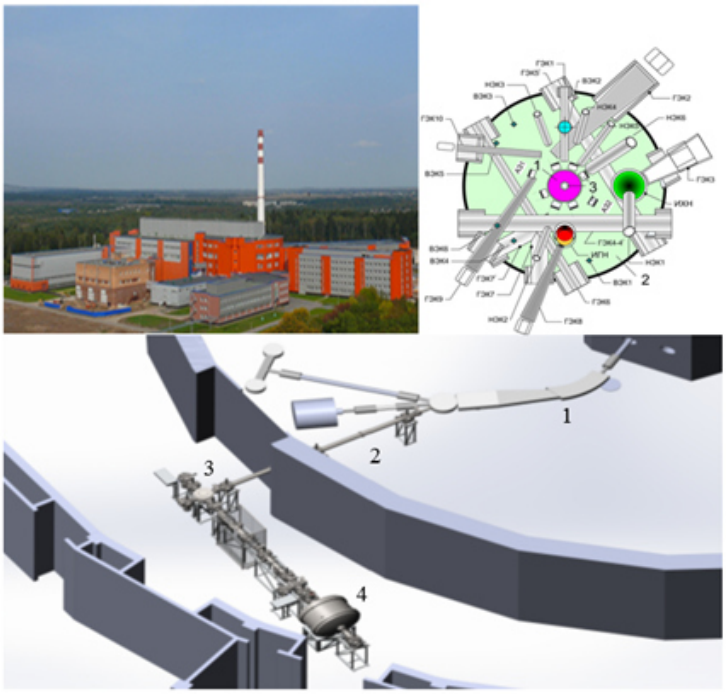

Figure 2. Collage of the reactor PIK properties [1,2] with basic characteristics: power: 100 MW; thermal neutron flux: 5×10^{15} n/cm^2 sec; horizontal channels: 13; inclined and vertical channels: 14; neutron guide channels: 8; 50 positions for neutron instruments. In the bottom of figure - arrangement of the setup PITRAP (4) is shown. It will use the horizontal channel GEK 5 and the electromagnetic mass separator (1) followed by ion channel (2) and bending dipole magnet (3).

The third proposed variant uses a massive hot target [10]. It is proposed that the target material in the form of ^{235}U carbide with a mass of 4 g in a graphite capsule be placed in a hermetic rhenium or tungsten container in a horizontal channel of the reactor (presumably GEK 5). The entire assembly is located in an evacuated volume cooled by distilled water. In the working regime with neutron fluxintensity 3×10^{13} sec$^{-1} \cdot$cm^{-2} through the target its temperature should not exceed 2500 K (melting temperature of the target substance is about 2800 K). The ion source (the surface ionization variant) consists of a tungsten tube, heated to a temperature of 2600 K either by direct current or by an electron bombardment. In the case of an ionization by electron impact, a variant of a plasma ion source, specially developed for the operating conditions in an intense neutron flux, will be used. The mass-separator system (1 in Figure 2) was envisaged for accelerating voltage

up to 50 kV. The collector chamber is followed by a chamber for separating the ion beams where three turning cylindrical condensers (switchyards) are supposed to be located followed by three ion channels equipped with focusing electrostatic quadrupole lenses for transporting ion beams into the low-background room. The dimensions of the ion beam should be equal to 2×2 mm at the locations of experimental facilities. The transmission of the beam from the ion source to the experimental facilities is supposed to be $60 \div 90$ %. The vacuum in the entire system of the mass separator must not be worse than $(2 \div 4) \times 10^{-4}$ Pa. One ion channel (2 in Figure 2) will be passed through the turning magnet for deflecting the ion beam to PITRAP. The nuclide generation rates in the target in comparison to other planned installations for unknown or poorly studied masses are presented in Figure 3. The productivity of the two types of targets (cold and hot) is approximately the same.

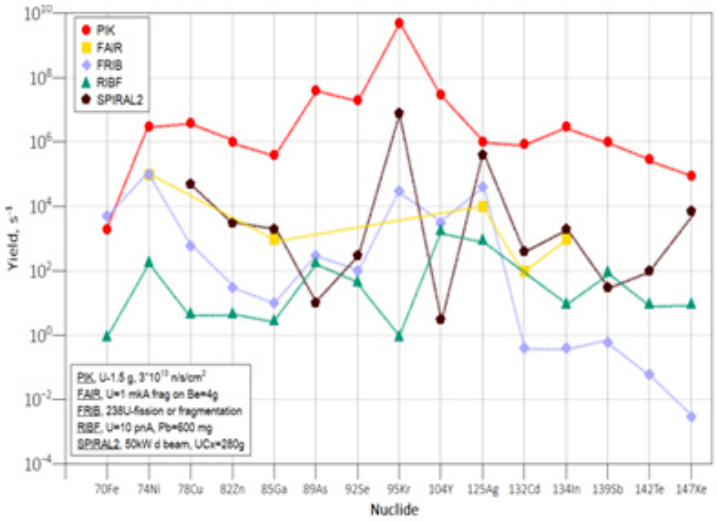

Figure 3. Comparative production yields expected from different on-line installations in the world.

PITRAP-Setup

The proposed variant of a PITRAP system is shown in Figure4. The magnet (1) turns the incoming ion beam by $90\,^{\circ}$. The ions are directed in to the deceleration section in front of a gas-filled radio frequency quadrupole (2) where they are moderated and focused. The radio-frequency quadrupole is filled with a buffer gas (helium) at pressure ≈ 1 Pa. It consists of four segmented rods to which a radio-frequency voltage is applied in order to keep the ions in the radial plane. A constant voltage can also be applied to the segments of rods in order to form an electric field along the axis of the system, having the minimum potential in the region of the penultimate segments. Colliding with the molecules of the buffer gas the ions lose kinetic energy and accumulate at the minimum of the potential. Thus, a group of ions is formed, which after reduction of the potential on the last segments of the rod scan be extracted from the radio-frequency quadrupole. Most of the elements of the radio-frequency quadrupole are supposed to be arranged on a high-voltage platform surrounded by a mesh (2 in Figure 4). The longitudinal

emittance of a 2.5 keV beam after the quadrupole will be 10 eV$\cdot$ μsec and the transverse emittance $\approx 10\,\pi\cdot$mm$\cdot$mrad. The cooling time in the gas-filledradio-frequency quadrupole is about 10 msec. The potential of the effluent group of ions is lowered by means of a pulsed change of their potential energy in the pulse cavity, comprising a tube where the voltage is switched as ions fly through it.

A group of ions enters a pulse cavity, where their potential is reduced to the required value. Next, ions are guided towards a time-of-flight mass-analyzer (3), which can operate as a mass-spectrometer for fast measurement of the ion mass or as a mass-separator for addition purification of the ion beam [12]. A group of ions in the operating regime of a time-of-flight mass-separator is transported toward the system of Penning traps, located in the superconducting magnet (4). In addition, an ion source for test measurements or experiments in the off-line regime, including calibrations, can be located in front of the turning magnet (1 in Figure 4).

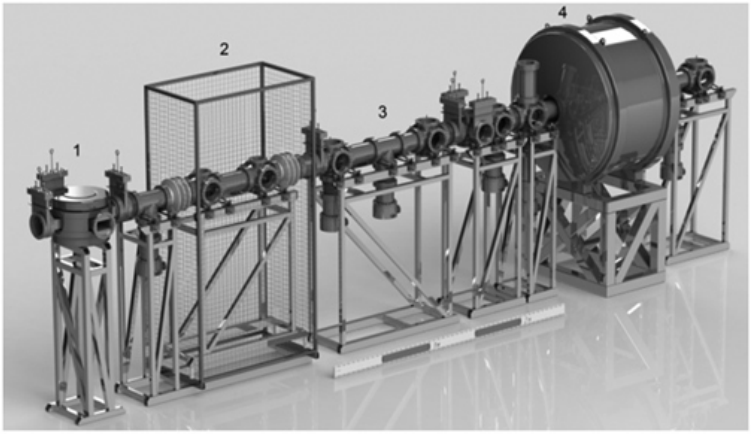

Figure 4. Model of the measuring facility with a Penning ion-trap (4). (1) is a turning magnet, (2) indicates the gas-filled RFQ, (3) is the multi-ToF system.

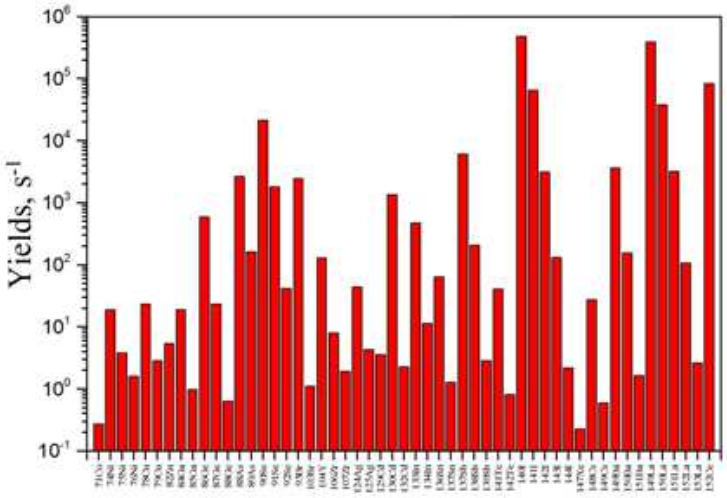

Figure 5. The rates of ions in the entrance of traps. The target of ^{235}U with the weight of 1.5 g has been used for estimations. The efficiency of He-jet transportation and cooling are assumed to 50 %, the ionization efficiency is of 0.1 %.

Penning traps system

The expected rates for some exotic nuclides at the entrance of the traps are shown in Figure 5. They are high enough for PTMS to perform the measurements. It is proposed that a variant with two cylindrical traps arranged in one tube of a superconducting magnet (B=7 T) (analog of the SHIPTRAP setup [13]) be used. Two centers of the highest homogeneity of the magnetic field, should correspond to the centers of the traps. The first preparatory trap, intended for mass-selective cooling of the ions in the buffer gas, is filled with helium at working pressure 10^{-4} Pa. It permits separating ions with a certain charge-to-mass ratio. The second trap under high vacuum ($10^{-6} \div 10^{-7}$) Pa is intended for high-precision measurements of masses. The traps are separated by a 1.5 mm (in diameter) diaphragm. In order to determine the masses (total binding energies) the cyclotron frequencies of ions which directly depends on the mass value in the traps (υ_c =Bm/q) have to be measured. It can be done by the ToF ion cyclotron resonance method [14] as well as by the novel phase-imaging method [6].

Conclusion

The high intensity of the neutron flux of the PIK research reactor at the PNPI in combination with the high sensitivity and precision of the ion trap opens prospects for multifunctional studies in different areas of science. The proposed Penning ion traps in tandem can be used on-line with secondary beams as well as off-line using fission products and products from neutron capture reactions. The on-line variant is of greatest interest for studying exotic neutron-rich nuclides for determining the true path of a fast neutron capture process in astrophysics. This r-process is assumed to be responsible for the creation of the chemical elements in nature. Its 'nuclide' path can be determined uniquely only by precise and reliable measurement of the masses of vast regions of exotic nuclides in a ground-based laboratory. Possibilities for using ion traps in the interests of atomic and neutrino physics by means of high-precision measurements of the mass difference of long-lived nuclides open up in the off-line measurement regime. The technical work up of the design takes account of these multifaceted problems. The design of the first Penning trap in Russia was developed using the many years of experience gained in working with different ion traps in foreign laboratories. The technical design project is presented in [15].

We are grateful to A.A. Vorobyov for stimulating the work on the Penning ion trap design at the PNPI and valuable discussions. We are also grateful to K. Blaum and M. Block for their interest in the project and for fruitful discussions.

References

[1] K.A. Konoplev, Main scientific results of the PNPI in 2000-2004 (2005) 18-23.
[2] V.L. Aksenov, M.V. Kovalchuk, www.NIKIET.ru (2015).
[3] K. Blaum et al., Contemp. Phys. **51** (2010) 149.

[4] E. Burbidge et al., Rev. Mod. Phys. **29** (1957) 547.
[5] S. Eliseev et al., Phys. Rev. Lett. **107** (2011) 152501.
[6] S. Eliseev et al., Phys. Rev. Lett. **110** (2013) 082501.
[7] S. Eliseev et al., J.Phys.G: Nucl. Part. Phys. **39** (2012) 124003.
[8] H.-J. Kluge, Yu. Novikov, Nucl. Phys. News **17** (2007) 48.
[9] A.G. Dernjatin et al., PNPI (1991).
[10] V. Panteleev et al., PNPI High Energy Physics Division (2013) 274.
[11] D. Simonovski et al., Atom. Energya (accepted).
[12] R. Wolf et al., Nucl.Instrum. Meth. A. **686** (2012) 82.
[13] M. Block et al., Eur. Phys. J. **45** (2007) 39.
[14] M. Konig et al., Int. J.Mass Spectrom. Ion Proc. **142** (1995) 95.
[15] Yu.N. Novikov et al., Report F-310. B.P. Konstantinov PNPI NRC Kurchatov Institute Gatchina (2016).