Studying multinucleon transfer on the $^{197}Au + ^{197}Au$ reaction

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Studying multinucleon transfer (MNT) at the Cyclotron Institute at Texas A&M University began around 2002. Its main goal from the start was to look for new superheavy elements(SHE) with the use of the MNT as an alternative method for their production. Since that day detector setup evolved several times, from BigSol, Passive Catcher, Active Catcher based on BC-418 to the Active Catcher based on YAPs [1,2,3]. In one of the last experiments [3] from 2016 where the $^{197}Au + ^{232}Th$ (7.5AMeV) were tested, several alpha-decay chains with high energies were found. It showed that superheavy elements can be created via MNT. Due to insufficient energy resolution of the used AC detectors and insufficient position information individual nuclides produced during experiments couldn't be identified.

In 2021 A. Hood projected an experiment with the use of the AC array and position-sensitive detector to study more carefully the process of the MNT and to confirm its usability in creating heavy nuclei [4]. The decision of using a position-sensitive detector was made to ensure greater granularity as well as better energy resolution.

Both types of modules, 30 single-anode PMT detectors and dynode + 4 anodes of the Position-Sensitive PMT (PSPMT), were connected to the SIS3316 digitizer. Each channel could trigger individually based on passing its threshold. Beam used during the experiment was 8.63 MeV/A $^{197}Au^{+31}$ in mode 100ms/100ms beam on/beam off. Data acquisition wasn't taken while the beam was in on mode and for the first 3 ms of the beam off-time - acquisition was turned off for 103 ms and on for 97 ms.

The tested reaction was $^{197}Au + ^{197}Au$. The experiment was optimized for the production and detection of isotopes like ^{220}Rn, ^{221}Ac, and ^{222}Th. Nuclides in alpha-chains which began with these isotopes are decaying via emission of the high energetic alpha particles (7-9 MeV) and have short lifetimes (on the level of ns-ms). Short lifetime is a desirable characteristic while SIS3316 ADCs allowed recording only 2 us of detected waveforms and while the experiment was focused on searching for (at least) two alpha particles that originated from the above-mentioned chains, presented in Fig. 1.

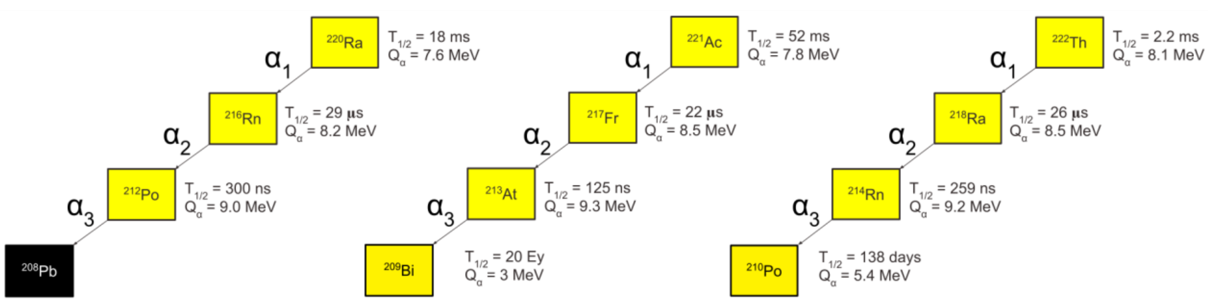

Fig. 1. Scheme of alpha decay chains for ^{220}Ra, ^{221}Ac, and ^{222}Th. Each of the chains ends with a stable (^{208}Pb) or long-lived (^{209}Bi, ^{210}Po) isotope.

Most promising results are collected by a position-sensitive detector borrowed from Robert Grzywacz from the University of Tennessee at Knoxville. This detector contains 64 segmented Hamamatsu H8500C position-sensitive photomultiplier tube, attached to the ISO100 flange, with a quartz light guide divided into 2 mm x 2 mm sections with 500micron YAP scintillator on it. This detector ensures better position resolution (dictated by the size of the light guide) than used until this time single anode YAP detectors with 2 cm diameter.

In the currently conducted data analysis were found several cases correspond to the registration of two alpha particles (two pulses) in one time window. An example of such an event is presented in Fig. 2. This figure contains a set of five waveforms registered from four anodes (returning energy information) and a signal waveform from one dynode (responsible for returning time information).

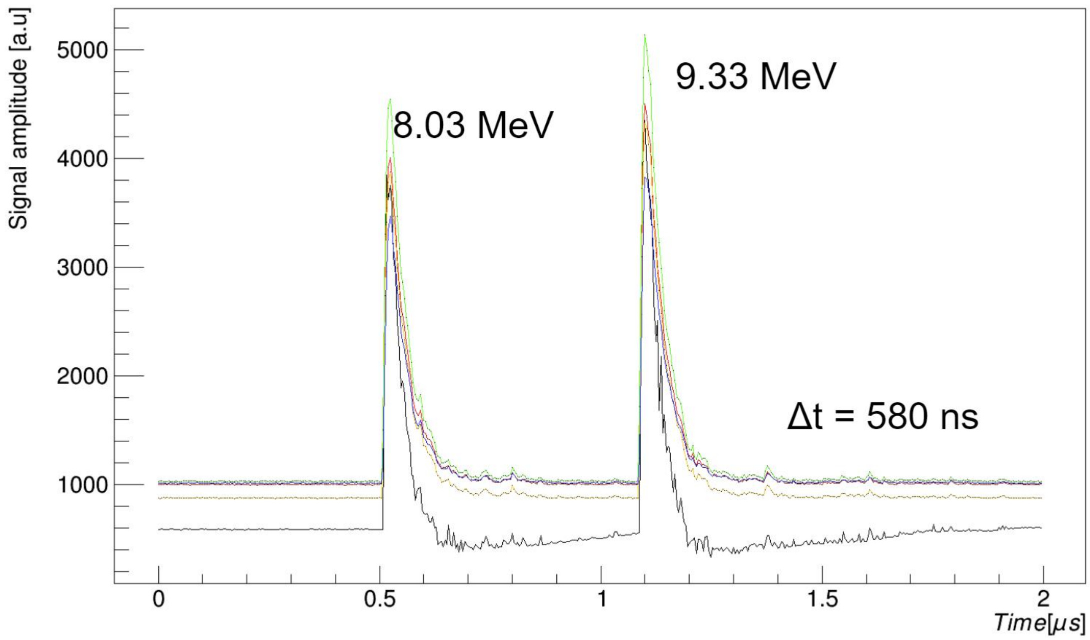

Fig. 2. The waveforms of the interesting event recorded during the experiment and detected in a position-sensitive detector. The waveforms recorded from the dynode are black, while the rest of the 4 colored signals are originating from 4 anodes of the PSPMT detector.

Energy calibration of such pulses and determination of their position is possible by using Anger logic. Knowing the energy value registered by four anodes (Q_{xa}, Q_{xb}, Q_{ya}, Q_{yb}) it is possible to calculate the position of the registered pulse in one of the pixels (1). The PSPMT detector is built out of 24 x 24 pixels, from which, due to poor statistics on the edges and corners, only 22 x 22 pixels can be considered in further data analysis.

$$X= Q_{xa}-Q_{xb} / Q_{xa} +Q_{xb} \quad , \quad Y= Q_{ya}-Q_{yb} / Q_{ya} +Q_{yb} \qquad (1)$$

Due to some imperfections of PSPMT, YAP, and light guide, it is necessary to conduct gain matching energy calibration for each pixel separately. For this purpose, the 2-dimensional distribution of the pixel's position was changed into 1-dimensional with the same algorithm (2) as Xiao et al. presented in their work [5].

$$N_{pixel} = Row \times 24 + Column \qquad (2)$$

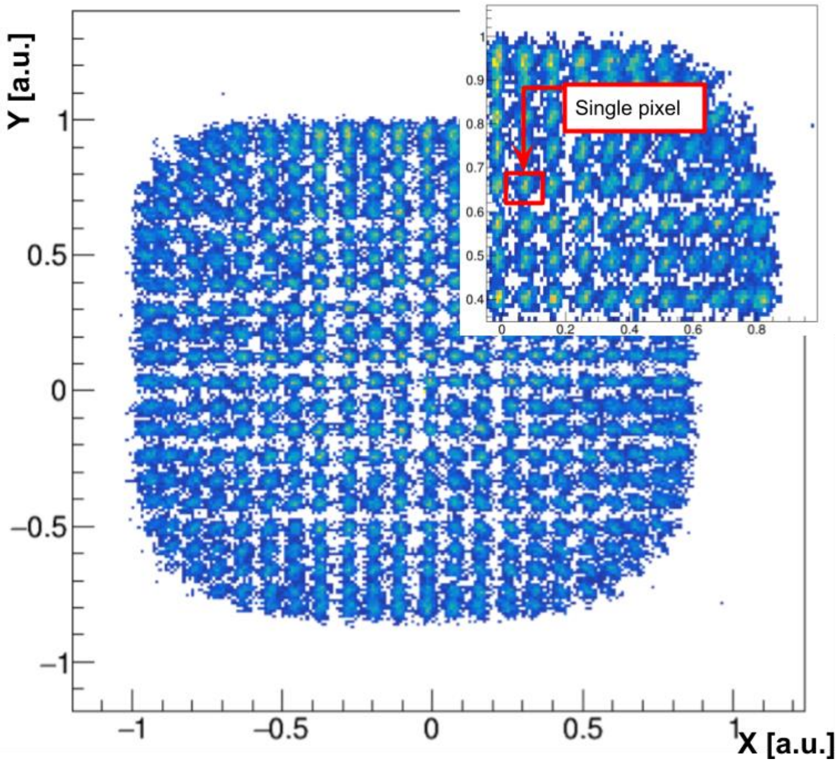

Fig. 3. Position distribution of signals reproduced by Anger logic plotted in arbitrary dimension unit. In the right-up corner, on the zoomed fragment of the distribution, by red rectangular is marked single pixel. Figure made for ^{228}Th source.

This step allowed not only control of the quality of the used calibration method but also made it possible to group pixels with similar amplitude amplification. This enabled the collection of better

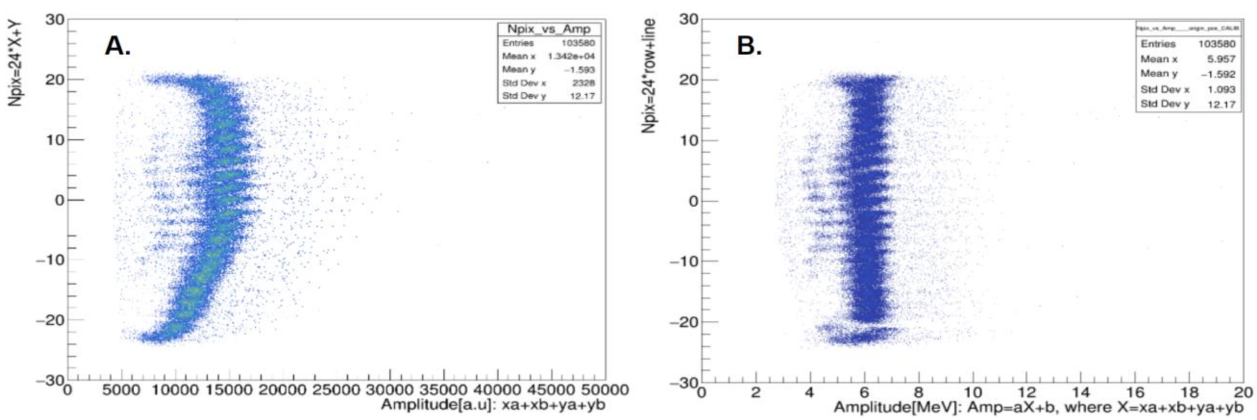

Fig. 4. 1-dimensional distribution of the pixel's position before (A) and after (B) energy calibration.

statistics for energy calibration and also made it easy to calibrate all pixels with the standard linear regression method. For this purpose run with ^{228}Th source was used. The result of using this calibration method is presented in the 1-dimensional distribution of the pixels, in Fig 4.

Position and energy calibration allowed us to look for double alpha peaks in one time window with the condition that the second peak will be located in the same or adjacent pixels. In the situation where we are considered only the first layer of adjacent pixels, there were found 24 events with double pulses (Table I), where two of them (marked with orange color) are fulfilling conditions of the high energy alphas from one of the alpha decay chains presented in Fig. 1. Note, one of the registered events is also presented in Fig 2.

Table I. Energies of double pulses registered by the position-sensitive detector, with condition that both pulses were detected in the same or adjacent pixels.

Amplitude of registered particle [MeV]				
1st peak	**2ed peak**		**1st peak**	**2ed peak**
7.50686	4.10122		6.08946	8.41894
8.38808	**9.58383**		5.63571	6.23469
8.03168	**9.33001**		5.08403	5.8017
3.17162	4.81703		3.29297	3.09121
3.39697	8.99234		7.24412	3.79912
3.1063	8.83049		7.43248	6.01956
3.15005	12.4871		3.06675	2.99565
9.93843	3.87343		7.50019	3.3672
6.04716	3.15369		3.15085	3.56148
4.89464	12.4349		3.36784	8.9571
3.08115	3.23072		4.39458	3.24214
4.39458	3.24214		6.08946	8.41894

These results are encouraging to continue the analysis of collected data and to enlarge the distance of studying double peaks in another layer of pixels. It will be also worth comparing the results from PSPMT with those from single-anode YAPs. The main tools for analyzing those data, which are pulse shape discrimination methods based on slow & fast components of the recorded puls, and moments methods, like mean value, variance, skewness, and kurtosis, are already prepared and are currently in use. Results of such comparison will help decide if replacing active catcher's modules with PSPMTs will be useful for MNT-SHE experiments in the future.

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[5] Y. Xiao *et al.*, Phys. Rev. C 100, 034315 (2019).