Test runs the multi-nucleon transfer reaction detector array for synthesis of heavy elements

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An 'Active Catcher' array was constructed in 2016 [1] to study multi-nucleon transfer reactions forming heavy elements. The array consists of 40 YAP scintillators coupled to Hamamatsu PMTs via Lucite light guides at forward angles, and 8 IC-Si detectors at backward angles. A schematic is shown in Fig. 1. In August 2016, experimental data were taken using this array: a beam of ^{238}U at 7.5 MeV/nucleon was incident on a ^{232}Th target. Digital signal processing was achieved using the Struck SIS3316 250MHz Flash ADC modules, and the results of this experiment have been published [2]. This first 'physics' measurement has shown tantalizing glimpses into the synthesis of elements with Z as high as 116 via correlated pair searches and measurements of alpha energies as high as 12MeV. Clear identification of alpha chains was not possible due to the difficulty of analysis and the relatively uncharted and violent reaction landscape of ^{238}U+^{232}Th.

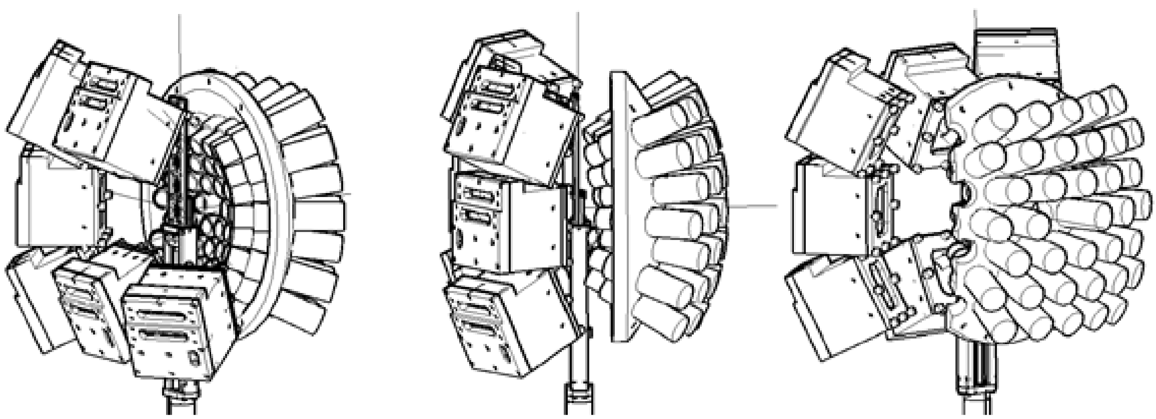

FIG. 1. Schematic of IC-Si and YAP detector array. In the central panel the beam enters from the left.

We have since conducted three experiments to benchmark the AC, progressing towards the grand goal of identifying alpha chains, and establishing parent-daughter relationships. Details of the measurements follow:

1. ^{22}Ne + ^{232}Th

A ^{232}Th target was bombarded with a ^{22}Ne beam at 143 MeV (6.5 MeV/A) to measure the production cross sections of ^{227}Th, ^{226}Ac, ^{225}Ac and ^{224}Ac. These nuclides are long-lived and were implanted in the forward angle YAP+PMT Active Catcher, to determine their activities and cross sections by offline alpha counting in the backward angle Si+IC array. Preliminary cross sections match the measurement of Kumpf and Donets [3], and a more detailed analysis is underway by Zach Tobin.

2. ^{197}Au + ^{208}Pb

This was a stepping stone to the ^{208}Pb+^{208}Pb reaction in the third run. A ^{208}Pb target was bombarded with a ^{197}Au beam at 7 MeV/A to measure the production cross sections of nuclei with 82<Z<92 and 208<A<228. These nuclides decay primarily by alpha emission with alpha energies between 7MeV and 10MeV, and half-lives ranging from ~1s down to a few 100ns.

The beam was pulsed ON for 30ms to build up activity in the nuclides of interest, and the pulsed OFF for 30ms to observe their decay in a low background (beamless) environment. Alpha lines corresponding to decays in the 7MeV to 10MeV range, and mean lives of a few ms were observed. However, we were unable to identify alpha chains and establish parent-daughter relationships due to software of the digital data acquisition system.

3. ^{208}Pb + ^{208}Pb

A ^{208}Pb target was bombarded with a ^{208}Pb beam at 7 MeV/A to measure the production cross sections of nuclei with 82<Z<92 and 208<A<228. Additionally the acquisition system was modified to allow continuous acquisition (i.e. no dead time between detector pulses). This modification fully exploits the capabilities of the SIS3316 250MHz Flash ADC modules. Analysis from this experiment is currently underway.

To complement to experimental work on the AC, a systematic series of TDHF calculations were performed for the ^{238}U+^{232}Th reaction (Fig. 2). Multi-nucleon transfer products were observed in the exit

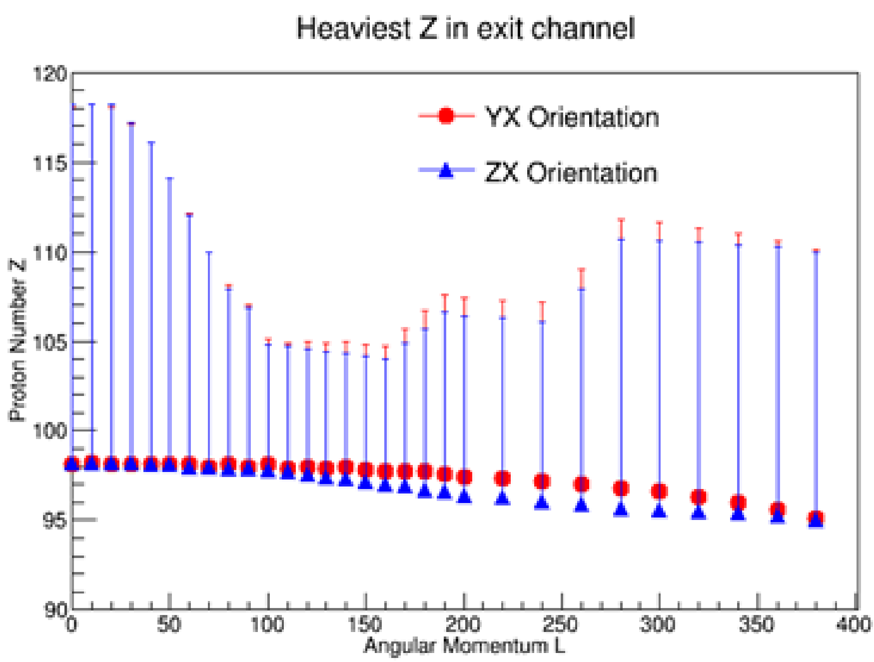

FIG. 2. Results from TDHF calculations of ^{238}U+232Th at 7.5AMeV. Exit channel proton number vs. entrance channel angular momentum. The points correspond to the TDHF prediction for proton number of the larger of two fragments in the exit channel. The bars correspond to mass widths as predicted by TDRPA (calculations by K. Sekizawa). Limits correspond to approximately 0.1microbarn cross section. Results are shown for two orientations of the entrance channel nuclei. Other cases lead to less exotic products.

channel, and TDHF suggests that elements with Z>100 can be produced in this reaction. TDRPA calculations, performed by our collaborator K. Sekizawa, suggest that the Z distribution of these fragments extends up to Z=118 with a cross section of 0.1 microbarns.

We have purchased two sCVD diamond detectors from Cividec, and Micron, and two preamplifiers on loan from each company. These will be tested with an alpha source, and protons from the K-150 to benchmark sCVD diamonds as a potential forward angle implantation detector.

[1] S. Wuenschel *et al.*, *Progress in Research*, Cyclotron Institute, Texas A&M University (2015-2016), p. II-21.

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

[3] H. Kumpf and E.D. Donets, Soviet Phys. Jetp, **17**, 3 (1963).