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# Multi-nucleon transfer reactions at ion catcher facilities - a new way to produce and study heavy neutron-rich nuclei

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# Multi-nucleon transfer reactions at ion catcher facilities - a new way to produce and study heavy neutron-rich nuclei

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**Abstract.** The production of very neutron-rich nuclides heavier than fission fragments is an ongoing experimental challenge. Multi-nucleon transfer reactions (MNT) have been suggested as a method to produce these nuclides. By thermalizing the reaction products in gas-filled stopping cells, we can deliver them as cooled high-quality beams to decay, laser and mass spectrometry experiments. High precision mass spectrometry will allow for the first time to universally and unambiguously identify the atomic and proton numbers of the ions produced in MNT reactions. In this way their ground and isomeric state properties can be studied in high-precision measurements. In experiments at IGISOL, Finland and at FRS Ion Catcher, Germany, we have done and will perform broadband measurements of the reaction products, with the aim to improve the understanding of the reaction mechanism and to determine the properties of the ground and isomeric states of the produced nuclides. First results and preparations for upcoming experiments are presented.

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## 1. Introduction

Heavy neutron-rich nuclei play a key role in the formation of the third abundance peak in the astrophysical rapid neutron capture process [1]. The production, separation and identification of these very neutron-rich nuclides heavier than fission fragments is a big experimental challenge, because other conventional methods using stable beams preferably produce neutron-deficient nuclei. Multi-nucleon transfer (MNT), with energies above the Coulomb barrier, between medium-heavy to heavy beams and heavy targets, have been suggested and investigated as a possible alternative method [2, 3]. Radioactive ion beams with energies at and slightly above the Coulomb barrier open a wide field for the study of MNT reactions of heavy nuclei and their application for the synthesis of new exotic heavy and superheavy isotopes [4, 5, 6, 7]. Experiments in this field can be divided in three main groups:

- Study of MNT reactions
- Production of interesting known isotopes and measurement of their properties (masses, half-lives, isomers, etc.)
- Production of new exotic isotopes and measurement of their properties

Understanding the distinct steps of these reactions is mandatory for their successful application for the synthesis of new isotopes. It will help to find optimum conditions such as projectile-target combination and beam energy. Our novel experimental approach will provide a new avenue to these longstanding questions and will provide new experimental data needed for comparison with calculations using different theoretical models [4, 8, 9]. Fig. 1 shows a comparison of model and measurements for cross-sections of a MNT reaction. As can been seen, it is sufficient to experimentally determine the order of magnitude of the cross section, if measured over a large region, to validate a model.

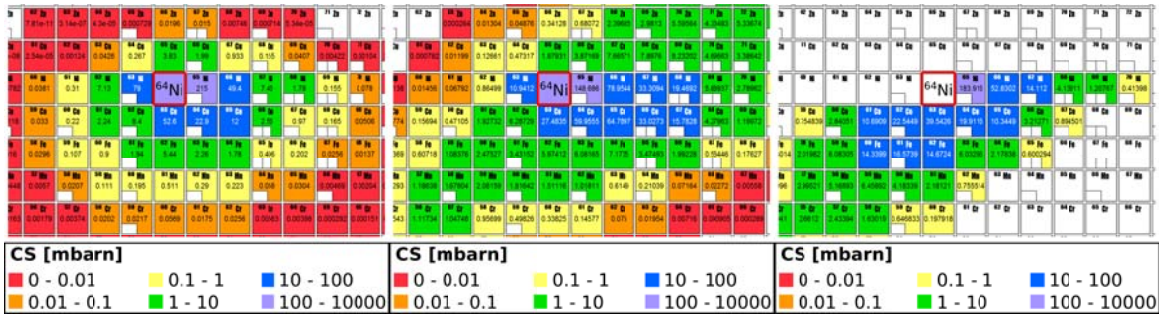


**Figure 1.** Comparison of models and experimental data for $^{238}$U + $^{64}$Ni. Left panel: GRAZING model[10]; Middle panel: Model of A. Karpov [11, 12]; Right panel: Measurements [13]. It can be clearly seen that the model of A. Karpov better describes the measured data.

The nuclides produced in MNT reactions can be thermalized in gas-filled stopping cells as singly or doubly charged ions to allow for a fast and efficient extraction from the stopping gas. They are delivered as cooled high-quality beams to decay, laser and mass

spectrometry experiments [14, 15]. In this way their ground and isomeric state properties can be studied in high precision measurements. The method has been pioneered at the KISS experiment at RIKEN, Japan [16], where the products are neutralized, extracted by the gas flow and then re-ionized by laser ionization. Experiments at IGISOL, Finland and the FRS Ion Catcher, Germany, have started, with the aim to measure the ground-state properties of the reaction products and to improve the understanding of the reaction mechanism itself. In these experiments production cross section (relative to the elastic cross-section of the beam or target) and isomer-to-ground state ratios can be measured. This information can be used to validate reaction models and to gain knowledge about the spin and excitation transferred in the reaction process. We describe here the two experiments and ways to obtain the information about the reaction process.

## 2. MNT reaction studies with the FRS Ion Catcher

At the FRS [17] and the future Super-FRS [18], a systematic study of MNT reactions with exotic ion beams will unveil the influence of a wide range of projectile isospin, binding energy, deformation as well as shell effects. Beams from the FRS and the future Super-FRS could complement reaccelerated ones at ISOL facilities, which are limited in energy and availability due to their chemical properties.

From previous investigations of MNT reactions with stable beams it becomes obvious that the produced nuclei shift towards the neutron-rich side of the chart of nuclides with increasing neutron number of the projectile and target nuclei. Therefore, neutron-rich intermediate-heavy and heavy radioactive ion beams (RIBs) such as Xe should lead to quite neutron-rich transfer products. This may be the content of subsequent experiments at the (Super-)FRS, following the success of the currently scheduled experiment on MNT studies at the FRS [19].

As a first step, reactions with slowed-down primary beams will be performed, as an intermediate step towards reaction with secondary beams in the future. In this experiment in FAIR Phase-0, we will use a $^{238}$U primary beam (with about $10^7$ ions per second) and $^{64}$Ni, $^{164}$Dy and $^{209}$Bi targets within the existing Cryogenic Stopping Cell (CSC) [20, 21] of the FRS Ion Catcher. In the next generation CSC for the Low-Energy Branch of the Super-FRS [22], the use of several targets in the stopping volume will be possible (Fig. 2), thereby making optimal use of RIBs with their broad energy and spatial distributions and possibly cocktail beams. In both CSCs the low-energy reaction-residues are extracted with high and almost elemental independent efficiency [19] and guided by RFQ systems to the high resolution mass spectrometer [23].

The identification and counting is done via precision mass measurements with a MR-TOF-MS [23]. This method is universal and applicable to all chemical elements. In contrast to other methods that measure the ionic charge to determine Z [13, 3] our method is not limited to light and medium-heavy nuclides. Therefore, we will provide for the first time unambiguous identification of the heavy reaction products. MR-TOF-

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MS can identify new isotopes independent of their half-life (ms $<T_{1/2} <$ stable) and also when their decay scheme and nuclear structure is not known. As a "by-product" of a reaction study the masses of all identified isotopes are determined with high accuracy. MR-TOF-MS can identify also long-lived (>ms) isomers of heavy isotopes and determine their isomer-to-ground state ratios [24, 25]. Thus, new isomers can be discovered in MNT reactions and isomer-to-ground state ratio can be used to investigate the spin transferred in the initial production mechanism. MR-TOF-MS can achieve simultaneously a high resolving power and cover a broad mass range of about 10% [25].

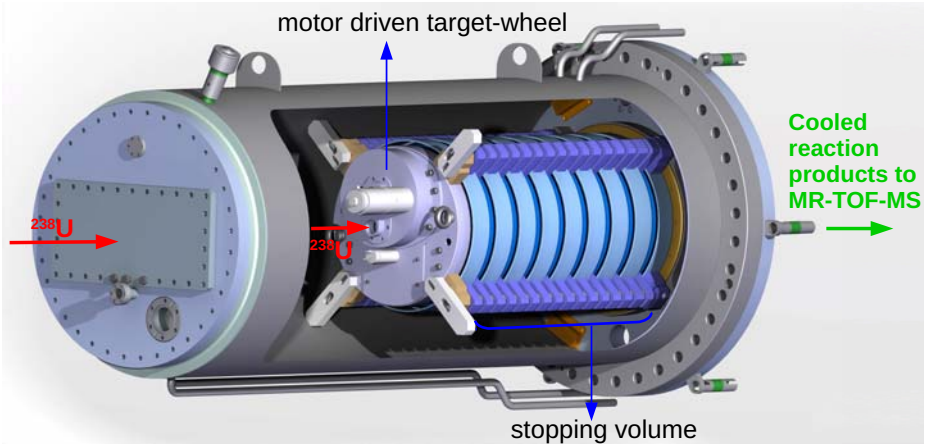


**Figure 2.** The cryogenic chamber of the CSC of the FRS Ion Catcher. Inside the chamber the target module with its motor driven target wheel and new electrode structure that forms the stopping volume for the MNT products is shown.

For these experiments we have built a shorter electrode structure and target module to be installed inside the existing CSC. The change-over between different targets, i. e. different reactions, will be as short as one minute due to a motor-driven target wheel inside the CSC, see Fig. 2. The experiment is simple and universal as the cross sections for target-like fragments (TLF) and projectile-like fragments (PLF) are measured with the same method in one experiment, because ions of all fragments are stopped in the CSC and are extracted essentially independent of their chemical nature [19]. The cross section measurements are estimated to have an uncertainty of up to a factor 2. Nevertheless, as shown in Fig. 1 and in the literature [26], an order of magnitude is sufficient to validate reaction models.

All parts of the process have been subject of detailed simulation studies, from the reaction in the target to the stopping of the ions in the gas (GEANT4 [27]) to the low energy transport in the CSC and the MR-TOF-MS (SIMION [28]). A simulated mass spectrum of the representative TLF region for the beam of $^{238}$U on target $^{64}$Ni is shown in Fig. 3.

In the first measurement campaign we expect to measure more than 150 cross-sections and about 15 new masses. These will be in the rare-earth region, providing mass data important for understanding the origin of the rare-earth peak in the r-process

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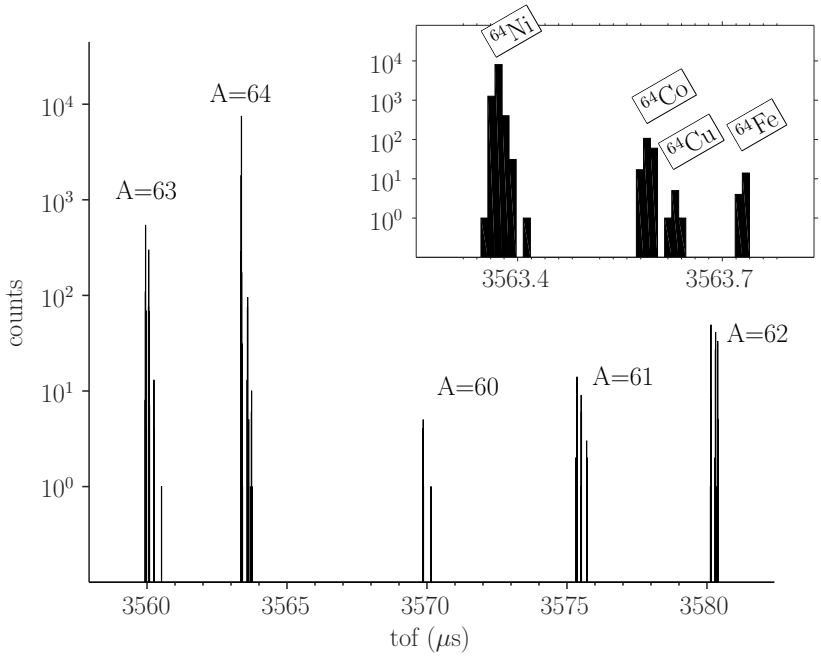


**Figure 3.** Simulated high-resolution and broadband mass spectrum of MR-TOF-MS measurement of target-like fragments for primary beam $^{238}$U on target $^{64}$Ni showing the unambiguous identification (A and Z) of the reaction products with the MR-TOF-MS. The ions are singly charged.

abundances, and the first direct mass measurements of neutron-rich trans-uranium isotopes above A>238. Moreover, we expect to find several new isomeric states, since MNT reactions can be a very powerful method for this [29].

## 3. MNT reactions experiments at IGISOL

The University of Jyväskylä has at the JYFL accelerator laboratory a K130 heavy ion cyclotron that provides beams to several experimental facilities. One of them is the IGISOL facility, where reaction products are stopped in a gas-filled stopping cell, extracted by gas flow and a sextupole ion guide [30]. The products are accelerated to 30 keV and mass-separated before they are delivered to different measurements stations shown in Fig.4. Yield measurements at IGISOL have been done, e.g. for fission fragments [31].

The first experiments that used MNT reactions at IGISOL have been done more than a decade ago [32]. However, these early experiments suffered from relatively low efficiencies of the stopping cell and limited counting and identification detection systems. Recently a dedicated campaign has been started to improve several aspects, with the aim of gaining orders of magnitude in sensitivity and establishing MNT reactions as a new reaction type to produce isotopes at IGISOL. There have been numerous upgrades to the ion source, accelerator and the IGISOL facility in general. For the MNT experiments

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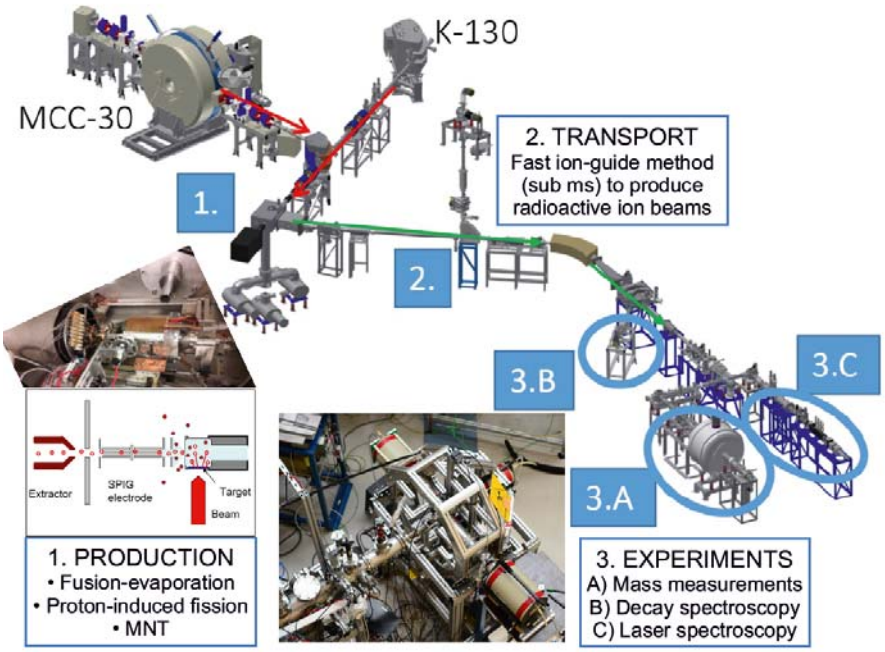


**Figure 4.** Layout of the IGISOL facility. At IGISOL a broad range of low-energy (30 keV) radioactive and stable ion beams for studies of atomic nuclei and their properties [11,12] are produced.

the new and flexible target module, the to-be-built dedicated stopping cell and the newly installed MR-TOF-MS will be very important. To optimize the yields and conditions, detailed GEANT4 simulations [33] have been done. To allow an easy and fast characterization of the setup in the start-up phase, $^{209}$Bi targets are used to produce $\alpha$-decaying isotopes, which are fast and easily identified without mass selection. Such an $\alpha$-spectrum measured during the first test experiment can be seen in Fig. 5. The detector was installed before the magnetic dipole, therefore no mass separation was done prior to detection.

The inset shows the zoom on the prominent alpha peaks from the ground and isomeric state of $^{211}$Po. As mentioned above the measurements of the isomeric-to-ground state ratio can be used to better understand the reaction process and the spin and excitation of the nucleus before evaporation [34, 35]. After the successful test of the $^{209}$Bi target and the alpha-spectroscopy of the reaction products at IGISOL, the same will be used for the commissioning of the experiments at the FRS.

## 4. Conclusions

We propose a novel method for reaction studies, which will pave the way for broad variety of studies with primary and secondary beams. To ultimately produce exotic nuclei which are not accessible by conventional production methods. The concept is based on the experimental setups at IGISOL, University of Jyväskylä, Finland and at GSI/FAIR,

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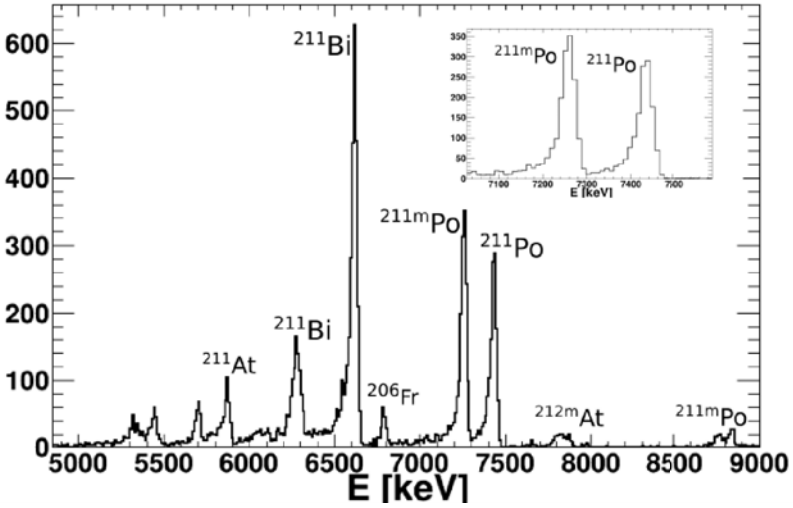


**Figure 5.** Alpha-decay from fragments for primary beam of about 10 pnA of $^{136}$Xe at 945 MeV beam energy on target $^{209}$Bi (thickness 5$\mu$m). By using high resolution MR-TOF-MS in upcoming experiments a similar unambiguous identification of decay products independent on their decay properties will be possible.

Germany. The CSC and the MR-TOF-MS have a world-wide unique combination of performance parameters that are needed to stop and measure the reaction products in a universal and efficient way. The measured masses will have an important input in the understanding of the rare-earth peak of the r-process and neutron-rich actinides. The systems are complementary to each other in many aspects, at IGISOL additional detection methods are available, such as laser and decay spectroscopy. But the system at the FRS has higher efficiency and allows to also study heavy primary beams, e.g. $^{238}$U.

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