Studying short-lived α-decaying multinucleon transfer reaction products with the active catcher array

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There has long been interest in studying the multinucleon transfer (MNT) reaction mechanism at the Cyclotron Institute at Texas A&M University. The active catcher array was developed for the purpose of identifying short-lived α-decaying MNT products. In 2018, the results of an experiment which surveyed the production of α-decaying heavy elements created in the ^{238}U + ^{232}Th reactions at 7.5-6.1 A MeV were published (Ref. 1). The results suggested that heavy and super heavy elements were produced with higher cross sections than had been predicted, though individual product nuclides could not be identified because of limited position and energy resolution. With these encouraging results, subsequent experiments have been performed with lower background and improvements to the detectors that provide higher position granularity and better energy resolution.

One major source of background mentioned in [1] came from α particles emitted by the ternary fissions of products with long-lived isomeric states. The half-lives of these states are similar to the half-lives of the products of interest, as are their α-emission energies. Thus, the approach shifted to looking for α-decaying products with Z and N ranging $84 \leq Z \leq 92$ and $126 \leq N \leq 136$, where fissioning isomeric states are not expected. These products include various isotopes of elements ranging from Po to U. In this mass region, many products decay to stable or longer-lived nuclei by chains of sequential α emission.

In fact, this mass region was highlighted in the work of Zagrebaev & Greiner (2013) as a good candidate for experimental investigation of MNT reactions because of the decay properties of the nuclei (Ref. 2). Zagrebaev & Greiner chose to highlight the reaction ^{192}Os+^{197}Au and predicted production cross sections for elements from At to U. Multiple isotopes of each element with Z up to Ac have predicted cross sections larger than 1 μb (see Fig. 1). This system, and systems like it, have been of interest to our group for the past few years.

During the years 2017-2019, Wakhle *et al.* conducted three experiments investigating short-lived α-decaying products of reactions in the systems ^{22}Ne+^{232}Th, ^{197}Au+^{208}Pb, and ^{208}Pb+^{208}Pb (Refs. 3 & 4). Analysis of these data increased understanding of the Struck Instrument Systems 3316 ADCs. As a result of this, this experiment was designed to have zero dead time, so that no events would be missed. This is critical because capturing all of those events enables identification of the products of interest with higher confidence.

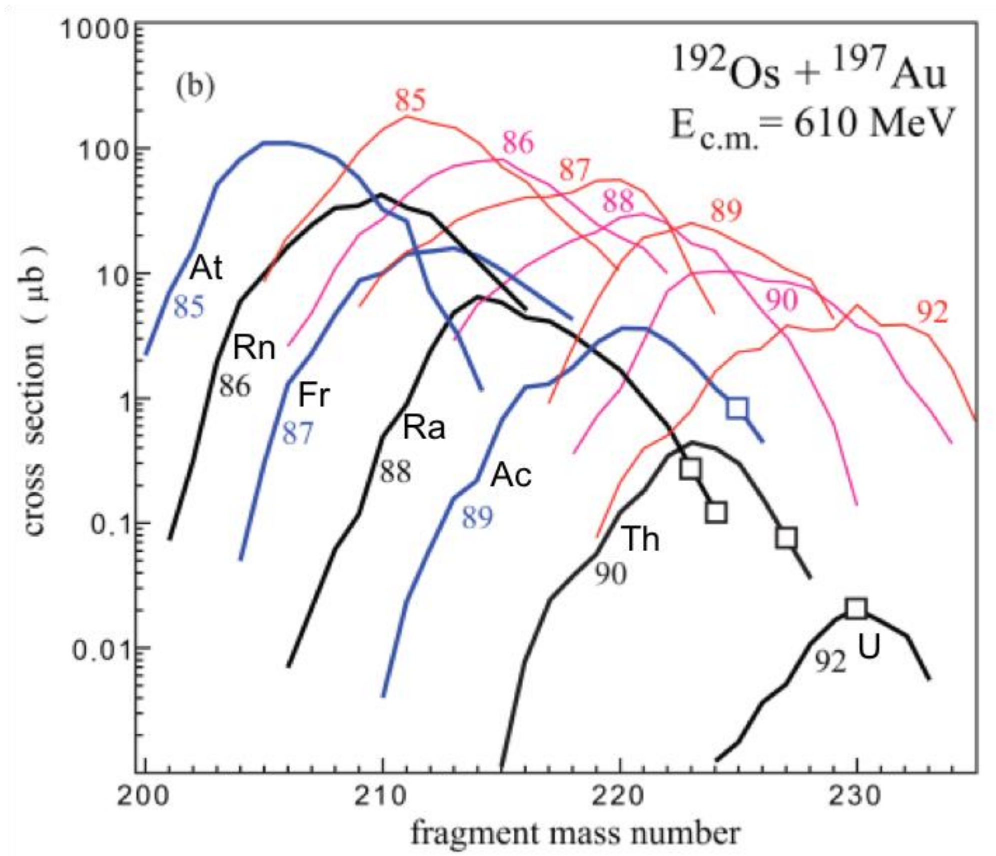

Fig. 1. Predicted cross sections for α-decaying products of multinucleon transfer reactions from ^{192}Os+^{197}Au. The red and pink thin lines show the initial cross sections for the excited products. The blue and black thick lines show the final predicted cross sections for the surviving deexcited nuclei. The boxes are highlighting nuclides that are good candidates for studying via radiochemical separation because they are long-lived. This plot is reproduced from Zagrebaev & Greiner [2].

In the reconstruction of chains of α decays, one must consider the probability that these arise from randomly correlated unrelated events. The number of possible random correlations is smaller when looking in a shorter time span, a smaller energy window, and a smaller spatial area. Analysis of the data from 2017-2018 therefore focused on identifying the shortest-lived reaction products expected based on the predictions for similar systems by Zagrebaev & Greiner. The data show that these nuclei were present, though the SIS 3316 digitizers were not optimized for their detection. This led to a new experiment aimed at producing and detecting these nuclei.

Inspired by the work of Zagrebaev & Greiner, production of an Os beam at the Cyclotron Institute was tested. We measured the beam intensity upstream of the MDM spectrometer with an electron-suppressed Faraday cup and determined that we were receiving 10^9 pps. However, during the test, the Os seemed to cause problems with the ion source. In order to measure a system very close in mass to ^{192}Os + ^{197}Au, ^{197}Au +^{197}Au was used instead. This system is expected to have the same products of interest, produced in slightly higher quantities.

This experiment was optimized for the production and detection of the three isotones: ^{220}Rn, ^{221}Ac, and ^{222}Th. These three nuclei were targeted because of the interesting properties of their decay chains. Each isotone decays via three quick and high-energy alpha emissions, ending in a very long-lived or stable nuclide. Fig. 2 shows the decay chain of ^{220}Rn, highlighting the half-lives and the α Q-values for

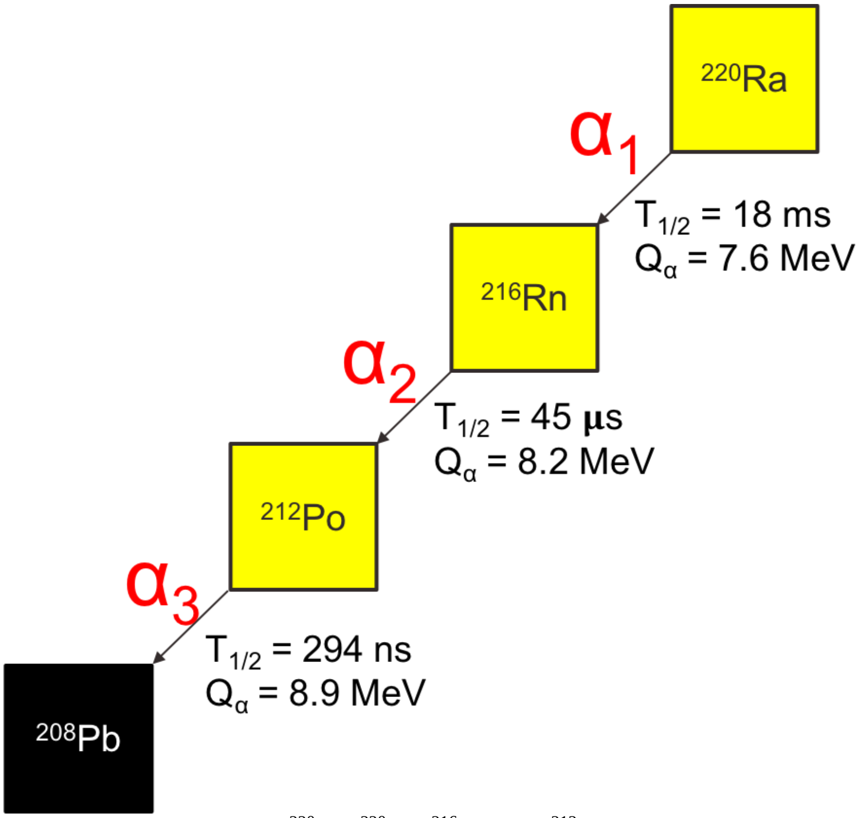

Fig. 2. Decay scheme for ^{220}Ra. ^{220}Ra, ^{216}Rn, and ^{212}Po decay by alpha emission with the shown half-lives and alpha emission energies. The decay chain ends at the stable ^{208}Pb nucleus.

each of the three decays. The first alpha decay in these chains is likely to be captured alone in a waveform. Then, when the second alpha decay triggers the acquisition, the third alpha decay is also seen in the same waveform. This is expected because the half-life of the granddaughter is very short (~ 300ns) and the SIS 3316 ADCs are set to capture a 2,000ns waveform. An example waveform with two high energy α particles is shown in Fig. 3. This waveform was collected in April 2021 and is a candidate for the decays of ^{216}Rn and ^{212}Po, resulting from the decay of ^{220}Ra. When looking only at high-energy alpha decay events occurring so closely in time, the chance that they are randomly correlated events is extremely small, given the amount of high-energy α particles seen in the Wakhle *et al.* data. The third decays in the chains of ^{221}Ac and ^{222}Th are similarly short-lived and we expect to see similar double α particles in a single waveform for them. By targeting these nuclei, their unique decay properties may allow us to make a positive identification of these product isotones, though the energy resolution will not be sufficient for elemental distinction.

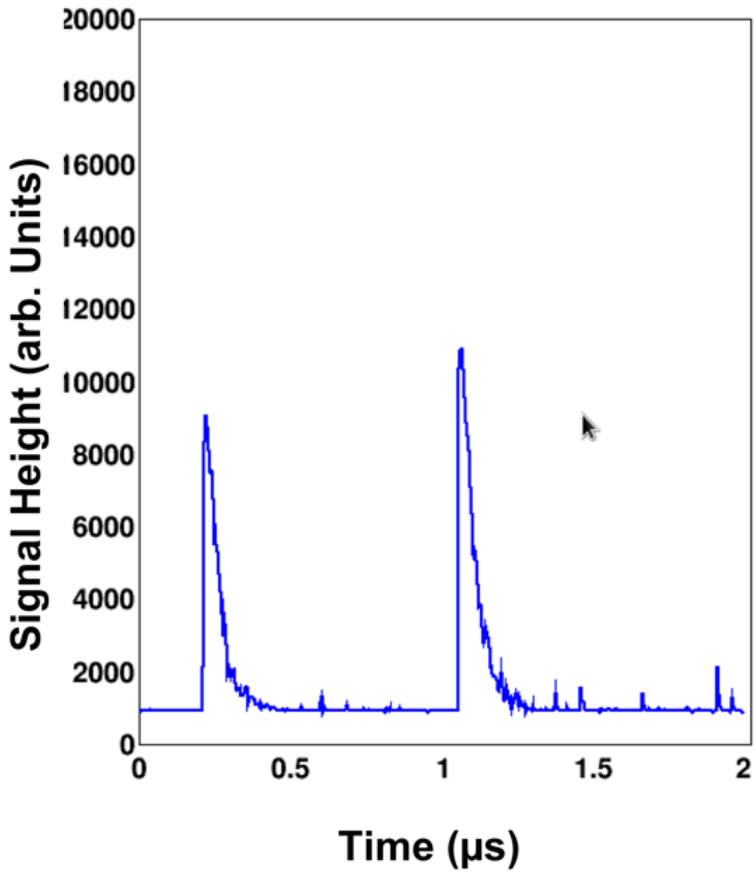

Fig. 3. A digitized waveform from the ^{197}Au+^{197}Au multinucleon transfer experiment conducted in April 2021. It has a 2 μs inspection window showing double alpha decays. The relative signal heights show that this is a candidate for the decays of ^{216}Rn and ^{212}Po occurring closely in time.

To further cut down on random correlations, part of the detector setup was improved to have better position resolution. A Hamamatsu H8500C position-sensitive photomultiplier tube (PSPMT) was borrowed from Robert Grzywacz from the University of Tennessee at Knoxville. The detector was cemented to an ISO100 flange, coupled with a quartz light guide segmented into 2mm x 2mm sections and a 500micron thick YAP scintillator. In past experiments, the active catcher array has used single-anode PMTs with cylindrical YAP scintillators that have a diameter of about 2cm. The identification of position was thus limited to that area, as one cannot distinguish multiple sources from a single source in a 2cm area. The PSPMT gives a position resolution of about 2mm, which is dictated by the light guide segment size.

Fig. 4a) shows the active catcher array inside the BBQ pit, as it was for the ^{197}Au+^{197}Au experiment in April 2021. Fourteen of the single-anode YAP-PMT detectors were removed to make space for the PSPMT and its flange to be attached to the array mount. Fig. 4b) shows a close up of the PSPMT detector without the mylar foil attached to it. The segments of the light guide can be seen through the clear YAP scintillator cemented to the front of it.

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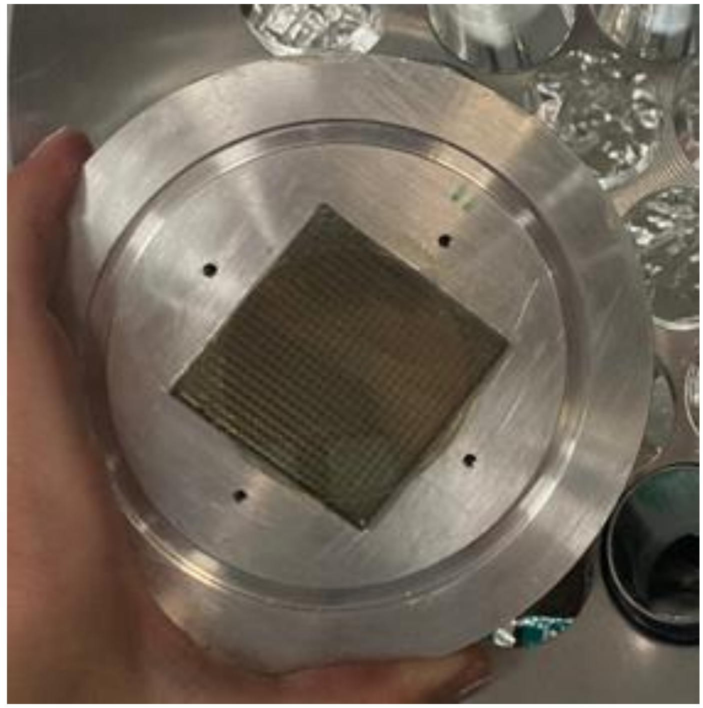
b) 

Fig. 4. a) The active catcher array as it was set up for the ^{197}Au+^{197}Au experiment in April 2021. b) The ISO100 flange that has a Hamamatsu H8500C position-sensitive photomultiplier tube cemented to it. A segmented quartz light guide and YAP scintillator are cemented to the front of the detector. The 2mm x 2mm segments of the light guide are visible in the image.

This year we also looked into upgrading the active catcher array with an array of diamond detectors. Unfortunately, our tests showed that they do not perform well after being bombarded with the products from our reactions of interest.

During the experiment, while monitoring the data as they were being collected, multiple candidate signals for the double-α single-waveform events, like the one shown in Fig. 3, were observed. To identify those interesting decay chains, the steps that need to be accomplished include:

1. Condition the data for analysis, including energy and position calibration. For overlapping signals in a digitized waveform, the signals need to be fitted and broken into their component contributions.
2. Correlate the daughter and granddaughter decays that are in a single waveform with the decay of the parent nucleus.

3. Identify a single chain of decays in the PSPMT, which will require the development of a clustering algorithm. This will look in a small area for multiple decays because there may be signal sharing of multiple pixels due to isotropic decays.

[1] S. Wuenschel *et al.*, Phys. Rev. C **97**, 064602 (2018).

[2] V.I. Zagrebaev and W. Greiner, Phys. Rev. C **87**, 034608 (2013).

[3] A. Wakhle *et al.*, *progress in Research*, Cyclotron Institute, Texas A&M University (2017-2018), p. IV-30.

[4] A. Wakhle *et al.*, *progress in Research*, Cyclotron Institute, Texas A&M University (2018-2019), p. II-15.