Ion guide simulation for GALS setup

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A new setup is under construction at the Flerov Laboratory of Nuclear Reactions (FLNR), JINR, Dubna, to study heavy neutron-rich nuclei along a closed neutron shell N=126. One of the important parts of the setup is the ion guide system. From several ion guide options, a Radio-Frequency Quadrupole (RFQ) ion guiding system was chosen. This special ion guiding system was developed and optimized using SIMION simulation software. Also, precise comparison with the alternative Linear-Sextupole Ion Guide (SPIG) system was performed. Along with ion guide simulation, modernization of reference cell was completed and it is ready for offline experiments to find optimal laser ionization scheme.

INTORDUCTION

Over the past several decades, more than 3,000 isotopes of 118 elements have been discovered. It is also estimated that about 3000-5000 more isotopes can be detected. More than half of these undiscovered isotopes are heavy neutron-rich nuclei. Exploring properties of heavy neutron-rich nuclei is very important for modern nuclear physics. Especially the region along the closed neutron shell N = 126, which is still a blank field of the nuclide chart, is of special interest [1-7]. This is the last so-called "waiting point" on the path of the *r*-process of astrophysical nucleosynthesis, which is responsible for creating about half of heavy elements, the path of this process is critically dependent on the Q-value of neutron capture for very neutron-rich isotopes. Production and study of such nuclei will make it possible to better understand the characteristics of nuclear structure and the processes of nucleosynthesis, and it is also important for basic nuclear spectroscopy. New information can be obtained about the changes of nuclear ground state properties, e.g., appearance of new or disappearance of the classical magic numbers (as in the light neutron-rich nuclei case) as well as the occurrence of rapid nuclear structural changes due to sudden onset of collectivity.

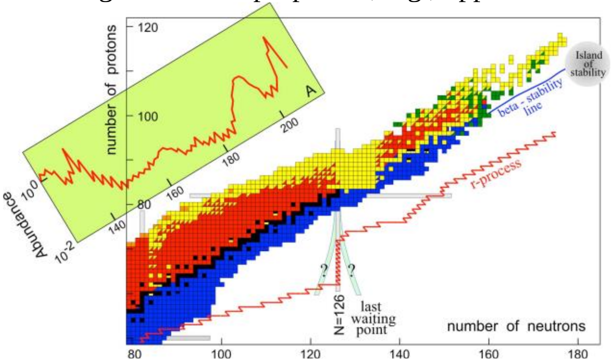

Fig. 1. Upper part of the nuclear map. r-process of nucleosynthesis is shown schematically.

But producing and studying these neutron-rich heavy nuclei presents two major challenges. First, it is difficult to synthesize, and second, it is difficult to separate the reaction products.

The heavy neutron-rich nuclei can be produced in multi-nucleon transfer reactions, fusion reactions with extremely neutron rich radioactive nuclei and rapid neutron capture processes [4]. The last two methods seem to be not possible nowadays due to insufficient intensity of radioactive beams and low neutron fluxes in existing nuclear reactors. Conversely, the low-energy multi-nucleon transfer reactions can be used to produce new neutron-rich isotopes not only in the region of $Z \approx 80$, but also in the region of superheavy masses. According to theoretical calculations, a significant number of new nuclides in the region of N = 126 and $Z \approx 75$ can be

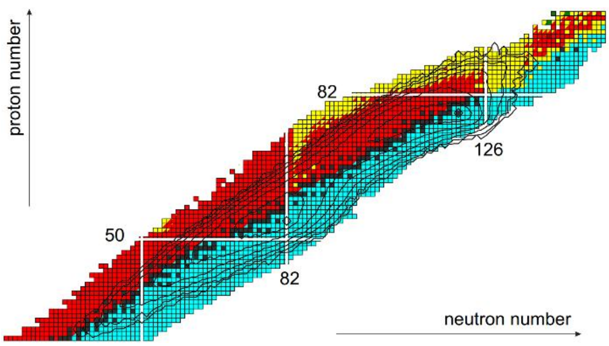

Fig. 2. Upper part of the chart of nuclides. The production cross sections in the $^{136}Xe + ^{198}Pt$ reaction at $E_{c.m.}$ = 643 MeV are shown by contour lines drawn over an order of magnitude of the cross section down to 100 nb (courtesy of A. Karpov and V. Sayko [8]).]

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produced in near-barrier collisions in ^{136}Xe + ^{208}Pb reaction [4]. For reactions of ^{136}Xe beam colliding with ^{198}Pt target, even higher cross sections were predicted (see Figure 2) [6, 8].

A new setup (GALS - **GA**s cell-based **L**aser ionization and **S**eparation setup) is at the construction stage at Flerov Laboratory for Nuclear Reactions in JINR, Dubna. It will use multi-nucleon transfer reactions and selective multi-step laser ionization to produce and study of heavy neutron-rich nuclei near the magic neutron number N = 126 and above.

EXPERIMENTAL SETUP AND ITS PRESENT STATUS

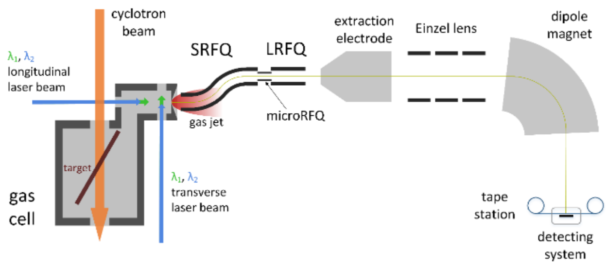

Fig. 3. *GALS setup scheme. After recoiling out of a thin target into the gas cell, MNT reaction products are thermalized and neutralized in collisions with buffer gas atoms (pure Ar, 500 mbar). Then the atoms of interest with a given value of Z are selectively ionized by 2 or 3 step laser radiation with appropriate wavelengths. The resulting ions with a charge of +1 are carried out by the buffer gas from the gas cell into vacuum through a supersonic nozzle. Then the ions are captured from gas jet and guided by the ion extraction system (containing S-shaped radio-frequency quadrupole (RFQ), micro-RFQ and linear-RFQ) and after acceleration go through mass separator and then to detectors.*

GALS experimental method combines simultaneous Z and A separation [9, 10]. Projectile beam from the existing U400M cyclotron hits the target in gas cell within GALS front end vacuum chamber, nuclear reaction products are neutralized and thermalized in buffer gas, subsequently laser-ionized, guided to high vacuum volume, accelerated and sent through analyzing magnet to detecting system. Figure 3 shows the scheme of GALS facility.

Depending on the element of interest, beams with 2 or 3 different wavelengths can be used for efficient selective laser ionization. They can be directed into the ionization chamber of the gas cell in longitudinal or transverse direction, or a combination or them. An option of ionization in gas jet is also considered for the future spectroscopic experiments. The first stage of laser system is based on three Sirah dye lasers pumped by two Nd:YAG EdgeWave lasers. There is also a narrow-band laser system including a Millennia pump laser, Sirah Matisse ring laser and a Sirah Wavetrain frequency doubler [11]. The GALS laser laboratory equipment (TiSa and Dye lasers, beam diagnostic, doubling optics etc.) currently is in process of commissioning and thorough testing.

From several theoretical calculations [4, 8, 17], Os seems very perspective candidate to achieve the neutron magic line N = 126.

Many spectroscopic data of Os I have been studied to find appropriate two or three-steps transitions for laser ionization. Although there are many observed spectral lines as yet the atomic spectra information is not complete: most of the transitions are not assigned [18–20] and the atomic strengths are not known. Nevertheless, several of the possible RIS scheme for Os have been previously studied [21, 22]. Three of them that seem to be more effective (see e.g. [22]) are shown in Fig. 4. The most ionization schemes are two colored three steps, the 3rd step being nonresonant. A summary of several two steps ionization schemes proposed in the present work is given in Table 1.

Table 1. Suggested two ($\lambda_3 = \lambda_1$ case A or $\lambda_3 = \lambda_2$ – case B) and three step (case C) ionization schemes. In all cases the first step begins from the ground state: $E_0 = 0$ cm^{-1} with configuration $5d^6 6s^2$ $^5D_4$.The third step of most two wavelength ionizations is non-resonant.

λ_1 (air), Å	E_1, cm^{-1}	State I	J_1	Λ_2 (air), Å	E_2, cm^{-1}	State II	J_1	case
2909.6	34365.33	6s6p $^5F^0$	5	4752.16	55402.47	6s7s?	?	C
3018.04	33124.48	6s6p ^7P	3	5580.66	51038.49	6s7s e^5D	0	A or B
3267.94	30591.45	6s6p ^7P	4	5509.33	48737.34	Unknown	4	A
3301.56	30279.95	6s6p ^7F	5	4815.96	51038.49	6s7s e^5D	4	A or B

4260.85	23462.90	6s6p ^{7}D	5	3157.24	55127.00	Unknown	?	A or B
4420.47	22615.69	6s6p ^{7}D	4	4066.69	48737.44	6s7s e^{7}D	4	A or B
4420.47	22615.69	6s6p ^{7}D	4	3827.14	47198.7	6s7s e^{7}D	5	A or B

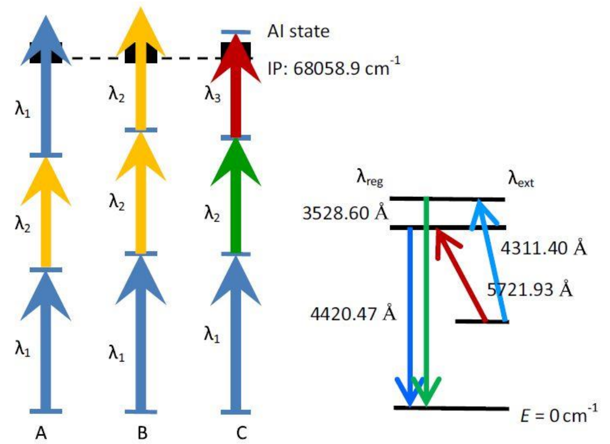

Fig. 4. *Left: possible ionization schemes of Os I: the wavelengths of the different cases are indicated in Table 1. Case C presents a 3 steps ionization scheme proposed in [18] with wavelengths given in the first row of Table 1 (λ_3 (air) = 6043.15 A°). Right: transitions for the offline test experiments*

Therefore, the first offline experiments are planned to be performed on Os 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, more optimized for laminar gas flow and thus more efficient, will be built. Also, modernization of the existing reference cell is currently being performed.

Most of the other GALS systems were developed, manufactured and delivered to JINR. Front-end vacuum chamber, gas cell, Einzel lens, mass analyzing magnet, focal chamber, gas purifying system are ready for the installation in the experimental room within U400M cyclotron hall. Along with that, some equipment is still in process of design, manufacture or testing (i.e. ion guide, tape station, detecting and DAQ systems).

Preparatory work on the GALS setup parts deployment at the U400M cyclotron was carried out. The scheme with a movable cyclotron beam bending magnet was simulated and technical requirements were formulated for its implementation. Also, a high-voltage platform for the GALS front end was developed and put into production.

ION GUIDE SIMULATION

In previous publications, a comparison of different options for GALS ion guide was made [12, 13, 14]. Initially, a single long Sextupole Ion Guide (SPIG) was planned to be used for ion transporting through differential pumping volumes of GALS front end chamber. But after more precise calculations it was estimated that mean time of flight of the ions transported through Linear-SPIG (630mm) is about 3ms, and kinetic energy goes down to 0.2 eV. Also due to collisions with residual gas molecules and longitudinal electric field absence, the ions get stuck, which dramatically increases transport time.

Therefore, an option of using an S-shaped segmented RFQ (Radio-Frequency Quadrupole) was also considered, to improve time of flight, energy parameters and overall efficiency. A multi-segmented RFQ allows to implement a longitudinal electric field dragging the ions through residual gas in vacuum chamber, thus improving transport time. The S-shaped ion guide also allows to direct laser beams towards the gas jet for in-gas-jet ionization, and it will prevent the gas jet from hitting the orifice between front end volumes.

Table 2. Simulated ions output parameters comparison

	SPIG	SRFQ + mRFQ + LRFQ
Before the end plate		
Mean longitudinal kinetik K_e	0,2 eV	12eV
Mean time of flight	3138,5μs	484,8μs
Efficiency	98,8%	99,4%
At analyzing magnet entry		
Mean longitudinal kinetik energy K_e	39783,7eV	39766,4eV
Standard deviation of kinetic energy σ_{Ke}	183,8eV	2,7eV

Mean time of flight t	3154,1μs	487,2μs	Horizontal emittance component	1 π·mm·mrad	6,3 π·mm·mrad
Standard deviation of kinetic energy σ_t	3409,5μs	58,6μs	Vertical emittance component	1 π·mm·mrad	6,4 π·mm·mrad
			Efficiency	97%	97%

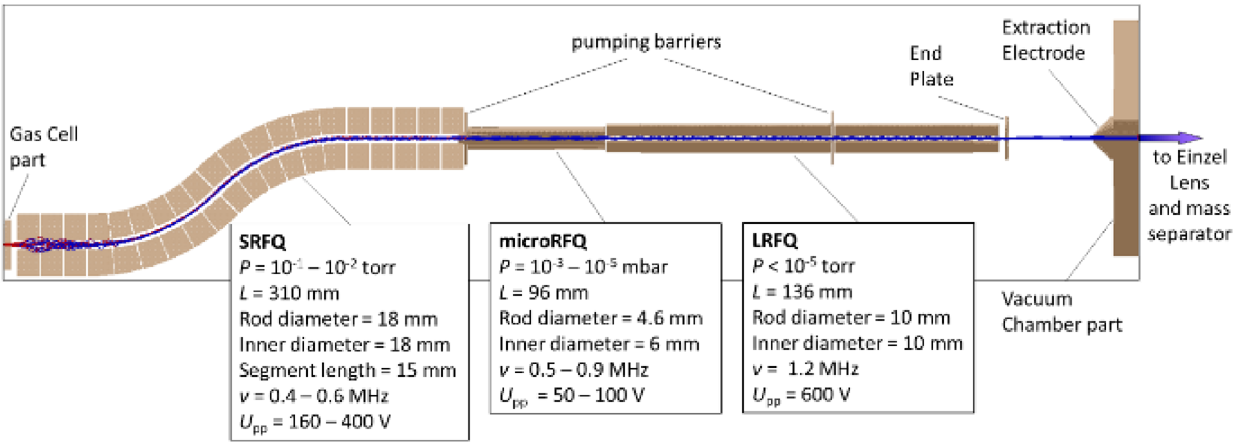

Fig. 5. *The ion guide model within GALS front-end vacuum chamber.*

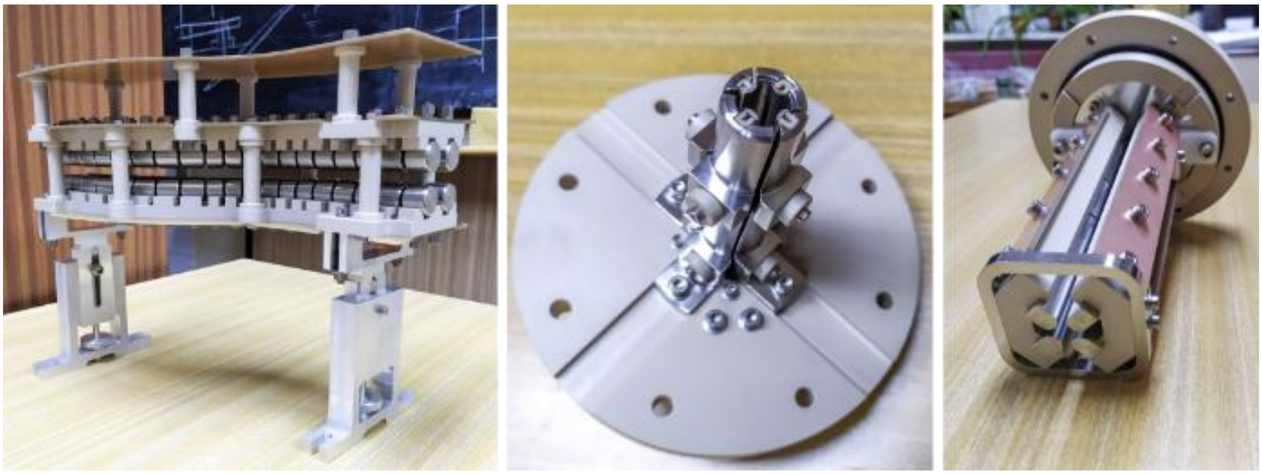

Fig. 6. *The SRFQ, microRFQ and LRFQ parts of the GALS ion guide system*

After series of in-depth simulations and optimizations [14] using SIMION software package, it was decided to use a more complicated but more promising ion guide scheme with S-shaped RFQ. Although it is a much more complicated system compared to the linear SPIG system, it has many advantages such as better transporting time and energy spread (Table 2). The final ion guide design is shown on Figure 5.

The ion guide consists of a 20-segment S-shaped RFQ, a wedge-type micro RFQ and a linear RFQ (Fig. 5), which guides the ions through the high-vacuum chamber straight to the high voltage extraction electrode. Then the ion beam goes through the Einzel lens towards the analyzing magnet. The residue gas pressure lowers from 500 mbar in the gas cell to 10^{-2} mbar in S-shaped RFQ vacuum chamber, 10^{-4} mbar in the middle differential pumping section (where micro-RFQ and front part of Linear-RFQ are located) and finally becomes 10^{-6} mbar in the extraction electrode section. It was calculated that average time of flight of ions through entire ion guide system should be 487.2 μs and the efficiency of transportation 97.7 %.

In the simulation, ions have mass = 204 amu, charge = +1e and their initial speed corresponds to thermal energy at 300 K. The total length (1876mm) of the ions transportation was simulated from the gas jet of the supersonic nozzle of the gas cell to the entry of analyzing magnet after Einzel lens.

Mechanical part of the ion guide was designed, manufactured and delivered to our laboratory (Fig. 6). RF power supply systems and other electrical components are being prepared for the forthcoming detailed testing of the whole ion guide system.

CONCLUSION & PLANNED EXPERIMENTS

A new GALS setup is under construction, uses multinucleon transfer reactions, multi-step laser ionization, efficient ion transporting and mass analyzing systems which can overcome physical and technical difficulties to produce and study heavy neutron-rich nuclei - near or above magic neutron number N=126.

Initially we intend to use Linear-SPIG system for ion transportation but after in depth of simulation we found out several disadvantages comparing to S-shaped RFQ ion guide system.

Linear SPIG system is quite simple design, but it has a disadvantage of long transporting time. On the other hand S-shaped RFQ is much more complicated system but can provide much better transporting time. In order to provide the best experimental transport efficiency, we chose complicated but more efficient SRFQ system. Ion guide system is already manufactured and ready for installation.

As we mentioned before Os seems promising candidate to achieve the neutron magic number N = 126 (see Figure 7). Therefore we are aiming to study osmium isotopes first. After thorough research [18-22], we have found several possible laser ionization schemes for osmium ionization, and we will continue to study these laser ionization schemes to choose the best scheme.

Further, we will investigate all possible isotopes around or above neutron number N = 126. Then we plan to continue with transfermium region also.

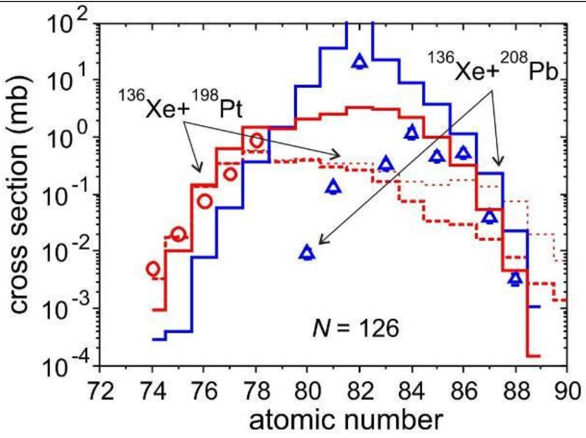

Fig. 7. *Calculated (histograms) and experimental (symbols) cross sections for production of isotopes with N = 126 in reactions* $^{136}Xe + {}^{198}Pt$, ^{208}Pb *[8]. The solid and dashed histograms are for* $E_{c.m.}$ *= 450 and 643 MeV, respectively. The thin and thick dashed curves are integrated 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. [15] and for* $^{136}Xe + {}^{208}Pb$ *are from Ref. [16].*

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