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Production and study of neutron rich heavy nuclei, GALS setup

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Production and study of neutron rich heavy nuclei, GALS setup

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Abstract. A new setup for production and investigation of exotic heavy neutron rich nuclei located in the "north-east" region of nuclear map is under construction at Flerov Laboratory for Nuclear Reactions (FLNR) of JINR, Dubna. The setup will use the available U-400M cyclotron beams for low energy multi-nucleon transfer reactions. Products of 4.5 to 9 MeV per nucleon heavy-ion collisions, such as ^{136}Xe beam on ^{208}Pb target, will be captured in a gas cell, selectively laser-ionized, transported towards mass separator by electrostatic ion guide extraction system and then to detecting system.

Introduction

Investigations in area of heavy neutron-rich nuclei are of great interest in nuclear physics [1-5]. Production and study of such nuclei is extremely important for the understanding of astrophysical nucleogenesis *r*-process, which is responsible for creation of about half of the heavy elements, and its path critically depends on the neutron capture *Q*-value of very neutron-rich isotopes. Of particular interest is still unexplored area along closed neutron shell $N = 126$ which is the last “waiting point” in the *r*-process pathway. Production and study of extremely neutron-rich nuclei is also important for basic nuclear spectroscopy.

Heavy neutron rich nuclei can be produced in three different ways: multi-nucleon transfer reactions, fusion reactions with extremely neutron rich radioactive nuclei and rapid neutron capture processes. Due to the low intensity of radioactive beams and low neutron fluxes in existing nuclear reactors, the last two methods seem to be unrealizable. In contrast, the low-energy multi-nucleon transfer reactions can be used for production of new neutron-rich isotopes not only in the region of $Z \approx 80$ but also in the superheavy mass area (discussed by V. Zagrebaev and W. Greiner in [4]). It was shown that several tens of new nuclides in the region of $N = 126$ and $Z \approx 75$ can be produced in near-barrier collisions ^{136}Xe + ^{208}Pb. Even higher cross sections were predicted for new neutron rich nuclei production in collisions of ^{198}Pt beam with ^{238}U target (Figure 1).

To produce and study such neutron-rich nuclei, the GAs cell-based Laser ionization and Separation setup (GALS) is being constructed at Flerov Laboratory for Nuclear Reactions in JINR. The setup will use multinucleon transfer reactions for production of heavy neutron-rich nuclei near to or above magic neutron number $N = 126$.

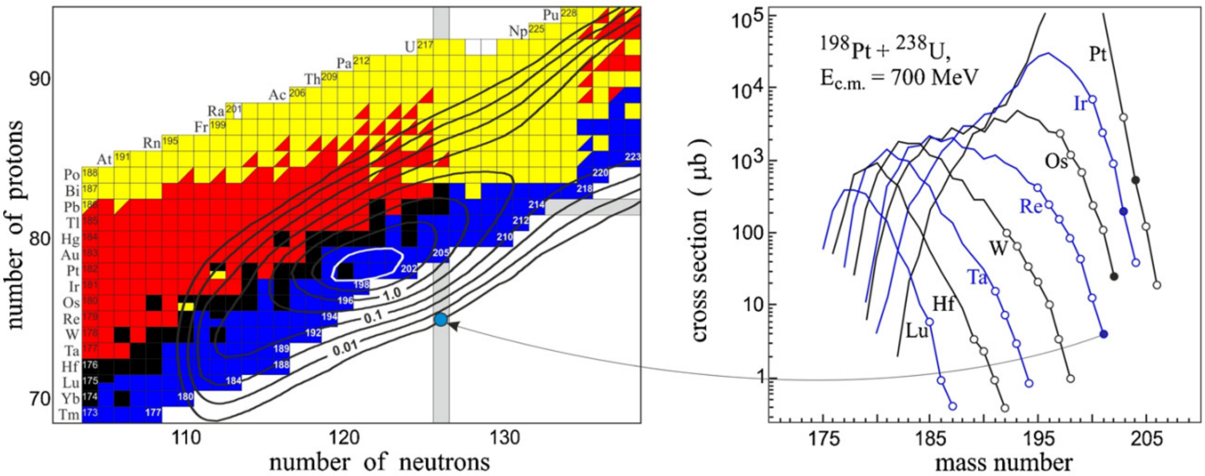

Figure 1. Heavy nuclei formation cross-sections in $^{198}Pt + ^{238}U$ collisions at 700 MeV center-of-mass energy [3]. Curves in the left panel show cross-sections in mb, and circles in the right panel correspond to unknown isotopes.

Experimental setup

The experimental technique was already described in detail in [1-3, 7, 8], and only a brief overview of the GALS setup experimental method is presented here. As proposed and applied in [7, 8], this method combines simultaneous *Z* and *A* separation by stopping of nuclear reaction products in a gas cell, their subsequent resonance laser ionization and mass-separation. GALS facility complete scheme can be found in [3].

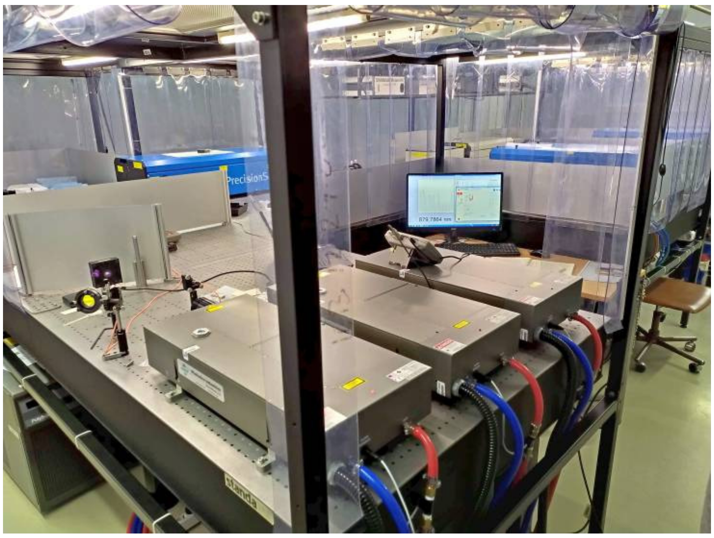

Figure 2. Laser laboratory is almost ready for the first experiments

The operation principle was described in a number of papers (see e.g. [9] and the references therein). The first stage of laser system is based on three Sirah dye lasers pumped by two Nd:YAG EdgeWave lasers. Laser laboratory preparation is almost finished, remaining laser equipment (TiSa and Dye lasers, beam diagnostic, doubling optics etc.) was delivered and now is being installed in the laser lab. Recently, three new Photonics Industries TU-H TiSa lasers were installed and tested. Their working parameters were optimized for performing our first off-line experiments.

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Figure 3. The whole GALS facility view in experimental room within the FLNR U-400M cyclotron hall.

Also, our work on GALS subsystems located in experimental room within the cyclotron U-400M hall is being continued. Figure 3 presents the view of GALS facility with its subsystems. A significant part of the subsystems is manufactured and ready for installation (e.g. front-end vacuum chamber, gas cell, Einzel lens, mass-separator analyzing magnet, focal chamber, gas purifying system), although some of the parts are still being designed or manufactured (e.g. ion guide, detecting and DAQ systems).

First experiments are planned to be performed with Os I laser ionization with preliminary offline experiments on the best ionization scheme determination. For these offline experiments, our existing reference cell is planned to be used, and also a new one will be built. The existing reference cell needs a modernization of vacuum system, which is also currently being performed.

The ion guide simulation

In the previous publications, it was shown that a sextupole ion guide (SPIG) can be used as an ion extraction and guiding system [13, 14]. But after more precise calculations it was estimated that mean time of flight of the ions transported through long (630 mm) SPIG is about 3 ms, and their kinetic energy goes down to 0.2 eV. To improve TOF, overall efficiency and energy parameters, and also to prevent the gas jet of the stopping cell from direct hit in the orifice between the chambers, an option of using an S-shaped quadrupole ion guide was considered (Fig. 4). This option is also more preferable for in gas jet laser ionization.

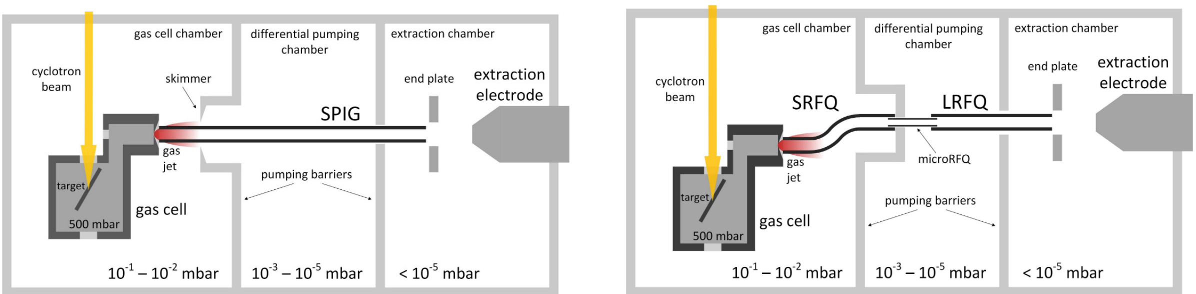

Figure 4. Two designs of the ion guide: SPIG (on the left-hand side) and S-shaped RFQ (right-hand side).

Designed ion guide consists of 20-segment S-shaped RFQ (Fig. 5), wedge-type micro RFQ and linear RFQ, which leads the ions through the high-vacuum chamber straight to the high voltage extraction electrode. Resulting ion beam then goes through the Einzel lens towards analyzing magnet. Simulation methods and initial ion parameters were the same as in the previous SPIG simulations [13, 14]. The simulations were performed in SIMION software package [15] using the hard sphere collision model and the additional code describing the gas jet [16, 17]. In different system regions, the residue gas pressure lowers from 500 mbar in the gas cell to 10^{-2} mbar in SRFQ vacuum chamber, 10^{-4} mbar in the middle differential pumping section (where mRFQ and front part of LRFQ are located) and finally becomes 10^{-6} mbar in the extraction electrode section.

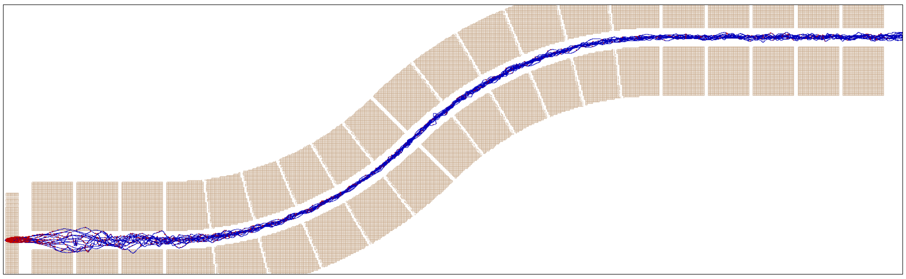

Figure 5. S-shaped RFQ and ion trajectories within it. Radiofrequency (0.67 MHz) voltage amplitude is set to 300 V, with overall longitudinal gradient of 20 V. Buffer gas (argon) pressure inside the gas cell is 500 mbar, and the pressure in the vacuum chamber is 10^{-2} mbar.

It was calculated that at analyzing magnet entry ions have an emittance of 6.5 $\pi \cdot$ mm $\cdot$ mrad (horizontal) and 10 $\pi \cdot$ mm $\cdot$ mrad (vertical). Average kinetic energy is 39766.4 eV with a standard deviation σ = 2.7 eV. Average time of flight is 487.2 μs (σ = 58.6 μs), transport efficiency is 97.7 %. For high resolution mass spectroscopy, such energy dispersion and emittance may become a problem, so some system improvements (e.g. voltage optimizations) are considered to be done.

Comparison of these two options of the ion guide sistem show the following. The advantage of SPIG is quite simple construction (single 6-rod structure ion guide through the whole front end vacuum chamber), at the same time it has a disadvantage of high risk that the ions get stuck inside long SPIG due to kinetic energy losses. RFQ ion guide with S-shaped ion guide can provide much better time of flight and efficiency. On the other hand, it is a much more complicated system. Nevertheless, in order to provide the best experimental transport efficiency of studied ions, it was decided to use the second option with segmented SRFQ. The system design is already finished and now it is being manufactured.

Conclusion and planned experiments

The new GALS facility at FLNR U-400M cyclotron is under construction. In this setup, the highly selective and efficient technique of stepwise resonant ionization in a gas cell with subsequent mass separation of elements of interest will be applied. The most efficient method of heavy neutron rich nuclei production, as motivated in [4], is the multi-nucleon transfer reactions.

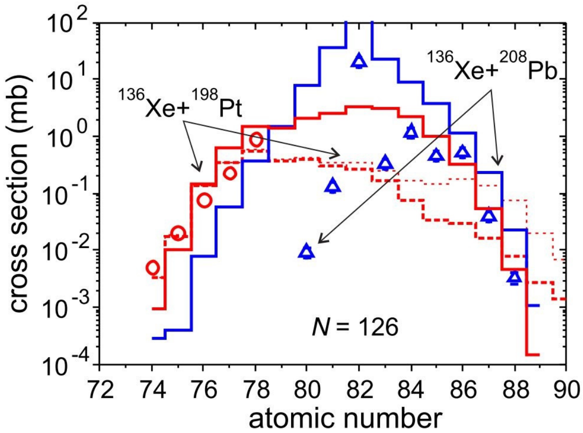

Figure 6. Calculated (histograms) and experimental (symbols) cross sections for production of isotopes with $N = 126$ in reactions ^{136}Xe + ^{198}Pt, ^{208}Pb (courtesy of A. Karpov and V. Sayko). The solid and dashed histograms are for $E_{\mathrm{c.m.}} = 450$ and 643 MeV, respectively. The thin and thick dashed curves are integrated over all angles and over the experimentally covered angles from 24° to 34°, respectively. The experimentally deduced cross sections for the ^{136}Xe + ^{198}Pt system are from Ref. [19] and for ^{136}Xe + ^{208}Pb are from Ref. [20].

Recent theoretical predictions by A. Karpov and V. Sayko show quite high cross section for ^{202}Os production in such ^{136}Xe + ^{198}Pt reactions [18]. Also, in the region of $N = 126$, another nuclei which are not yet investigated, will be available for our experiments (see Figure 6). During the offline experiments it is planned to study Os I laser ionization schemes [13] and their efficiencies in order to determine the best ionization scheme.

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