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Title: Production of exotic nuclei via MNT reactions using gas cells

PRODUCTION OF EXOTIC NUCLEI VIA MNT REACTIONS USING GAS CELLS*

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The use of multi-nucleon transfer (MNT) reactions to produce neutron-rich nuclei in the heavy region has received an increased attention in the last decade. The feasibility of employing such reactions at the FRS Ion Catcher facility at GSI and the IGISOL facility at JYFL is studied using a combination of theoretical calculations and experiment simulations. The reactions are computed within a Langevin-type model, and the Geant program is used to simulate the transport of the resulting products within the experimental setups of the above-mentioned facilities. The angular distribution of ion release, possible target choices and target-to-beam-dump distances are discussed.

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1. Introduction

Studies of neutron-rich nuclei have always been of great interest as a tool for expanding our understanding of nuclear structure or of nucleosynthesis processes, such as the r-process [1]. The production cross sections

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of reactions traditionally used to produce such nuclei, namely fission and fragmentation, steeply decline in the heavy region above $A > 180$, making such reactions inefficient.

The multi-nucleon transfer (MNT) reaction has been known and studied for more than six decades, but is still not well-understood. Only in the last decade it was proven to provide larger cross sections than the fragmentation process, with a slower decrease in the region of the $Z > 65$ heavy nuclei [2]. Thus, MNT reactions are considered to be a possible tool for studies in the neutron-rich region of heavy nuclei. Several experiments have demonstrated feasibility of such studies, *e.g.* at VAMOS at GANIL [2] and KISS at RIKEN [3].

The present paper presents first results of an optimization study of the MNT experimental setups at two IGISOL-type facilities, the FRagment Separator-Ion Catcher (FRS-IC) at GSI and Ion Guide Isotope Separator On-Line (IGISOL) facility at JYFL Accelerator Laboratory, which are shortly described in Sec. 2, together with the experimental programs aiming to use MNT reactions to study heavy nuclei. This first step of calculations is the optimization of the target-to-dump distance. The reaction cross sections calculated with a Langevin-type model are discussed in Sec. 3. Section 4 presents the results of the simulations for the two considered setups.

2. Facilities for exotic nuclei

Experimental programs to utilize MNT reactions are planned at the IGISOL facility at JYFL and at the FRS Ion Catcher [4] at GSI. At the IGISOL facility, a ^{136}Xe beam impinging on ^{209}Bi and ^{198}Pt targets will be used, while at GSI, a ^{238}U beam will impinge on ^{64}Ni and ^{164}Dy targets. At both facilities, exotic nuclei will be produced and studied utilizing the gas cell technique. However, there are many differences between them in terms of the availability of different primary beams, type and size of the gas cells, ion selection and measurement devices, *etc.* The study presented here is focused on the possibility of using these reactions at the two facilities.

At the IGISOL facility, the produced ions of interest are first slowed down in a gas-filled chamber. A SextuPole Ion Guide (SPIG) extracts the ions, which are accelerated to 30 qkV, where q is the ion charge, before a mass separator dipole magnet and further detection setups. The Heavy-ion IGISOL platform (HIGISOL), originally designed for heavy-ion fusion–evaporation reactions at IGISOL [5–7], is used for the MNT reactions. It allows the target to be moved with respect to the beam axis and distance to gas cell window making, therefore, possible the control of the angular distribution of the released ions that can enter the gas cell.

At the FRS-IC [8], ions are thermalized in a cryogenic gas cell [9] and analyzed with the Multiple-Reflection Time-Of-Flight Mass-Spectrometer (MR-TOF-MS) [10]. For the MNT measurements, the primary beam is transported with the FRS towards the gas cell and the interaction takes place inside the He gas by placing the targets inside. A schematic drawing of the experiment is shown in Fig. 1.

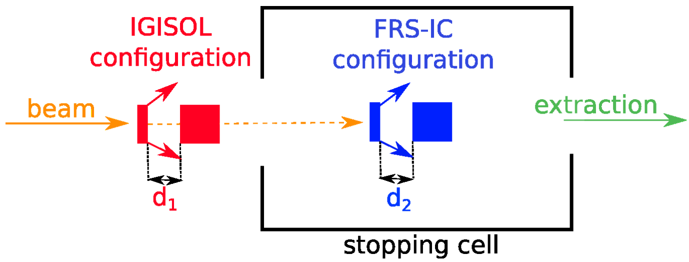

Fig. 1. Schematic drawing of the MNT experimental setups. The target-to-beam-dump distances d_1 and d_2 can be varied.

3. Langevin-type model cross sections for MNT reactions

The MNT process is defined by an exchange of nucleons that happens when two nuclei, colliding with an impact parameter smaller than for a quasi-elastic reaction, interact by forming an excited deformed nuclear system. It further breaks into fragments. The products are emitted in a wide angular range allowing their separation from the primary beam penetrating the target.

In the past, several theoretical models have been established and improved for a more precise characterization of the process. Lately, a new model based on Langevin equations has been developed [11, 12]. The increased number of degrees of freedom together with a different treatment of the potential energy and the equation of motion allows for a more accurate description of the system. Predictions of this model, developed specifically for the analysis of MNT in deep-inelastic collisions of heavy ions, were used as input in our simulations.

Figure 2 shows the cross sections for target-like fragments (TLFs), but it refers to products formed by adding or removing any combination of five or less nucleons from the target nucleus. Two of the reactions have been studied before, namely $^{238}\mathrm{U} + {}^{64}\mathrm{Ni}$ [13] and $^{136}\mathrm{Xe} + {}^{198}\mathrm{Pt}$ [2], making them a useful tool in validating the experimental programs along with extended studies of these reactions. The other two reactions, $^{238}\mathrm{U} + {}^{164}\mathrm{Dy}$ and $^{136}\mathrm{Xe} + {}^{209}\mathrm{Bi}$, would provide new experimental results for neutron-rich heavy projectile-like fragments (PLFs) and TLFs.

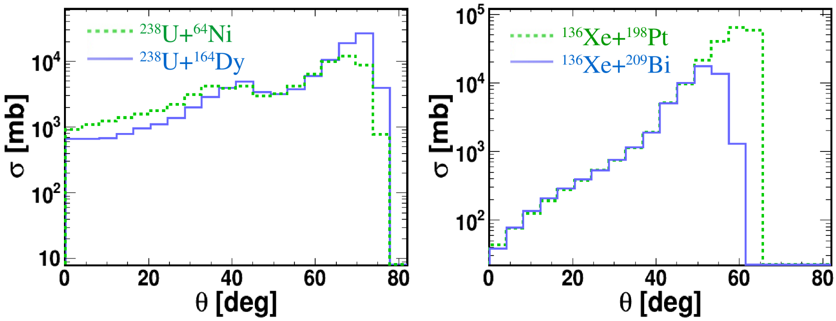

Fig. 2. Reaction cross sections for TLFs, calculated within the Langevin-type model, as a function of the emission angle for the reactions considered for experiments at the two setups: FRS-IC (left panel) with ^{238}U beam at 2856 MeV on ^{64}Ni and ^{164}Dy, and IGISOL (right panel) with ^{136}Xe at 890 MeV on ^{209}Bi and at 885 MeV on ^{198}Pt.

All reactions shown in Fig. 2 present large cross sections at high angles, making it possible to use the same optimization of the experimental setup. A beam dump, which will block the primary beam from going further into gas, is planned for both experimental programs (schematically shown in Fig. 1). While the ions emitted at low angles will be stopped by the beam dump together with the primary beam, the cross section at higher angles is comparable (for ^{238}U beam) or higher (for ^{136}Xe beam). The ^{238}U beam will be degraded in FRS in order to achieve the required energy before entering the gas cell, while the ^{136}Xe beam will be extracted from cyclotron and transported to the experimental setup.

4. Geant simulations

The primary beam energy changes when travelling through the target, and the reaction products created at different beam energies have different kinetic energies and angular distributions. Moreover, the two setups are limited in their energy and angular acceptance. Hence, a precise optimization of the experiment is crucial in order to maximize the yields. This can be obtained by adapting the Geant4 [14] simulation program. At the IGISOL setup, due to the small dimensions of the stopping volume, only ions within a narrow energy range can be stopped and further measured. Moreover, since the reaction takes place outside the stopping cell, the entrance window, beam dump and distance between the target and the gas cell are limiting the angular acceptance. The Cryogenic Stopping Cell (CSC) of the FRS-IC offers the opportunity of stopping ions with a broad range of energies due to its dimensions. Nevertheless, at high angles, the stopping is limited by the radius of the DC cage and by the beam dump at small angles. The use of thick targets results in losses in energy and rates that have to be taken into consideration.

As a first step, the beam properties, a Gaussian profile of the energy distribution in the case of the ^{238}U beam and monoenergetic in the case of the ^{136}Xe beam, and the cross sections predicted by the theoretical model were implemented in the simulation program. Further, simulations regarding the generation and release of ions from targets have been performed. The target thicknesses used in the simulations are 40 μm and 70 μm for ^{64}Ni and ^{164}Dy, respectively, targets and 5 μm and 6 μm for the ^{209}Bi and ^{198}Pt targets, respectively. The thick targets used for the FRS-IC reactions provide a transmission of 2% for ^{64}Ni and 3% for ^{164}Dy. For IGISOL, the percentage of stopped ions in the target is negligible.

Figure 3 shows the rates of the released TLFs from the target, integrated over an interval of +/− 5 nucleons, for the two sets of experiments. The results are normalized with respect to the expected primary beam intensity (10^7 ions/s for FRS-IC and 10^{10} ions/s for IGISOL). The integrated PLFs and TLFs release rates are of the order of 10^2 ions/s for the ^{238}U beam experiments and 10^5 ions/s for the ^{136}Xe beam experiments.

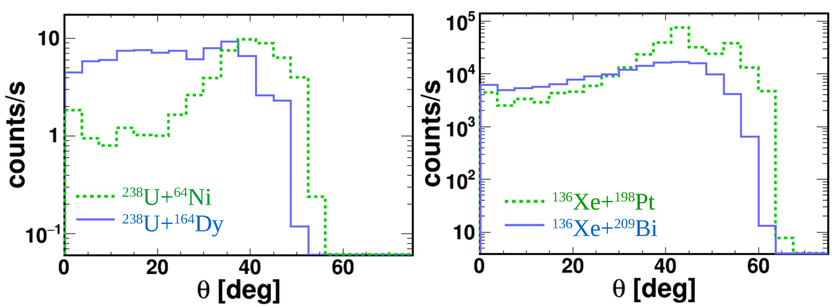

Fig. 3. Release rates of TLFs as a function of their release angle for the reactions shown in Fig. 2 (see explanations in the text).

For both reactions, the probability of emission at higher angles was shown to be similar or higher than that for small angles, facilitating the use of a beam dump. Based on the simulation results combined with geometry limitations, the optimal distances between the target and the dump were proposed to be 5 cm (FRS-IC geometry) and 12 mm (HIGISOL geometry).

5. Conclusions

This work investigated the release rates of the TLFs and PLFs from the target, together with the optimal distance between the target and the dump, for two proposed MNT experiments at the IGISOL facility in the JYFL Accelerator Laboratory and at the FRS Ion Catcher facility at GSI. The presented results are based on Geant4 simulations of the chosen reactions, having the Langevin-type model as an input and aiming at defining the optimal distance between the target and the dump. The rates of released ions at higher angles are facilitating the stopping of the ions of interest in gas, according to the usual stopping efficiencies of the setups (60% [15] for FRS-IC and 0.5% [16] for IGISOL).

The present study will be extended by taking into consideration the stopping in the gas cells after the targets and the full geometry of the experimental setups. The results of this development will allow a more precise optimization of the systems.

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