Implementation of flash digitizers in the ParTI phoswich array for identification of charged pions

A. Zarrella, L. Heilborn, A. Jedele, A.B. McIntosh, and S.J. Yennello

The Partial Trunctated Icosahedron (ParTI) phoswich array has been designed and constructed for the purpose of detecting charged pions emitted through the pionic fusion process. This process is quite rare with measured cross sections ranging from hundreds of nanobarns to hundreds of picobarns depending upon the size of the reacting system [1-12]. The experimental plan is to mount the ParTI array inside the target chamber in the Momentum Achromat Recoil Spectrometer (MARS) beam line where it will detect charged pions created at the target position from pionic fusion reactions while the pionic fusion residues will be collected at the back of the MARS. The low reaction cross section, broad angular distribution, and the resulting high beam intensity necessary to measure these reactions have necessitated the development of advanced triggering and data acquisition techniques, which have been made possible through the use of fast-sampling ADC digitizers.

The ParTI array is made up of 15 phoswich detector units oriented such that they cover approximately the hemisphere backward of the target (with respect to the beam). Each phoswich is made up of 4 parts: a 3 mm thick EJ-212 fast-scintillating plastic, a 1.5 cm thick CsI(Tl) scintillator, a 1 inch thick Lucite light guide, and a R-1924A Hamamatsu photomultiplier tube. All faces of the detectors are wrapped in white Teflon tape except the front face which is covered with a sheet of aluminized mylar. The phoswiches come in three different shapes - hexagons, pentagons, and partial hexagons - corresponding to the faces of the truncated icosahedrons. Fragments from the nuclear reactions on the target enter the front face of the detectors and deposit energy in the two scintillating components differentially with respect to the energy and species of the fragment. Using the different scintillating characteristics of these detectors, it is possible to achieve elemental separation through at least Z = 5 and isotopic resolution up to at least Z = 2 using fast and slow gating pulse shape discrimination (PSD) techniques. Please refer to the annual report entitled “The ParTI Array for Studying Pionic Fusion” for examples of the particle identification capabilities of these detectors.

The charged particle identification capabilities for phoswich detectors are fairly well established and can be accomplished with analog electronics [12-17]. The ParTI array, though, will be tasked with identifying charged pions resulting from the very rare pionic fusion process from a background of gamma rays, neutrons and charged particles that will be 6-7 orders of magnitude higher intensity. A GEANT4 simulation of the phoswich detectors was produced which showed that charged pions could be identified in the traditional manner of fast and slow pulse shape discrimination as a charged particle band below the protons and similar to the charged baryon lines. Fig. 1 is a fast vs. slow particle identification plot which shows charged baryons in black, pions in red, neutrons in blue, and gammas in green. This result was expected and encouraging. However, the simulation also predicted the pion line to extend through regions of the particle ID space populated by neutrons, gamma rays, and incomplete light collection in other charged baryon events. This has since been confirmed in several test beam experiments and, in practice, these background processes will completely swamp the few pionic fusion pions that we expect in any given detector. Pions interacting with the detectors will also have characteristic decays (first, the pion-to-muon decay with average lifetime of around 30 ns followed by the muon-to-electron decay with average lifetime around 2.2 μs) which will deposit energy in the scintillators at varying times with respect to the PSD gates. As a result, many pions do not lie on the particle ID line and have values on the slow axis beyond the neutron/gamma line.

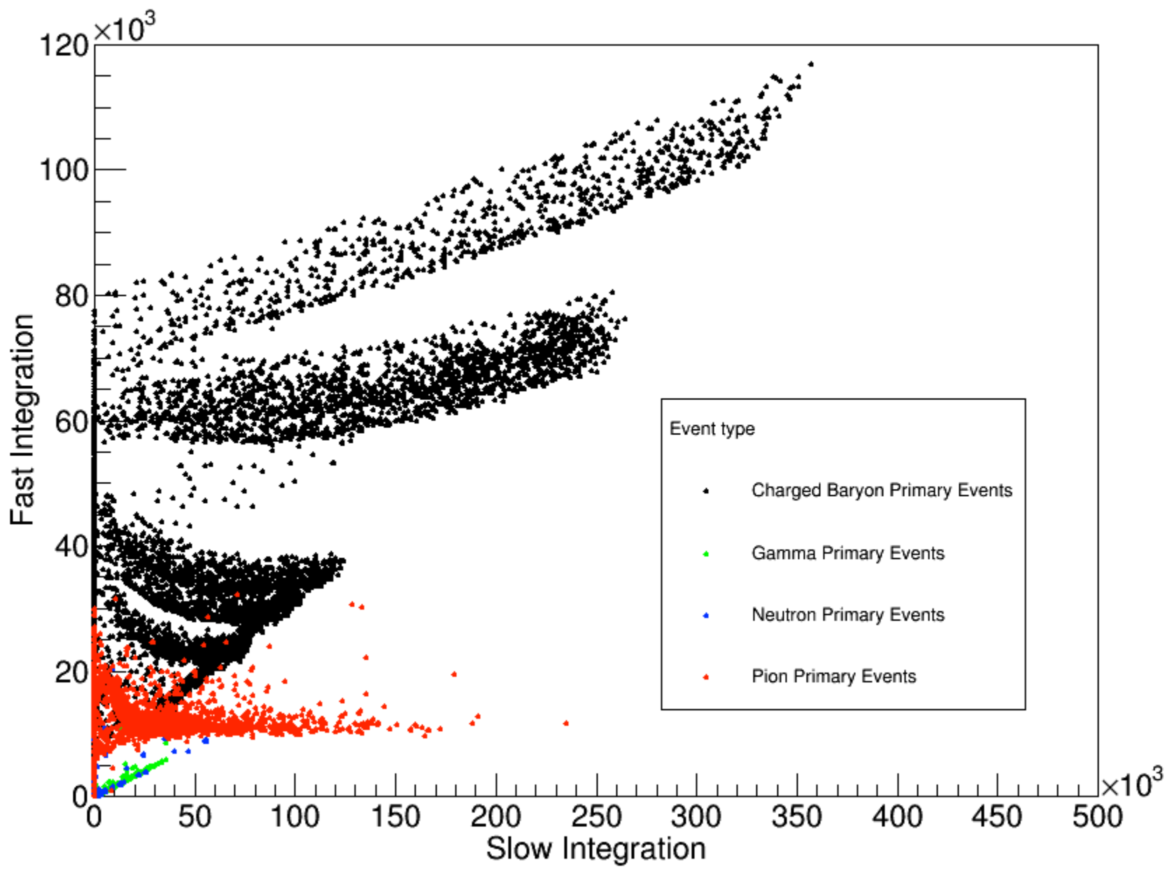

FIG. 1. A fast vs. slow (ΔE-E) particle identification plot produced by the GEANT phoswich simulation. The x-axis is the integrated phoswich signal inside of the slow gate which is 400 ns wide and starts 1 μs from the beginning of the signal. The y-axis is the integrated phoswich signal inside the fast gate which is 15 ns wide and begins at the start of the signal. Moving up from the bottom of the figure, neutron and gamma events (blue and green points, respectively) populate the neutron/gamma line. Above that is the pion band shown in red followed by particle bands for the light charged baryons. There is good isotopic resolution of p, d, and t followed by a Z = 2 band populated by ^{3}He and ^{4}He and finally a band for ^{6}Li.

Ultimately, it has become clear that relying on a pronounced fast vs. slow particle ID line for pions is not an option given the very low stats, high background in the region, and uncertainty of the position of individual pions. However, the GEANT simulation was also able to predict the full waveform response of the phoswiches. Figure 2 shows representative GEANT-simulated phoswich responses for charged baryons, neutron/gammas, and pions (panels a, b, and c, respectively). The characteristic decay of the muon associated with pion implantations that was contributing to the difficulty of identifying pions using fast vs. slow integrations could be used to identify pions using the total waveforms. In order to accomplish this, one needs to digitize the phoswich signals, parse the waveforms (either in the hardware FPGA mounted on the digitizer or in the software backend) for the presence of a second pulse, and then cross check both pulses using the fast vs. slow PSD technique to eliminate background events. Using this technique in a beam test performed in February of 2016 with the phoswich detectors, we have been able to efficiently classify pion candidate events. When this technique is combined with the coincident measurement of the complementary fusion residue in MARS, we will be able to identify pionic fusion events with extremely high accuracy.

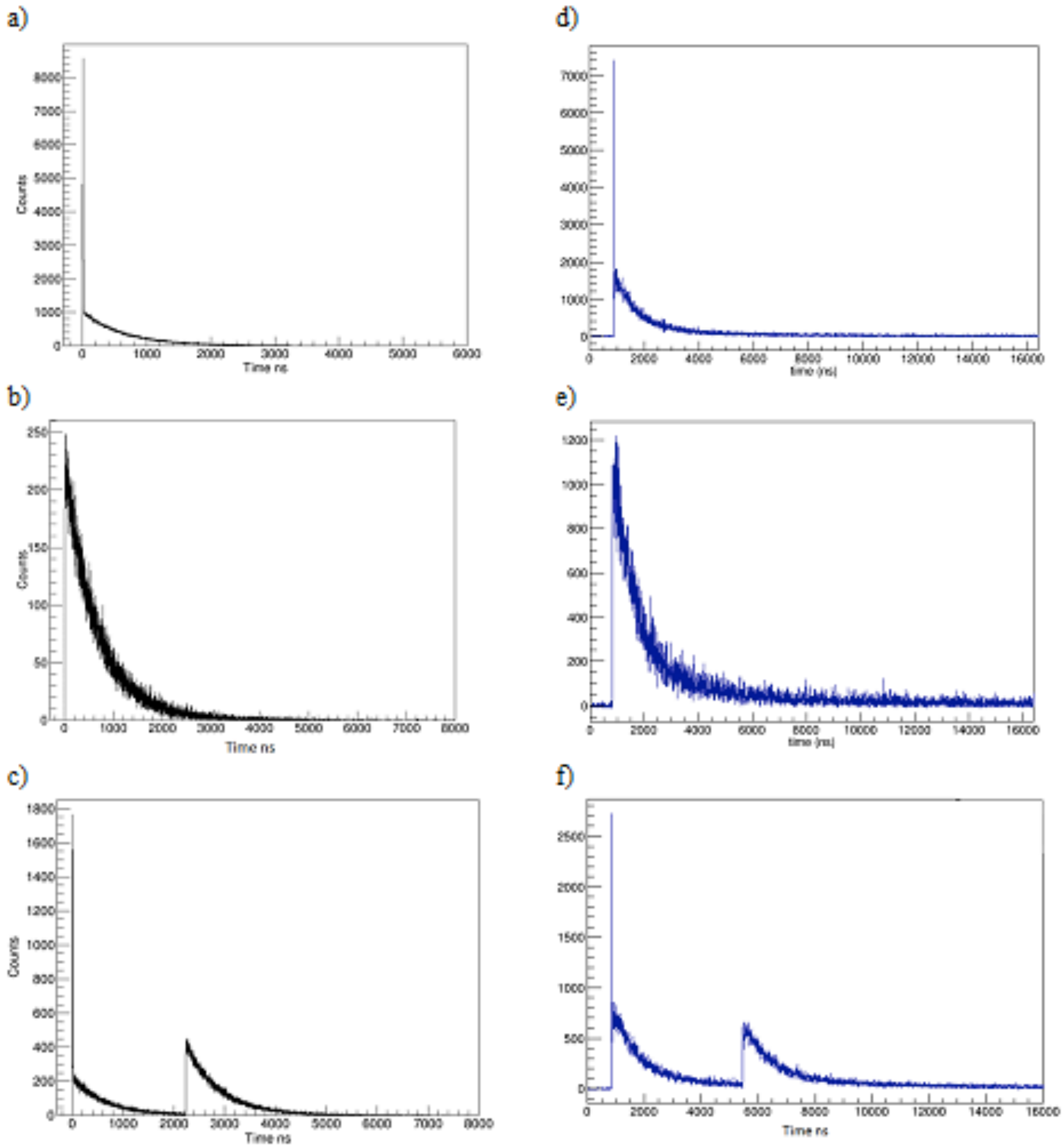

FIG. 2. Predicted phoswich responses produced by the GEANT4 simulation for representative events of a light charged baryon, neutron/gamma, and pion (panels a, b, and c, respectively) with comparable representative digitized experimental events from the February 2016 beam experiment in panels d, e, and f. The muon decay, with mean lifetime of 2.2 μs accompanying pion implantations,provides a very clear pion event signature.

For the fast-sampling digitizer we have chosen to use the SIS3316 unit produced by Struck Innovative Systeme. This is a 16-channel, 14 bit resolution VME unit with a 250 MSsamples/s sampling rate. In beam tests, we have shown that we can perform the fast vs. slow PSD technique by integrating over sampled bins (see annual report for the ParTI array noted previously). In panels d, e, and f of Figure 2 are shown three digitized phoswich waveforms from the test run in February of 2016 which correspond very closely to their respective response types predicted by the GEANT4 simulation. The waveform in Figure 2f is a very strong pion candidate possessing the characteristic decay pulse with a reasonable decay time, a primary peak with a fast vs. slow particle identification located between the proton and neutron/gamma line, and a secondary peak with a fast vs. slow particle identification located in the expected area for the decay electrons.

While the complete waveforms digitized by the SIS3316 have allowed for the more accurate identification of pions, their necessity has also increased the data overhead of the acquisition by approximately 4000x (>8000 digitized bins per channel vs. one fast and one slow integration per channel from the QDCs). The consequence of collecting this much more data per event is that it greatly reduces the event rate that can be written to disk while maintaining and acceptable dead time for the low cross section reactions of interest. In order to circumvent this new issue, we will utilize an advanced triggering mechanism implemented in the on-board FPGA of the digitizer that was developed by Struck Innovative Systeme and Dr. Sara Wuenschel. This "pileup" trigger parses the signals coming into the module in real time in order to identify secondary peaks. Upon finding a second peak in a given time window, a trigger will be produced and the event of interest is written to disk. In practice, this advanced triggering mechanism will suppress the number of triggers resulting from non-pion events and allow for much higher beam rates as a result. The pileup trigger has been tested in the laboratory and beam tests.

The ParTI array and digitizer-based pion identification technique described above will be used in the pionic fusion experiment scheduled for 2016 and the following data analysis. There will also be a detector test at the pion/muon beam facility at the Paul Scherrer Institute in Switzerland. In this test run, a beam of pions/muons will be scattered into representative phoswich modules in order to better constrain the detector's response to charged pions and the corresponding muon decays.

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