IGISOL-BASED SETUP FOR PRODUCTION AND INVESTIGATION OF NEUTRON RICH HEAVY NUCLEI

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It is proposed a new setup to produce and investigate heavy neutron rich nuclei located along the neutron closed shell N=126. This "blank spot" of the nuclear map can be reached neither in fusion–fission reactions nor in fragmentation processes widely used nowadays for the production of exotic nuclei. A new way was recently proposed for the production of these nuclei via low-energy multi-nucleon transfer reactions. The estimated yields of neutron-rich nuclei are found to be rather high in such reactions and several tens of new nuclides can be produced in the near-barrier collision of ^{136}Xe with ^{208}Pb, for instance. This setup could definitely open a new opportunity in the studies at heavy-ion facilities and will have significant impact on future experiments.

1. Physics objectives

Properties of light and medium mass nuclei located far from the stability line have been studied already for many years. As a rule, the light exotic nuclei are produced in fragmentation processes and the medium mass neutron rich nuclei with A~100 – in fusion reactions. Production and study of heavier neutron rich nuclei with A>160 encounters both physical and technical problems. Due to the

"curvature" of the stability line (its increasing bending to the neutron axis), fusion reactions of stable nuclei produce only proton rich isotopes of heavy elements. For example, in fusion of rather neutron rich ^{18}O and ^{186}W isotopes one may get only the neutron deficient ^{204}Pb excited compound nucleus, which after evaporation of several neutrons shifts even more to the proton rich side. As a result, on the nuclear map there are, for example, 19 known neutron rich isotopes of cesium (Z = 55) and only 4 of platinum (Z = 78). For elements with Z > 100 only neutron deficient isotopes (located to the left of the stability line) have been synthesized so far. That is the main reason also for the impossibility to reach the center of the "island of stability" (Z~114 and N~184) in the superheavy mass region, and neutron deficient isotopes of elements with Z>120 (being synthesized in fusion reactions) should have very short half-lives (less than one microsecond), insufficient for their separation and identification.

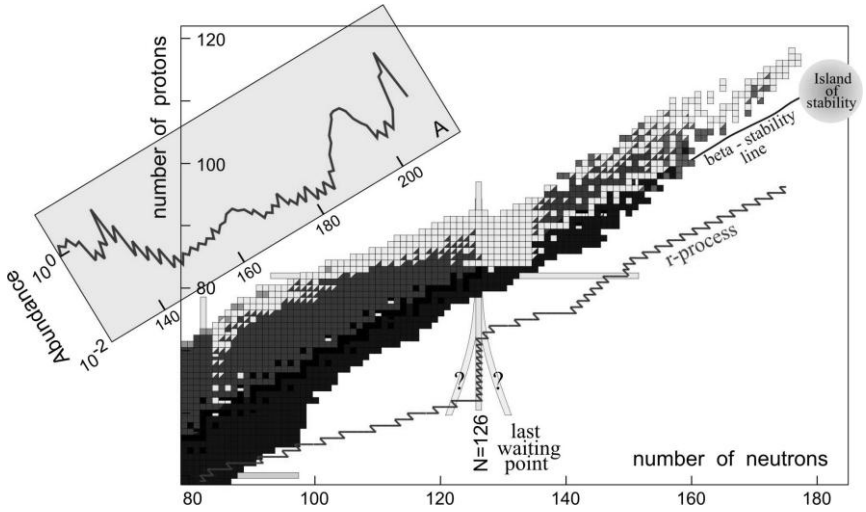

Figure 1. Upper part of the nuclear map. r-process of nucleosynthesis is shown schematically.

At the same time, the unexplored area of heavy neutron rich nuclei is extremely important for nuclear astrophysics investigations and, in particular, for the understanding of the r-process of astrophysical nucleogenesis (a sequence of neutron-capture and β^-–decay processes). Just in this region the closed neutron shell N=126 is located which is the last "waiting point" in the r-process (see Fig. 1). The half-lives and other characteristics of these nuclei are extremely important for the r-process scenario of supernovae explosions. Study of the structural properties of nuclei along the neutron shell N = 126 could also

contribute to the present discussion of the quenching of shell gaps in nuclei with large neutron excess.

There are three possibilities for the production of such nuclei. These are the multi-nucleon transfer reactions [1], fusion reactions with extremely neutron rich radioactive nuclei and rapid neutron capture processes. Today the two last methods look unrealizable because of low intensity of radioactive beams and low neutron fluxes in existing nuclear reactors. On the contrary, the low-energy multi-nucleon transfer reactions, as well as the quasi-fission processes [2] (which are similar) are quite practicable. They can be used for the production of new neutron rich isotopes not only in the region of Z~80 but also in the superheavy mass area [3]. Theoretical estimations show that several tens of new nuclides in the region of N=126 and Z~75 can be produced, for example, in the near-barrier collision of ^{136}Xe with ^{208}Pb (see Fig. 2).

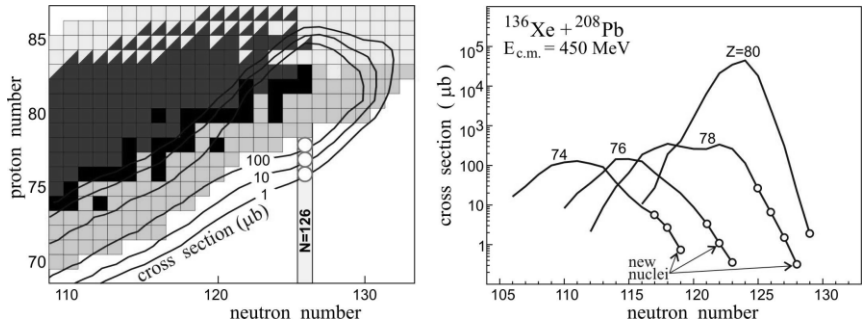

Figure 2. Cross sections for formation of heavy nuclei in collisions of 136Xe+208Pb at center-of-mass energy of 450 MeV [1]. Open circles in the right panel correspond to unknown isotopes.

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Neutron rich isotopes of transfermium elements can be also produced in the multi-nucleon transfer reactions at low-energy collisions of actinide nuclei.

Production and study of properties of neutron rich fermium isotopes (A > 260) are extremely interesting for several reasons. Firstly, as mentioned above, all known isotopes of fermium (and of more heavy elements) are located to the left side of the beta-stability line (see Fig. 1). Secondly, the well known "fermium gap" (isotopes $^{258-260}$Fm with very short half-lives for spontaneous fission) impedes formation of nuclei with Z>100 by the weak neutron fluxes realized in existing nuclear reactors. In this connection, it is extremely interesting to know what is the first β^-–decaying fermium isotope and how long is its half-life. This is important not only for reactor but also for explosive nucleosynthesis in which this fermium gap might be bypassed.

Unfortunately, the neutron rich heavy nuclei with Z>70 formed in the multi-nucleon transfer reactions cannot be separated and studied at available setups created quite recently just for studying the products of deep inelastic scattering (such as VAMOS, PRISMA and others). These fragment separators (as well as other setups) cannot separate heavy nuclei with Z>70 by their atomic number (mass separation is more simple with time-of-flight technique, for example).

2. Scheme of setup

However during the last several years a combined method of separation has been intensively studied and developed based on stopping nuclei in gas and subsequent resonance laser ionization of them [4-6]. This method was used up to now for separation and study of light exotic nuclei and fission fragments. Such techniques allows one to extract nuclei with a given atomic number, while a separation of the single ionized isotopes over their masses can be done rather easily by a magnetic field. Half-lives of heavy neutron rich nuclei, which we are interested in (as a rule, β^-–decaying), are much longer than the extraction time of ions at such a setup.

The scheme of this setup is shown in Fig. 3. Neutron rich isotopes of heavy elements are produced in multi-nucleon transfer reactions with heavy ions accelerated up to 5–10 MeV/nucleon (depending on projectile target combination). The target, a foil of about 300 μg/cm^2 thickness (or larger), is placed at the window of gas cell (or inside it). Nuclear reaction products, escape the target as multi-charged ions, are decelerated and neutralized due to collisions with the atoms of buffer gas in the gas cell filled with pure argon or helium. Then the desired atoms (with a given Z number) are ionized by means of two or three-step resonance laser irradiation and extracted through the supersonic nozzle or skimmer into the vacuum volume as positive charged ions

(Q=+1) with slow energies of about 0.2 eV. In vacuum the ions are transported through the sextupole or quadrupole ion–guide system (see below), which helps to pump away the residual buffer gas and keep the ions.

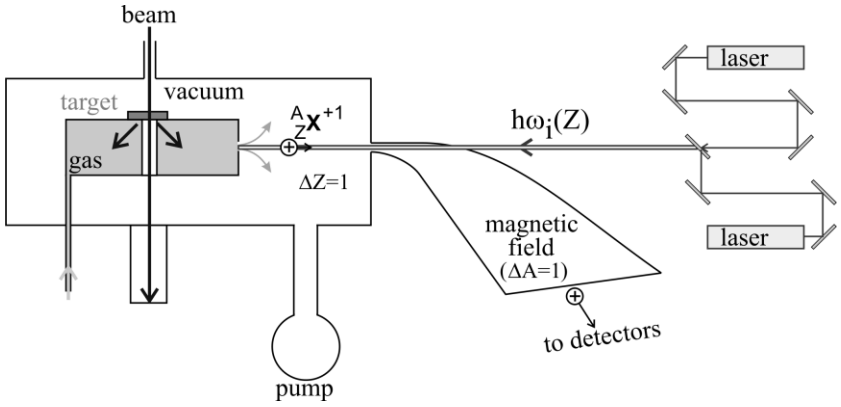

Figure 2. Schematic view of setup for resonance laser ionization of nuclear reaction products stopped in gas with subsequent mass separation of them and transportation to detecting system.

Then the ions are accelerated up to 30–60 keV and separated by the magnet of the mass–separator. Detailed description of the technique of stopping and cooling the ion beams in buffer gas, laser ionization and separation can be found in [4-6, 9, 10, 15, 16]. In this way a low-energy beam of single ionized atoms is produced with an extremely small emittance. Atomic nuclei of this beam have a definite value of charge number and a given (chosen) mass value, there are neither isobars nor isotopes. This allows one to perform subsequent high sensitive analysis of spectroscopic and decay properties of these nuclei, as well as a measurement of spins, dipole magnetic and quadrupole electric moments and charge radii of these nuclei by means of laser spectroscopy.

The setup consists of the following elements (units):

- laser system,
- mass-separator,
- front end system including:
  - gas cell,
  - system for extraction of the cooled ion beam and its cleaning from the buffer gas,
  - electrostatic system for final formation and acceleration of the ion beam,
- system for delivery and cleaning of the buffer gas and pressure stabilization inside the gas cell,
- vacuum system,

- high voltage and radio frequency units,
- diagnostic and control systems for the ion beam.

2.1. *Laser system*

A choice of specific laser scheme, type and number of lasers is defined by the ionization potentials of the elements under study and by the configuration of the ion-guide part of the setup. In our case the three-step scheme of ionization looks more favorable. Such scheme allows one to choose more effective optical transitions to increase the yield of resonance-ionized ions. This does not exclude also the two-step ionization scheme if it is needed.

Laser power is defined by the saturation condition of optical transitions at each step of excitation. Required energy density of laser radiation is [7]

$$\Phi = h\nu/2\sigma, \qquad (1)$$

where $h\nu \sim 3.10^{-19}$ J is the energy of photon with $\lambda = 600$ nm and σ is the cross section of optical transition (it is about 10^{-11} - 10^{-12} cm^2 for well allowed resonance transitions, 10^{-14} –10^{-15} cm^2 for the Rydberg and autoionization states and 10^{-17}–10^{-18} cm^2 for ionization to continuum [8]). Thus, the required energy densities for different steps of excitations are about 10^{-7} J/cm^2, 10^{-4} J/cm^2 и 10^{-1} J/cm^2, correspondingly.

In the first and second cases variable-frequency radiation is needed. Required energy density here could be obtained by the Dye lasers or tunable Ti:Sapphire solid state lasers developed intensively last years [6]. In the third case (and also for pumping of the Dye and Ti:Sapphire lasers) one needs more powerful laser radiation of visible (or UV) spectrum. This may be supplied by the Eximer lasers, by the copper vapor lasers (CVL) and by the Nd:YAG lasers with frequency doubling. Frequency repetition of the eximer lasers is limited by several hundreds of Hz. It is in principle sufficient for efficient ionization in gas cell [13]. The copper vapor lasers may operate with 10 kHz frequency. However at this frequency they generate significant electrical noise which complicates an operation of all the electronics and detecting part of the setup.

Table 1. Lasers used for multi-step resonance ionization

Laser type	Output power, (average) main & harmonics: (2^{nd}), {3^{rd} & 4^{th}}, W	Pulse frequency repetition, Hz	Pulse length, ns	Wavelength, nm
Dye laser	3, (0.3)	10^4	10-30	213 - 850
Ti:Sapphire	2, (0.2), {0.04}	10^4	30-50	210 - 860
Eximer laser	30	400	10-20	308
CVL	30-50	10^3-10^4	10-30	510.6 & 578.2
Nd:YAG	(80-100)	10^4	10-50	532

The Nd:YAG may also operate with 10 kHz frequencies but do not interfere so much with other electronic devices [6]. Thus, the use of them looks more preferable.

2.2. *Gas cell and Ion-Guide system*

During last years Ion-Guide [9] and Ion Catcher [10] systems are used rather wide. In this kind of systems reaction products are stopped in gas, thermalized, gain a charge state +1 and extracted to mass separator by the gas flow. General features of operation of such systems are well known [11]. Low efficiency is the main drawback. As a rule, no more than 1% of all the reaction products keep their charge state. Other ions are neutralized up to atomic state. Only in very specific cases the efficiency may reach 10%.

Resonance laser ionization of neutralized atoms is a specific feature of the proposed setup. Efficiency of this process may reach 100%. This method is already used and developing in CRC (Belgium) [12, 13], JYFL (Finland) [14], and the same kind of setup is planning to build up at RIKEN (Japan). At CERN successfully used laser ionization in vacuum ion source [4].

General requirements to the laser ion source systems, based on gas cell looks as follows [6, 12,13]:

- pressure in gas cell: 100–500 mbar depending on energy of reaction;
- working gas is He or Ar (the latter looks preferably because its stopping capacity and efficiency of neutralization are higher);
- gas purity: better than 99,9999%
- cell volume is about 100–200 cm^3;
- vacuum in intermediate camera not lower than10^{-2} mbar;
- vacuum in the entrance into the mass separator is 10^{-6} mbar;

Some specific requirements, stipulated by the use of the resonance laser ionization, should be also taken into account [14, 15]:

- gas cell should be two-volume to separate the area of thermalization and neutralization from the area of resonance laser ionization;
- extraction of ions from the cell and guiding them into the mass separator have to be provided by the sextupole (quadrupole) radio-frequency system which allows one to increase the mass-separator resolution and to separate high pressure area in gas cell and high vacuum area in mass-separator. It increase the total efficiency of the setup and allow us to perform ionization of atoms in the gas jet outside the gas cell;
- the input-output setup must be supplied by the system of optical windows and by the system of explicit positioning (0.3 mm) of the gas cell, guide mirrors and prisms.

2.3. *Mass separator*

All extracted ions have charge state +1 because only neutral atoms are ionized to this state by the lasers while all "non-resonant" ions are removed by electric field before reaching the area of interaction with laser radiation. In this case the extracted particles can be easily separated by masses in dipole magnet. For low-energy (30–60 keV) beams of +1 charged ions no specific requirements are needed for the dipole magnet. It could be a standard magnet separator similar to ISOLDE II [16], for example:

- turning angle 40^{o}–90^{o},
- turning radius of about 1–1.5 m,
- focal length of about 1 m,
- rigidity of about 0.5 T.m.

Mass resolution is the only critical parameter which should be not less than 1500 (4000 is theoretically feasible). Camera of the separator must have an optical input if laser ionization is used in the sextupole ion-guide (SPIG).

3. Required beams of accelerated ions

The use of the designed setup for separation and study of heavy neutron rich nuclei does not require any specific beams of accelerated ions. The ion beams available at FLNR (JINR, Dubna) are well satisfied our requirements which look as follows.

- Ions: ^{16,18}O, ^{20,22}Ne, ^{24,26}Mg, ^{32,34,36}S, ^{40}Ar, ^{40,44,48}Ca, ^{48,50}Ti, ^{54}Cr, ^{58}Fe, ^{62,64}Ni, ^{84,86}Kr, ^{136}Xe, ^{238}U (i.e., quite different depending on the problem to be solved).

- Beam energies: 4,5 – 9 MeV/nucleon (slightly above the Coulomb barrier)
- Beam intensity: not restricted (up to 10^{13} pps).
- Beam spot at the target: 3–10 mm in diameter (not very important).
- Beam emittance: 20π mm mrad.
- Targets: different, including actinides Th, U, Pu, Am, Cm.

It is evident that the proposed method allows one to extract not only heavy transfer reaction products but also any other nuclei with half-lives longer than a few tens of milliseconds including neutron rich fission fragments, fusion reaction products and light exotic nuclei. Such studies are already performed at the similar setups, for example, in CERN, Finland and Belgium. Estimated efficiency of such setups is about 10% and depends on half-life of extracted ion. This is quite sufficient for study of nuclear reaction products formed with cross sections of about 1 microbarn at beam intensity of 0.1 pμA. This method allows one to study structure and decay properties of new exotic nuclei as well as spectroscopic properties of the corresponding atoms. At higher beam intensity this setup could be used also for separation and study of neutron rich long living superheavy nuclei produced in multi-nucleon transfer reactions with actinide targets (see above).

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