MULTINUCLEON TRANSFER REACTIONS IN THE ^{238}U + ^{238}U SYSTEM STUDIED WITH THE VAMOS+AGATA+ID-Fix*

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The measurement of the production cross sections of exotic neutron-rich heavy nuclei, in the uranium region, in the vicinity of the $N = 152$ deformed shell gap was carried out via multinucleon transfer reactions of ^{238}U + ^{238}U at 7.193 and 6.765 MeV/A using the VAMOS++ magnetic spectrometer coupled to the AGATA and ID-Fix photon detection arrays. This article reports on the status of the VAMOS++ data analysis and results on the population of the strongest ($\pm 1n$) transfer channels observed from the decay of long-lived products after irradiation.

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1. Introduction

Neutron-rich uranium-like nuclei near the $N = 152$ deformed shell gap are of special interest as they can yield important nuclear-structure features related to shell effects and deformation. However, due to experimental challenges concerning production and identification, the data available on these nuclei are rather limited. The possibility to investigate neutron-rich isotopes of superheavy nuclei at the island of stability, including also the ones in the region of our interest, using multinucleon transfer (MNT) reactions has regained attention thanks to the improved performances of large acceptance magnetic spectrometers, *e.g.* the mass resolution of $\Delta A/A \simeq 1/263$ achieved at VAMOS++ [1]. Cross sections of the order of a few tens of μbarn are predicted for MNT in collisions of actinide nuclei [2, 3]. This value, being beyond reach for other reaction mechanisms like fusion–evaporation, awaits experimental verification. The present work aims to measure the production cross sections of exotic neutron-rich heavy nuclei in the uranium region via MNT reactions of ^{238}U + ^{238}U and is intended to serve as a basis for possible future nuclear structure studies.

2. Experimental setup

The experiment was performed at GANIL using a beam of ^{238}U at energies of 6.765 and 7.193 MeV/A impinging on a 615 μg/cm^2 ^{12}C-sandwiched metallic uranium target. The magnetic spectrometer VAMOS++ [1, 4] was used to identify the atomic mass of the products. It has an angular coverage of $\theta = \pm 7^\circ$ and $\phi = \pm 11^\circ$, and was placed at the grazing angle of $\theta_{\mathrm{lab}} = 40^\circ$ relative to the beam axis. To slow down the reaction products and improve the time-of-flight (TOF) resolution, which in turn would improve the resolution in mass, an Al degrader with a thickness of 20 μm was placed behind the target. To determine the atomic number of the products, coincident X-rays were detected with the γ-ray spectrometer AGATA [5, 6] together with the X-ray detector array named ID-Fix [7]. AGATA was placed at 23 cm from the target covering $\sim 10\%$ of the total solid angle. ID-Fix comprises 3 Low Energy Photon Spectrometers (LEPSs). Each LEPS was mounted at ~ 4 cm from the target, looking through a window of 1.5 mm Al + 0.5 mm Ti, covering altogether a solid angle of $\sim 7\%$. Figure 1 shows a schematic view of the setup.

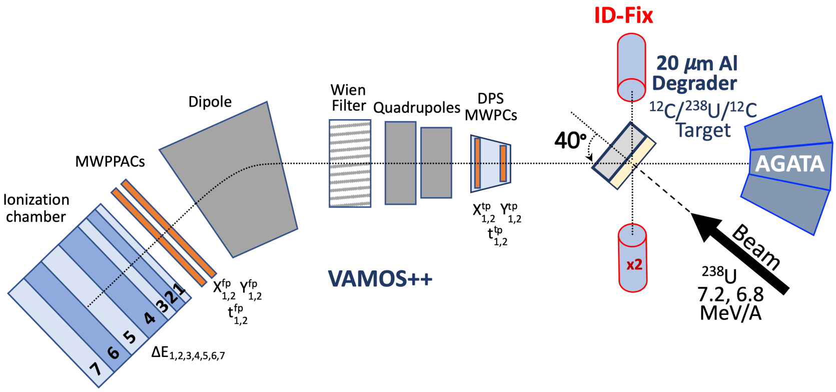

Fig. 1. Schematic layout of the experimental setup. The quantities measured with the VAMOS++ detectors are indicated. They include the positions ($X_{1,2}$ and $Y_{1,2}$) and the time signals ($t_{1,2}$) from the first and the second multi-wire detectors at the entrance (tp) and the focal plane (fp) of the spectrometer as well as the energy losses ($\Delta E_{1,2,3,4,5,6,7}$) in a segmented ionization chamber having 7 rows. The Wien filter was not used in this work.

3. Data analysis

The reaction products entering VAMOS++ are deflected in the horizontal direction according to their magnetic rigidities ($B\rho$). The $B\rho$ and the flight path length (L) are reconstructed based on the positions and the angles of the products measured using multi-wire detectors at the entrance and the focal plane of the spectrometer. These detectors also provide the TOF measurements. To achieve the mass resolution needed for the identification of the uranium-like products, a fine calibration of the detectors is needed. This is particularly important for the focal plane multi-wire detectors which had been newly installed before the experiment. The mass over charge state ratio (A/q) of the products is determined by the following relation

$$A/q \propto \frac{B\rho \times \mathrm{TOF}}{L} \,. \tag{1}$$

Figure 2 shows the A/q of the reaction products. Assuming that the most populated products are elastically scattered ^{238}U, one can determine the charge states ($238/(A/q)$) of the reaction products as shown in the insets of figure 2. Presently, the reconstruction of the masses of the uranium-like products is being pursued.

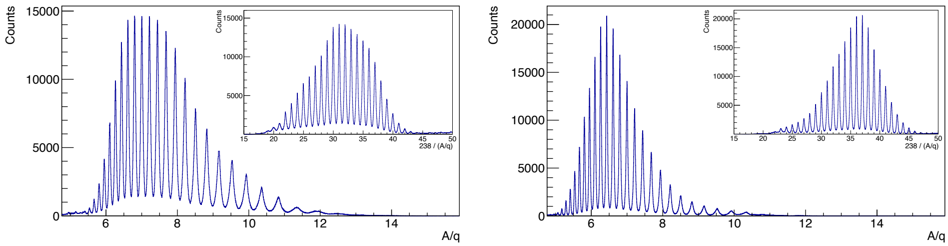

Fig. 2. The mass over charge state (A/q) of the reaction products for $E_{\mathrm{beam}} = 6.765$ MeV/A (left) and 7.193 MeV/A (right). The charge states ($238/(A/q)$) of the products are shown in the insets assuming that the most populated products are ^{238}U.

4. Decay of long-lived products after irradiation

The Al degrader served as a catcher foil at angles $\theta_{\mathrm{lab}} > 52.5°$ with respect to the beam axis for $E_{\mathrm{beam}} = 6.765$ MeV/A. To search for the decay of long-lived products stopped in the Al degrader, emitted γ-rays and X-rays were measured after the experiment using ID-Fix and AGATA. Figure 3 shows single and coincident spectra measured with ID-Fix, the

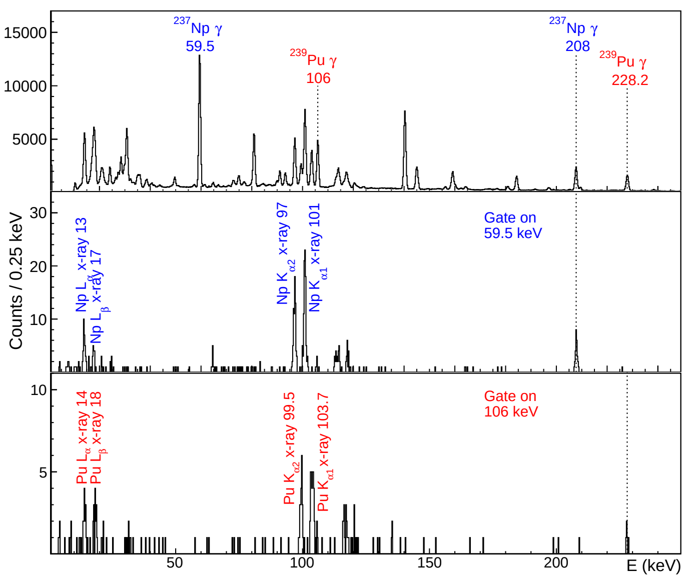

Fig. 3. X-rays and γ-rays, emitted from the reaction products implanted into the Al degrader, measured with ID-Fix. Top panel: Single spectrum. Spectra gated on the 59.5 keV γ-ray of ^{237}Np and 106 keV γ-ray of ^{239}Pu are shown in the middle and the bottom panel, respectively (see the text for details).

measurement with AGATA will be reported in [7]. ^{237}Np and ^{239}Pu were identified by gating on the associated γ-rays and observing the coincident K and L x-rays of neptunium and plutonium. They were produced via β decay of ^{237}U ($T_{1/2} = 6.75$ d) $\rightarrow$ ^{237}Np, and ^{239}U ($T_{1/2} = 23$ min) $\rightarrow$ ^{239}Np ($T_{1/2} = 2.35$ d) $\rightarrow$ ^{239}Pu confirming that the strongest ($\pm 1n$) transfer channels were populated in the experiment of the present work.

5. Summary

In this paper, the status of the VAMOS++ data analysis of the recently performed ^{238}U+^{238}U MNT measurement aiming at the production of exotic neutron-rich heavy nuclei is reported. The A/q distributions of the reaction products were obtained, the reconstruction of the masses is presently ongoing. The post-experiment γ–X-ray coincidence measurement of the reaction products implanted in the Al degrader confirmed that the strongest ($\pm 1n$) transfer channels were populated in the present experiment.

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