The ParTI array for studying pionic fusion

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Pionic fusion is the process by which two nuclei fuse during a collision and then deexcite by the exclusive emission of a pion. The resulting compound nucleus is left in or near its ground state [1]. The process requires that nearly all of the available kinetic and potential energy in the colliding system be concentrated into two degrees of freedom - the rest mass and kinetic energy of the emitted pion. Thus, the energy of the emitted pion is limited by the number of available final states of the fusion residue [2]. The combination of limited available energy and the extreme coherence required in the process ensures that the pionic fusion channel is greatly suppressed. Indeed, the measured pionic fusion cross sections range from hundreds of nanobarns for the lightest systems (He + He) to hundreds of picobarns as one moves to larger systems (A_{tot} = 6 - 24) [2-12].

During this past year we have continued progress towards measuring pionic fusion cross sections using the Momentum Achromat Recoil Spectrometer (MARS) [13]. In May of 2014 we conducted an experiment in MARS to measure the transmission efficiency of our pionic fusion residues of interest through the spectrometer. In August of that year, prototype phoswich detectors were tested in beam as a proof of concept for fast vs. slow light charged particle identification and digitizer waveform readout. Following the results of the August experiment, the design for the Partial Truncated Icosahedron (ParTI) phoswich array was finalized and the array was constructed in the winter of 2014. The phoswich detectors will be used to detect the charged pions resulting from pionic fusion reactions. They have been built and are currently in the process of being tested. The GANDALF digitizer module [14] will be used to identify the charged particle events and is currently in the process of being ported into CycApps for use in our standard ROOT environment.

From the MARS transmission efficiency test experiment we were able to determine the optimum MARS settings for the residues of interest and we achieved a transport efficiency of approximately 61%. A beam of ^{16}O was produced by the K500 cyclotron at the Cyclotron Institute at the predicted energy of the pionic fusion recoils, stripped of electrons using a mylar foil and transported through MARS. Faraday cups were used to measure the beam intensity before and after the spectrometer. The ratio of the intensity measured at the back of MARS to the intensity measured before MARS is the transport efficiency. A semi-empirical formula [15] was used to predict equilibrium charge state distributions of the ^{16}O beam leaving the mylar foil. We produced ^{16}N in the ^{15}N(d,p)^{16}N reaction to determine optimum MARS settings for these residues as well.

During the test experiment in August we tested prototype phoswich detectors of two types: fast plastic/slow plastic (EJ-212 and EJ-240, respectively purchased from Eljen Technologies) and fast plastic/CsI(Tl) where the fast plastic in both cases produces a dE, short emission time component to the produced signal and the slow plastic and CsI(Tl) produce long emission time components proportional to the total energy. Fast vs. slow pulse shape analysis was performed on the signals produced by both types of phoswich and it was decided that the CsI(Tl) type detectors will be the design moving forward as particle identification was never achieved with the plastic/plastic units. Fig. 1 is an example of the fast vs. slow pulse shape discrimination for a fast plastic/CsI(Tl) phoswich. The vertical axis is the integrated fast component and the horizontal axis is the integrated slow component of the waveforms. We see particle identification lines for Z = 1 and Z = 2 isotopes. We expect pions to be located between the Z=1 and neutron/gamma lines in these plots.

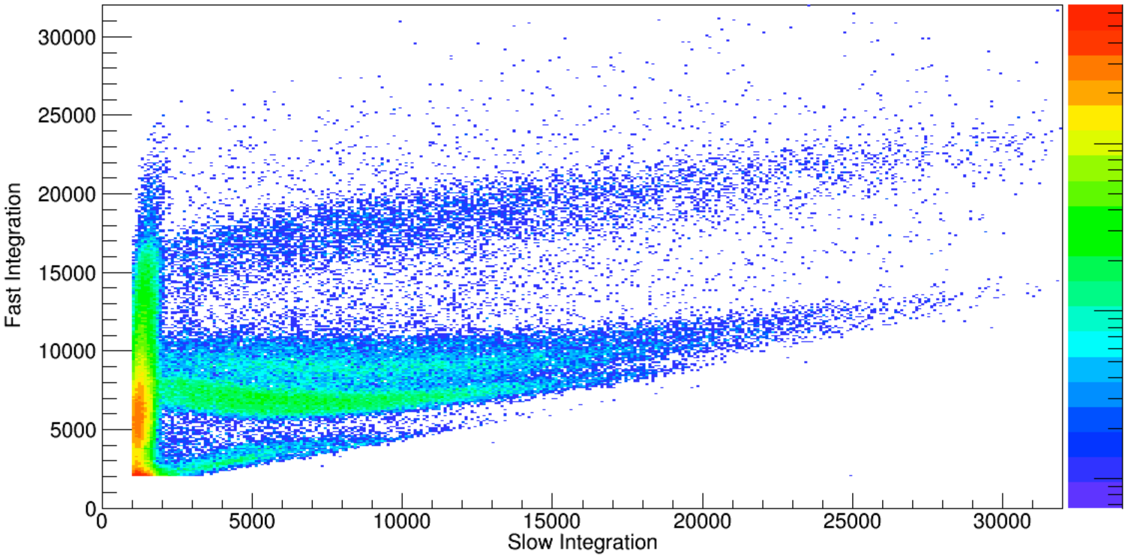

FIG. 1. A fast vs. slow particle identification plot for a fast plastic/CsI(Tl) phoswich detector. Moving up from the bottom of the plot, there is a straight line corresponding to neutron and gamma event, at least two particle identification lines for Z = 1 isotopes and, lastly, a thick line corresponding to Z = 2 isotopes. Pions are expected to mostly populate the area between the neutron/gamma line and protons.

Fig. 2 is a picture of the ParTI array fully built but not populated with the 15 total phoswich detectors. The design is also modular such that the array can be used in many different configurations in order to increase its utility in future experiments. The centers of each hexagonal detector are located on a sphere of radius 4.63 inches centered on the target position while the centers of each pentagonal detector are located 4.75 inches from the target position. Three partial hexagonal detectors will populate the center frame. These detectors will be positioned as a standard hexagonal unit with a hole through the center for beam to enter the chamber. For pionic fusion experiments, the array will be positioned backward of the target in order to minimize detection of background fragments produced by more standard reaction mechanisms while also taking advantage of the reported forward-backward peaked pion emission distribution that has been reported in previous pionic fusion experiments [2,3,4].

Fig. 3 is a picture of the pentagonal and hexagonal detector shapes. Moving backwards from the front face, these detectors consist of a 3 mm thick piece of EJ-212 fast scintillating plastic, a 1 cm thick CsI(Tl) crystal and a 1 inch thick light guide which mates the face of the CsI to the face of a 1924a Hamamatsu photomultiplier tube (PMT). Aluminized mylar is wrapped around the front face of the detectors to protect them from delta rays and to provide a light-tight surface of uniform thickness for particles to pass through. The rest of the detector, from the sides of the fast plastic to the base of the PMT, is wrapped with Teflon tape to provide a diffusely reflective and light-tight surface around

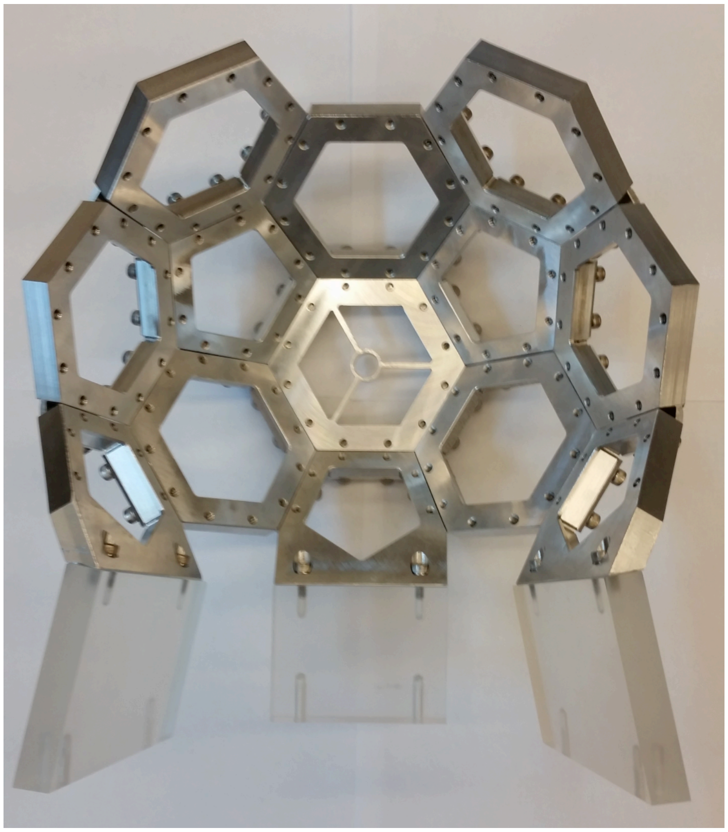
FIG. 2. The ParTI array in the configuration to be used in the coming pionic fusion experiments.

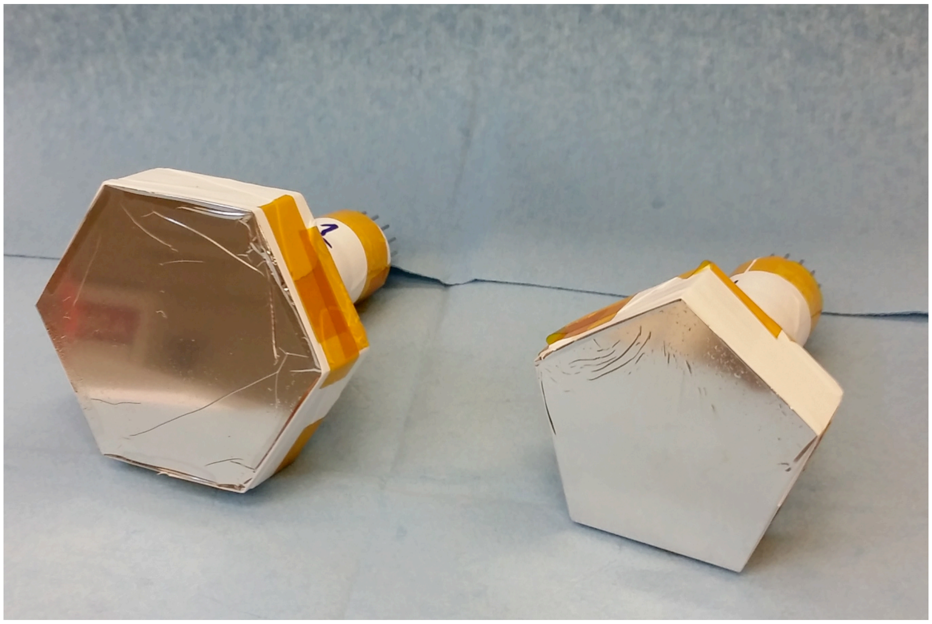
FIG. 3. A picture of the two regular polygon phoswiches that will populate the ParTI array. These detectors are 1.5” along each side.

the detectors.

The GANDALF digitizer is a 16-channel (8 channel interleaved) fast sampling ADC with 12-bit resolution at approximately 500 MS/s (1 GS/s interleaved). The module also includes a customizable FPGA which will be used to perform real time pulse analysis of the phoswich waveforms with the intent of looking for particular shape characteristics consistent with pion decays. Using this method we believe we can suppress the recording of background events to increase the live time of our electronics. We are currently in the final stages of working the module into the ROOT environment. Once this is completed, work will begin on FPGA coding and testing.

In the coming summer of 2015 we will run two final test experiments. The first will be a calibration of the phoswich detectors. A phoswich will be mounted in the MARS detector chamber and secondary beams of light charged particles at known energies will be used to determine the shapes of particle identification lines for these detectors. We will also be able to test the position dependence of the phoswich performance. The second test will be of a fully populated ParTI array. In this test we will align the ParTI array inside the MARS production chamber and successfully read out all 15 phoswich detectors using the cube feedthrough chamber that was recently added to the line. Contingent upon these two successful tests, we expect to be able to begin measuring pionic fusion reactions in the fall of 2015.

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