The past, present, and future of multinucleon transfer research using in-flight separator RITU

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Abstract. The correlation of target-like and projectile-like fragments can be an instrumental tool in investigating the multinucleon transfer mechanism. In laboratories with large angular acceptance separators, such methods are readily applied at significant angles away from the beam axis. With separators closer to 0°, at Coulomb barrier energies, it is a more challenging venture; In direct kinematics, the projectile-like fragments move with very shallow angles backward along the beam, and hence are hard to detect. In this report, recent advances of the simultaneous detection of both fragments with the in-flight gas-filled separator RITU will be discussed. Starting with how the germanium detector array JUROGAM can be used for the determination of the excitation energy of the multinucleon transfer products. In more recent years, JUROGAM has been used in tandem with a CD-type silicon detector in direct kinematics experiments to detect the projectile-like fragments that move backwards closely along the beam. With the results of these experiments, a new specialized Big Ultra-Large Long Enclosure for Transfer products (BULLET) target chamber will be introduced to more effectively research the multinucleon transfer process around 0° angles in the actinide region.

1 Introduction

To reach the extremes of the nuclear chart, several methods are employed. For neutron-deficient nuclei over the full range of the nuclear chart, fusion evaporation has been shown to be the best tool. Whereas, for the production of neutron-rich isotopes, projectile fragmentation and induced fission have been the most successful methods. However, these processes are not suitable for the production of heavier neutron-rich nuclei. Multinucleon transfer (MNT) has been proposed as a method for studying heavy neutron-rich nuclei. For example, it has been suggested to be applicable near the doubly magic ^{208}Pb region, where relatively few neutron-rich isotopes are known, as well as in the actinide region. The multinucleon transfer mechanism is still poorly described by theory; The models diverge rapidly as the number of transferred nucleons increases or the effects of excitation energy are not included [1, 2]. To gain a better understanding of the reaction mechanism, several laboratories have employed methods to detect both the target-like fragments and the projectile-like fragments simultaneously. With the correlations between the fragments, properties such as excitation energy can be determined. For example, at the VAMOS++ [3] and PRISMA [4] large angular-acceptance separators, which usually only detect the light fragment, secondary arms have been used to also measure the time of the passing heavy fragment, after which basic spectroscopy can be performed. These separators are positioned to guide the transfer fragments that have scattered at non-0° angles with respect to the beam. To investigate MNT properties closer to 0° a gas-filled separator such as the Recoil Ion Transport Unit (RITU) [5] at the university of Jyväskylä can be used. However, a complication with this approach is that, in direct kinematics, the projectile-like fragments will fly backwards closely along the beam; it is challenging to stop them on a detector without obstructing the beam. This is not an issue at the large angular acceptance separators when a secondary arm is used, as each fragment will fly at significant angles away from the beam axis. In this report, recent developments in the detection of projectile-like fragments at the 0° separator RITU will be discussed. First, the use of JUROGAM [6][7] in the correlation of both fragments will be reviewed, after which recent work on using a CD detector and new developments for future 0° studies will be presented.

2 The past analysis

In a previous experiment, the reactions ^{65}Cu + ^{209}Bi and ^{48}Ca + ^{209}Bi were studied at the Bass interaction barrier. The RITU setup was used, with JUROGAM I [6] at the target and a Double-sided Silicon Strip Detector (DSSD) + Germanium detector array at the focal plane of the separator. To study target- and projectile-like fragments simultaneously with energies around the Coulomb barrier, JUROGAM I was used to observe their prompt γ-ray de-excitation. Each fragment will have their own signature de-excitation energies, and the partners can be temporally correlated. As JUROGAM I is observing γ rays from a variety of angles around the target, a relativistic Doppler-

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correction should be applied to align spectra for a recoiling nucleus. Since the two fragments have different mean velocities and move in opposite directions, the Doppler shifts are different. This implies that target- and projectile-like fragments can be differentiated on the basis of which lines dominate in their respective Doppler-corrected spectra. Then γ-γ coincidences can be applied to correlate the partners if one γ-ray spectrum is corrected according to the target-like fragment and the other according to the projectile-like fragment. An example of this is shown in Figure 1 for the reaction ^{65}Cu + ^{209}Bi.

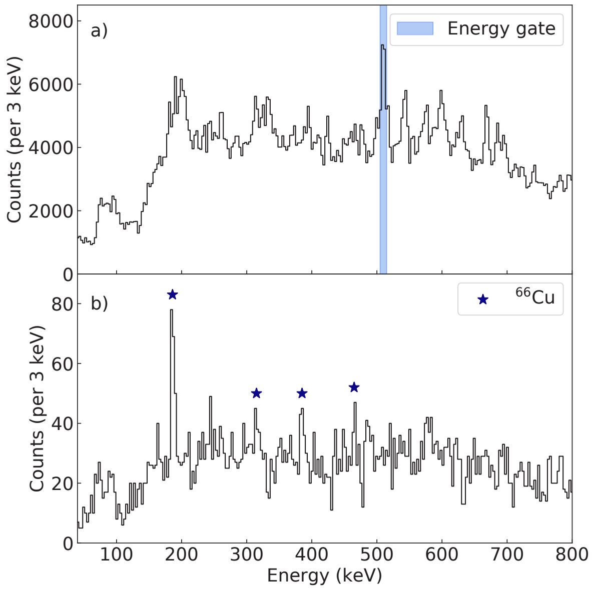

Figure 1. a) A γ-ray spectrum recorded by JUROGAM I, correlated with implantations at the focal plane DSSD, Doppler-corrected according to the velocity of the target-like fragment. A gate is placed on a line at 510 keV which belong to ^{208}Bi. b) A γ-ray spectrum showing the measured energies in coincidence with the gated area in *a)* corrected according to the projectile-like fragment. γ peaks can be observed from the partner of ^{208}Bi, namely ^{66}Cu.

In Figure 1a, a gated γ-ray spectrum is presented, Doppler corrected according to the target-like fragment energy, as measured by JUROGAM I. For γ-γ correlation, the gate is placed on the line at 510 keV, which belongs to the isotope ^{208}Bi. Its natural partner, barring neutron evaporation, is ^{66}Cu. In Figure 1b, the coincident spectrum corrected according to the projectile-like fragments is presented, showing that the partner ^{66}Cu is produced. Some background was removed from these spectra by requiring that the events be correlated with an implantation at the DSSD. To remove a more substantial amount of background, one can require that the events in JUROGAM I be correlated to an implantation that can then, in turn, be correlated to an α decay. An example of this is shown in Figure 2, for the isotope ^{213}Rn, in the reaction ^{65}Cu + ^{209}Bi. In this figure, the JUROGAM I γ-ray spectrum Doppler corrected according to the projectile-like fragment is shown. The natural partner of ^{213}Rn is ^{61}Fe. However, no ^{61}Fe is observed in the γ-ray spectrum. Instead, the isotopes ^{58}Fe, ^{59}Fe, and ^{60}Fe are observed. This is evidence of the evaporation of neutrons following the transfer process. It cannot be determined from these observations which fragment evaporates the neutrons. A typical assumption holds that the internal energy is spread evenly between the nucleons of each fragment, implying that the target-like fragment takes the most energy and hence is most likely to be the evaporator. Under such an assumption, the pre-evaporation excitation energy can be investigated.

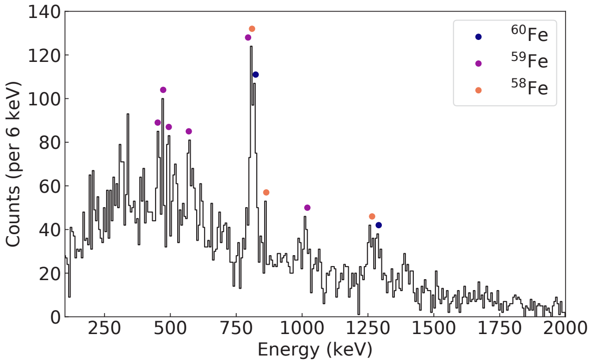

Figure 2. A γ-ray spectrum recorded by JUROGAM I Doppler-corrected according to the projectile-like fragments. The shown spectrum was correlated to ^{213}Rn α-decay events. The spectrum shows various isotopes of Fe. This points to neutron evaporation.

There are also downsides to using JUROGAM to investigate the MNT process. In addition to the usual background, spectra recorded by a germanium detector array will always be a combination of lines belonging to the target- and projectile-like fragments, this complicates the identification of γ lines. An example of such a γ-ray spectrum is Figure 1a. Furthermore, one cannot gain a precise understanding of the reaction kinematics on a per nucleus basis, even when fragments can be correlated. To reconstruct the kinematics, gas counters or implantation detectors are required to measure the time of the back-scattering projectile-like fragments and the forward-scattering target-like fragments. These options are being explored for RITU in recent years.

3 The present plan

As stated above, the problem with the detection of both fragments with a 0° separator like RITU is that the projectile-like fragments move anti-collinearly to the beam. This makes it difficult to detect the fragments without cutting part of the primary beam. To solve this problem, a CD detector was positioned upstream of the target. The detector is an annular double-sided silicon strip detector with a hole in the middle. The detector is segmented according to polar coordinates (r, θ), with 45 uniformly spaced rings (r) located at 12.96 mm to 35.05 mm from the center, and 16 uniformly spaced sectors (θ). The beam passes through the hole, and the projectile-like fragments land on the active area. In recent years, an experiment was carried out with the reactions ^{76}Ge + ^{209}Bi, ^{208}Pb, and ^{207}Pb. JUROGAM 3 [7] was positioned around the target and the CD detector to measure the prompt γ rays. This allows for background reduction in the spectra based on the coincidence information of the focal plane and/or the CD detector. A photo of the setup inside of the target chamber is shown in Figure 3.

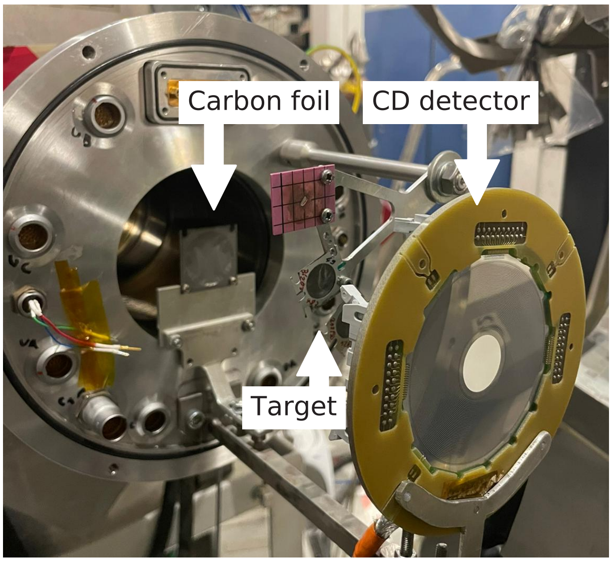

Figure 3. A photo of the setup inside the target chamber for the experiment using the CD detector. The beam would fly to the back of the image. Furthest downstream is a larger foil of carbon. The foil further upstream is the target of ^{209}Bi. Furtherest upstream the CD detector can be seen.

The angular acceptance of RITU is larger in the vertical direction (±85 mrad) than in the horizontal direction (±25 mrad), which results in a vertical signature on the CD when correlating with events at the DSSD. This can be seen in Figure 4, where the events at the CD detector, correlated with ^{211}Po α-decay events in the DSSD, have been shown. At the start of the experiment, the target was placed in the focal plane of RITU and JUROGAM, and the CD was located 6.5 cm upstream of the target. Here, the CD detector covers angles ranging between 152° and 169°. It became evident that most of the correlated events occur in the inner rings of the CD detector. This can be observed in Figure 4a. It was concluded that most of the transfer products had a too shallow angle and were flying back through the opening in the CD detector. The fraction of detected events at the CD detector compared to the number of detected α-decay events constitutes $\sim$ 30%. To solve this problem, the target was moved as far away from the CD detector as possible, which is the location of the carbon foil in Figure 3, at 17.5 cm from the CD detector. Here, the CD detector covers angles ranging between 168° and 176°. The effect on the pattern on the CD detector can be seen in Figure 4b. The increased distance causes the projectile-like fragments to travel further away from the beam axis, resulting in a more spread-out pattern. The detected fraction compared to detected α decays increased to $\sim$ 45%. This shows the importance of covering angles close to 180°.

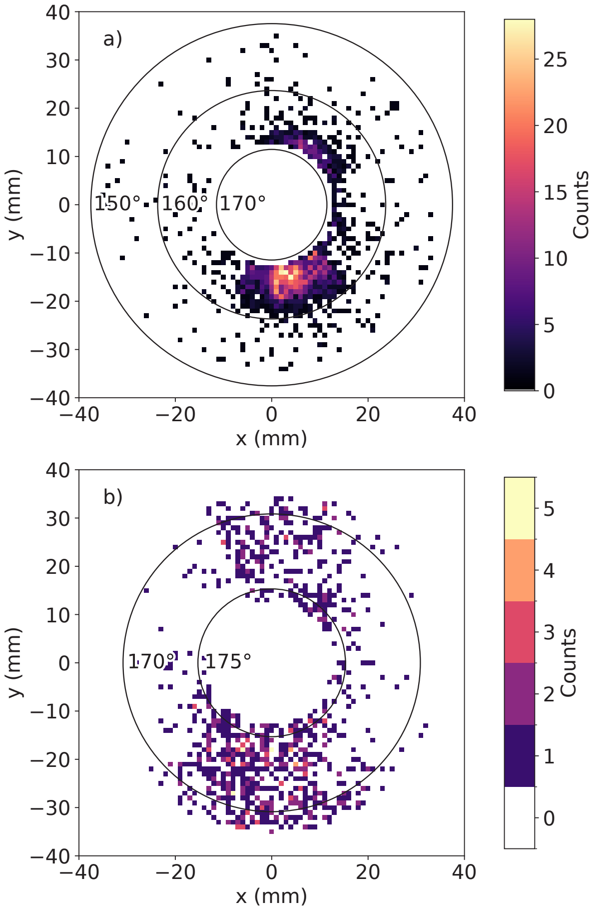

Figure 4. a) Detected events at the CD detector correlated to ^{211}Po α-decay events at the DSSD. The target was placed at a) 6.5 cm and b) 17.5 cm downstream of the CD detector. The circles represent angles with respect to the target.

4 The future experiment

During the experiments conducted in the past years, preliminary analyses have shown promising results. However, certain improvements have also become evident, which will improve future MNT experiments, especially in the actinide region. Firstly, in the experiment with the CD detector described above, it was shown that it is possible to detect projectile-like fragments. However, it was established that with the target in the conventional position, the CD is too close to the target to efficiently correlate the MNT events. In addition, in an earlier MNT experiment with an actinide target, isotopes were identified by their isomers. However, the use of in-beam detectors close to the target in that experiment limited the beam current because of the high count rates. This limits the production of more exotic MNT products.

As such, a new experiment was proposed and accepted with the goal of expanding on those results. It aims to measure and compare the MNT and quasi-fission products synthesized with 4 different beams, ^{36,40}Ar and ^{78,86}Kr, on a target of ^{238}U. A hand full of improvements are expected to be realized by using the Big Ultra-Large Long Enclosure for Transfer products (BULLET) target chamber. The

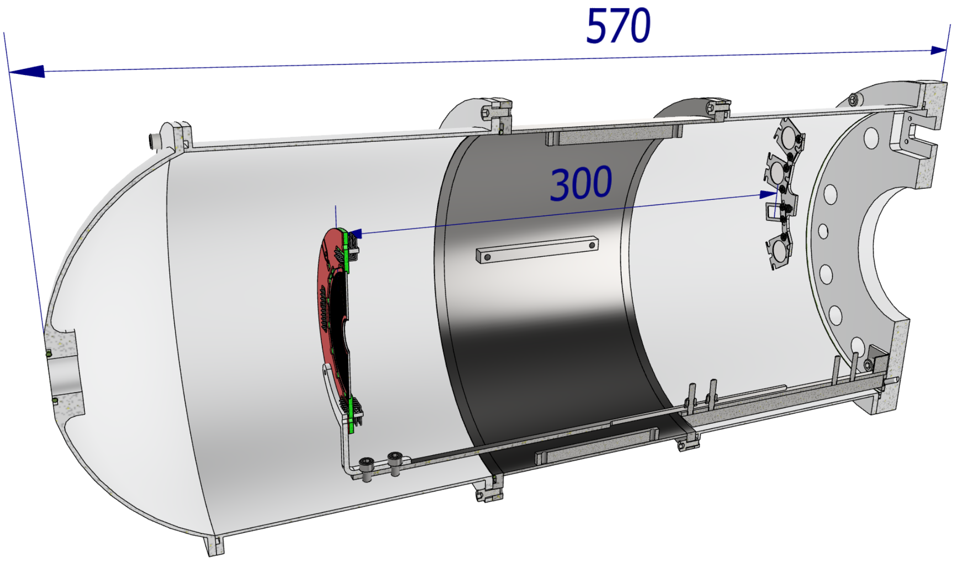

Figure 5. A schematic of the Big Ultra-Large Long Enclosure for Transfer products (BULLET). The beam comes from the left. It first passes through the hole in the CD detector. It then hits the target further downstream. The measurements in the figure are given in millimeters.

target chamber is roughly three times the length of the target chamber used in the first experiment using the CD detector and increases the distance between the target and the CD detector from 17.5 cm to a variable distance between 25 cm and 35 cm. The sketch of the setup is shown in Figure 5. It allows for an angular coverage at 30 cm between 173° and 178°.

The increase in the distance between the target and the CD detector has two consequences. The detection of projectile-like fragments closer to 180° will be possible. However, it may also result in a decrease in the geometric efficiency. The variable distance of 25 cm - 35 cm was chosen as it aligns best with the angular acceptance of RITU whilst also covering angles close to 180° for these reactions. The option of placing a second CD detector at $\sim$ 9 cm from the target remains open as well. Furthermore, in the proposed experiment, JUROGAM 3 will not be used around the target, as it would limit the beam current. Instead, JUROGAM 3 can be moved along the beam axis, which allows it to be placed around the CD detector. With it, delayed γ-ray energies can be measured of isotopes implanted in the CD detector. Most importantly, this refers to γ rays from isomeric states and β decay. Furthermore, JUROGAM 3 will also be complemented by $LaBr_3$ scintillators, provided by the Complutense University of Madrid, for lifetime measurements. This allows for the identification of the projectile-like fragment. Furthermore, the increased distance helps, as the angular coverage with respect to the prompt γ rays will be small, and hence the spectra will have less background. Additionally, the angle at which the events are detected in the CD detector and the time difference between the gas counter prior to the DSSD and the CD detector can be used to determine the kinetic energy loss and excitation energy around 0° with $\sim$ 3 MeV precision. Lastly, the four different beams can be used to compare and investigate the quasi-fission probability at $\sim$ 0°.

5 Conclusion

Multinucleon transfer reactions at the University of Jyväskylä has been and continues to be a topic of interest. The accelerator laboratory has the facilities not only to investigate the reaction mechanism at 0°, but also to detect and correlate both reaction fragments. In the past and now, γ-ray arrays, such as JUROGAM 3, have been used to identify projectile- and target-like fragments in the MNT reactions. Now, after observing the relevant information collected by the CD detectors in these MNT reactions at 0°, a new solution has been explored. The solution is the BULLET chamber, which is currently under construction. This chamber will be used in our next experiment that aims to investigate the production of MNT fragments around ^{238}U with four different beams.

Aknowledgements

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