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PRODUCTION AND STUDY OF HEAVY NEUTRON RICH ISOTOPES – GALS SETUP

S.G. Zemlyanoy[1]*, K.A. Avvakumov[1], G.V. Myshinsky[1], V.I. Zhemenik[1], B. Zuzaan[1], T. Tserensambuu[1], Yu. Kudryavtsev[2], V. Fedosseev[3], R. Bark[4], R.K. Kabytayeva[1, 5]

[1]*Joint Institute for Nuclear Research, Flerov Laboratory of Nuclear Reactions, Dubna, Russia,*
[2]*KU Leuven, Instituut voor Kern- en Stralingsfysica, Leuven, Belgium,*
[3]*CERN, Switzerland,*
[4]*iThemba LABS, Nat. Research Foundation, South Africa,*
[5]*Gumilyov Eurasian National University, Kazakhstan*

Abstract
GALS (**GA**s cell based **L**aser ionization **S**etup) is a new setup which is under construction at the Flerov Laboratory of Nuclear Reactions (FLNR) of JINR, Dubna. It aims for production and study of heavy neutron rich isotopes located along the magic neutron number N = 126. The setup uses low energy multinucleon transfer reactions, resonant laser ionization technique, efficient ion transporting and mass analyzing systems which bring us closer to exploration of heavy neutron rich nuclei properties.

Introduction

Exploring properties of heavy neutron rich nuclei is very important for modern nuclear physics. 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 nucleogenesis, 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.

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. The low-energy multi-nucleon transfer reactions can be used to produce new neutron-rich isotopes in the region of $Z \approx 80$, and 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 produced in near-barrier collisions in ^{136}Xe + ^{208}Pb reaction. For reactions of ^{136}Xe beam colliding with ^{198}Pt target, even higher cross sections were predicted (see Figure 1) [6, 8].

A new setup called 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 to produce and study of heavy neutron-rich nuclei near the magic neutron number N = 126 or above.

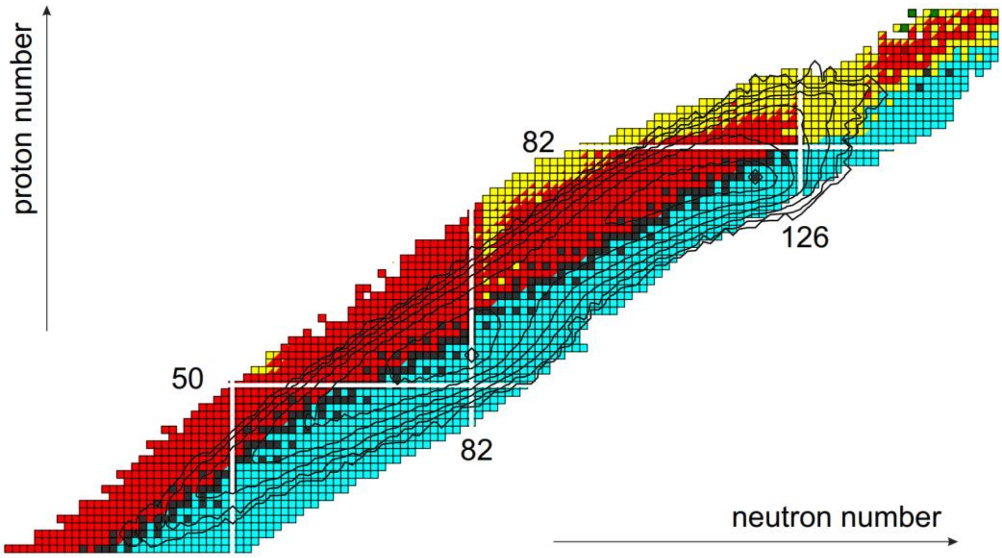

Figure 1. Upper part of the chart of nuclides. The production cross sections in the ^{136}Xe + ^{198}Pt reaction at $E_{c.m.}$ = 643 MeV are shown by contour lines drawn over an order of magnitude of the cross section down to 100 nb (courtesy of A. Karpov and V. Sayko [8]).

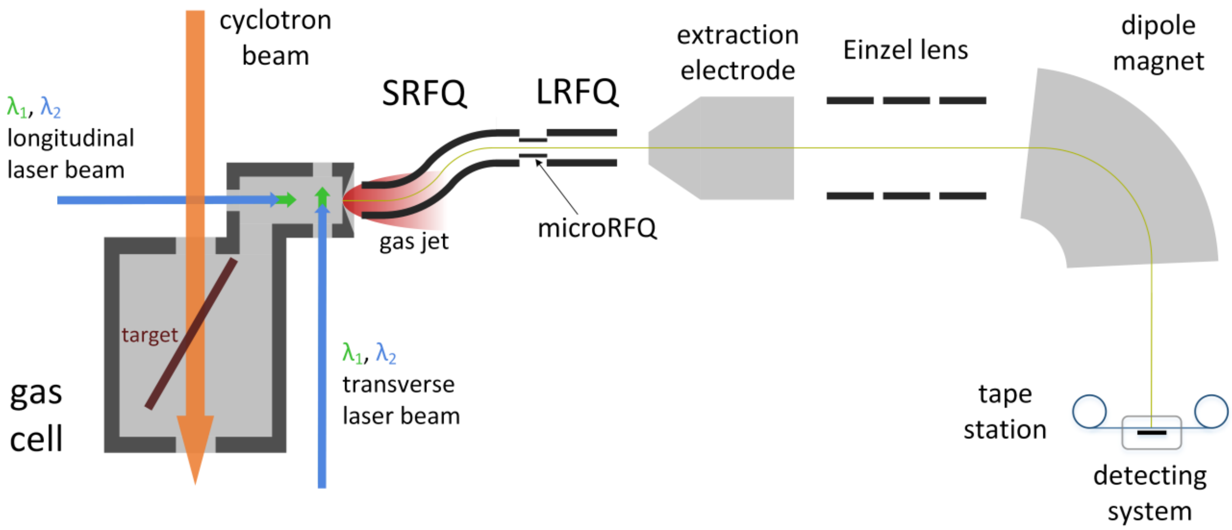

Figure 2. GALS setup scheme. After recoiling out of a thin target into the gas cell, MNT reaction products are thermalized and neutralized in collisions with buffer gas atoms (pure Ar, 500 mbar). Then the atoms of interest with a given value of Z are selectively ionized by 2 or 3 step laser radiation 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 radiofrequency quadrupole, micro-RFQ and linear RFQ) and after acceleration go through mass separator and then to detectors.

Experimental Setup

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 2 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 through testing.

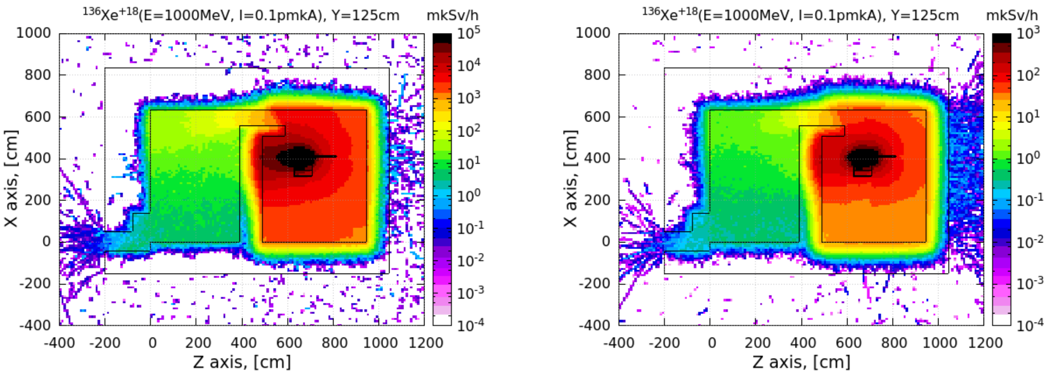

Figure 3. FLUKA simulations of radiation conditions in the GALS setup physical cabin. Left-hand side: neutron radiation, right-hand side: photon radiation.

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. Simulations of the radiation conditions in the physical cabin were performed using FLUKA software (see Fig. 3) and requirements for the modernization of radiation protection were developed. 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.

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. An option of using an S-shaped segmented RFQ (radiofrequency quadrupole) was also considered. The RFQ divided into many segments allows to implement a longitudinal electric field dragging the ions through residual gas in vacuum chamber, improving transport time. The S-shaped ion guide also allows to direct laser beams towards the gas jet for in-gas-jet ionization, and also it will prevent the gas jet from hitting the orifice between front end volumes.

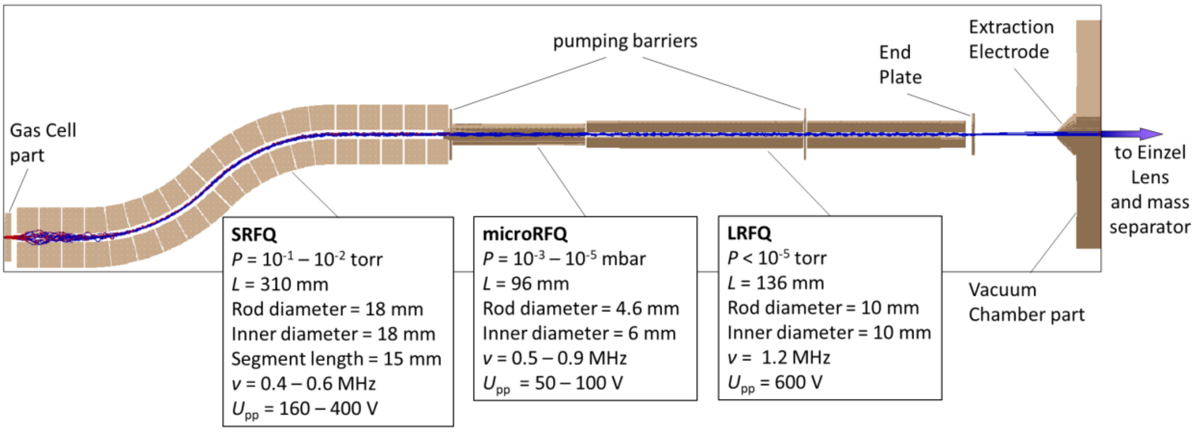

Figure 4. The ion guide model within GALS front-end vacuum chamber.

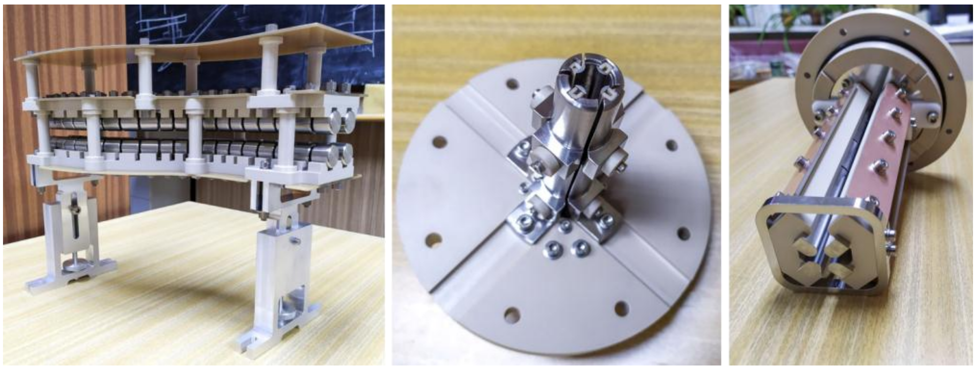

Fig. 5. The SRFQ, microRFQ and LRFQ parts of the GALS ion guide system.

After series of in-depth simulations and optimizations [14] using SIMION software package [15], 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 SPIG, it provides better transporting time and energy spread. The final ion guide design is shown on Figure 4.

The ion guide consists of a 20-segment S-shaped RFQ (Fig. 4), a wedge-type micro RFQ and a linear RFQ, 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 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. It was calculated that at analyzing magnet entry the ions should have an average time of flight 487.2 µs and transport efficiency of 97.7 %.

Mechanical part of the ion guide was designed, manufactured and delivered to our laboratory (Fig. 5). RF power supply systems and other electrical components are being prepared for the forthcoming detailed testing of the whole ion guide system.

Planned Experiments

Significant progress in construction of the new GALS facility at FLNR U400M cyclotron was made. In this setup, highly efficient technique of selective stepwise resonant ionization in a gas cell and mass separation of elements of interest will be used. For heavy neutron rich nuclei production, the most efficient method is the multi-nucleon transfer reactions [4].

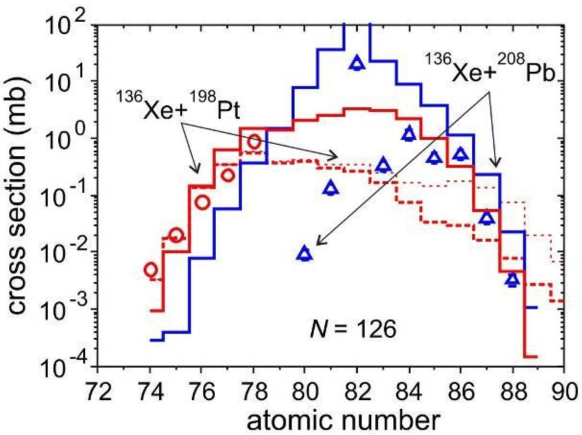

Figure 6. Calculated (histograms) and experimental (symbols) cross sections for production of isotopes with N = 126 in reactions ^{136}Xe + ^{198}Pt, ^{208}Pb [8]. The solid and dashed histograms are for $E_{c.m.}$ = 450 and 643 MeV, respectively. The thin and thick dashed curves are integrated over 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. [16] and for ^{136}Xe + ^{208}Pb are from Ref. [17].

Theoretical calculations by A. Karpov and V. Sayko show high enough cross section for ^{202}Os production in such ^{136}Xe + ^{198}Pt reactions [8]. Figure 6 shows that a number of not yet investigated nuclei in the region of N = 126 will be available for our experiments in these reactions. Estimations show that at target thickness of 0.3 mg/cm, ion beam of 0.1 pmA and the overall setup efficiency of 10 % it will be possible to measure decay properties of 1 new isotope per day. During the forthcoming offline experiments, Os I laser ionization schemes [11] and their efficiencies will be studied in detail in order to determine the best ionization scheme.

References

1. Zagrebaev, V.I., Zemlyanoy, S.G., Kozulin, E.M., Kudryavtsev, Yu., Fedosseev, V., Bark, R., Othman, H.A.: Production and study of heavy neutron rich nuclei formed in multi-nucleon transfer reactions. Hyperfine Interacs. **216,** 109 (2013)
2. Zagrebaev, V.I., Zemlyanoy, S.G., Kozulin, E.M. et al.: Gas-cell-based setup for the production and study of neutron rich heavy nuclei. Hyperfine Interacs **227,** 181 (2014)
3. Zemlyanoy, S., Zagrebaev, V., Kozulin, E., Kudryavtsev, Yu, Fedosseev, V, Bark, R., Janas Z.: GALS - setup for production and study of multinucleon transfer reaction products: present status. J. Phys.: Conf. Series **724,** 012057 (2016)
4. Zagrebaev, V., Greiner, W.: Production of New Heavy Isotopes in Low-Energy Multinucleon Transfer Reactions. Phys. Rev. Lett. **101**, 122701 (2008)
5. Long Zh, Zhao-Qing Feng, Feng-Shou Zhang: Production of heavy neutron-rich nuclei in transfer reactions within the dinuclear system model. J. Phys. G: Nucl. Part. Phys. **42,** 085102 (2015)
6. Hirayama, Y., Watanabe, Y. X., Imai, N. et. al.: β-decay spectroscopy of r-process nuclei with N = 126 at KISS. AIP Conference Proceedings. **1594**, 380 (2014)
7. Savard G., Brodeur M., Clark J. A. et al.: The N = 126 factory: A new facility to produce very heavy neutron-rich isotopes. Nucl. Instrum. Methods Phys. Res. B **463**, 258 (2020)
8. Karpov, A. V., Saiko, V. V.: Modeling near-barrier collisions of heavy ions based on a Langevin-type approach. Physical Review C **96**, 024618 (2017)

9. Kudryavstev, Y., et al.: Beams of isotopes produced at LISOL by laser ionization after thermalization of energetic ions in a gas cell. Nucl. Instrum. Methods Phys. Res. B **204**, 336 (2003)
10. Moore, I.D., et al.: Development of a laser ion source at IGISOL. J. Phys. G: Nucl. Part. Phys. **31**, S1499 (2005)
11. Zemlyanoy S., Avvakumov K., Fedosseev V., Bark R., Blazczak Z., Janas Z.: Current status of GALS setup in JINR. Hyperfine Interact. **238**, 31 (2017)
12. Zemlyanoy S. et al.: Heavy neutron rich nuclei: production and investigation. J. Phys.: Conf. Ser., **1023**, 012004 (2018)
13. Zemlyanoy S. et al.: Production and Study of Neutron Rich Heavy Nuclei, GALS Setup. Proceedings of the International Symposium on Exotic Nuclei EXON-2018 2020. Singapore: World Scientific, ISBN 978-981-120-944-4, 492
14. Zemlyanoy, S., Avvakumov, K., Zuzaan, B. et al. Further development of GALS setup at JINR. Hyperfine Interact **241,** 38 (2020)
15. http://simion.com/
16. Watanabe Y. X., Kim Y. H., Jeong S. C. et al.: Pathway for the Production of Neutron-Rich Isotopes around the N = 126 Shell Closure. Phys. Rev. Lett. **115**, 172503 (2015)
17. Barrett J. S., Loveland W., Yanez R. et al.: ^{136}Xe + ^{208}Pb reaction: A test of models of multinucleon transfer reactions. Phys. Rev. C **91**, 064615 (2015)