Timing capabilities of the ParTI phoswich array

A. Zarrella, E. Churchman, J. Gauthier, K. Hagel, A. Jedele, A.B. McIntosh, A. Rodriguez Manso,
A. Wakhle, and S.J. Yennello

The Partial Truncated Icosahedron (ParTI) phoswich array [1] is made up of 15 phoswich detectors arranged on faces of the truncated icosahedrons geometry. The array has approximately 2π solid angle coverage. Its modular design allows for flexibility in its applications as detector units can be easily added or removed from the truncated icosahedron geometry or the detectors can be rearranged to form other geometries such as a wall. The phoswich detectors are designed in 3 different geometries - hexagonal, pentagonal and 3 partial hexagonal constructions. The regular hexagonal and pentagonal geometries correspond to the appropriate faces of the truncated icosahedrons shape. The three partial hexagonal detectors are designed such that there is a hole through the middle and they populate the single hexagonal face that the beam passes through. Each phoswich detector consists 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).

The ParTI array has been utilized in two experiments for the purpose of detecting low energy charged pions. The first of those experiments was conducted at the Paul Scherrer Institute (PSI) where beams of charged pions were scattered into ParTI phoswiches to characterize the detector response. The second experiment was a cross section measurement for the pionic fusion reaction ^{4}He + ^{12}C → ^{16}N + π^+ conducted at the Cyclotron Institute. Over the past year, analysis of the data collected during these two experiments has highlighted many of the timing capabilities of the array when used with the Struck SIS3316 digitizers. Specifically, we have shown the capability to measure the mean lifetime of $\mu+$ using the time difference between the pion implantation and the muon decay response, construct event coincidences from two separate detector systems within an experiment, and selectively look for rare decays by searching for events which are uncorrelated with the beam RF frequency.

The pion beam data from PSI has already been used to show that the ParTI phoswiches are capable of identifying charged pions based on their energy lost in the two scintillating components using a fast vs. slow pulse shape discrimination method on the detector's response to the pion's implantation [1]. Once implanted, the pion will quickly decay into a muon with an average lifetime of 26 ns which will be followed by the muon's decay into a positron with an average lifetime of 2.2 μs. Since the entire detector response is being recorded we have access to timing information associated with these particle decays. In general, the pion's decay into the muon happens too fast and deposits too little energy in the detector for its response to be distinguished from the much larger implantation response. The muon's decay, however, is regularly easily separated from the implantation due to its much longer average lifetime and its larger deposited energy. For each event that is identified as a π^+ primary using fast vs. slow particle identification (PID), the time is calculated between the beginning of the particle implantation response and the muon's decay (dt). This distribution of times can then be used to create a decay curve for muons. Fig. 1 shows this experimental curve for one of the phoswiches used in the PSI experiment. An exponential fit of this data (the red curve overlaid on Fig. 1) can then be used to extract the measured mean lifetime for μ+. For the three phoswiches in the PSI experiment, the measured muon lifetimes are within 2% of the known value. This is an exceptionally strong indication that the ParTI phoswiches are behaving as expected with respect to the detection of π^+.

During the pionic fusion experiment, data was being collected simultaneously using a silicon stack at the focal plane of the Momentum Achromat Recoil Spectrometer (MARS) [2] and inside the line's target chamber using the ParTI array, approximately 75' upstream. In the case that a particle was detected in the MARS silicon, the ParTI phoswiches were recorded as slaves. The phoswiches, however, are subject to a much higher rate of incident charged particles in the target chamber so it becomes necessary to determine whether a phoswich response was due to a charged particle originating from the same event as the particle in the MARS silicon. In order to do this, the ParTI signal's time location within its digitization window is found for each event that the phoswich was read as a slave to MARS. When sorted on the identification of the particle in MARS (because the velocity of the transported particle changes with species according to Bρ), the distribution of ParTI signal times shows a sharp peak corresponding to particles detected in the phoswiches from coincident events with the MARS particle.

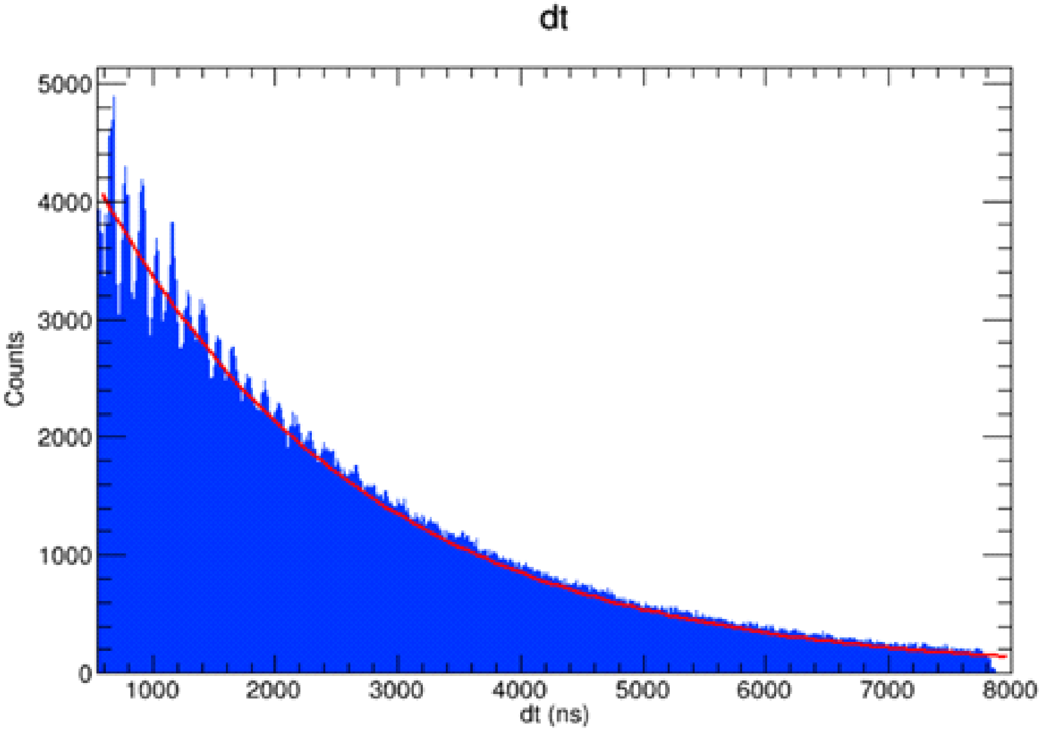

FIG. 1. The decay curve for μ^+ measured by a ParTI phoswich during the PSI charged pion beam experiment. The horizontal axis is the time difference, dt, between the implantation of the charged pion and the pulse due to the decay of the muon in ns. The red curve is an exponential fit of the data from which the average lifetime is extracted.

Fig. 2 (a) shows this distribution of phoswich signal times when the event was triggered by a ^{7}Li particle detected at the MARS focal plane. The horizontal axis is the time bin location of the start of the phoswich signal and a clear peak is present corresponding to event coincidences. This peak location can be extracted for each MARS-identified particle type (with sufficient statistics) and the time bin location can be compared to the velocity of that particle given the MARS Bρ setting. Fig. 2 (b) shows the calibration of the phoswich signal's relative time bin given the velocity of the particle identified in MARS. On an event-by-event basis, then, a particle detected in a phoswich can be determined to be from the same event as a particle detected at the MARS focal plane if the timing of the phoswich response is consistent with the calibration in Fig. 2 (b).

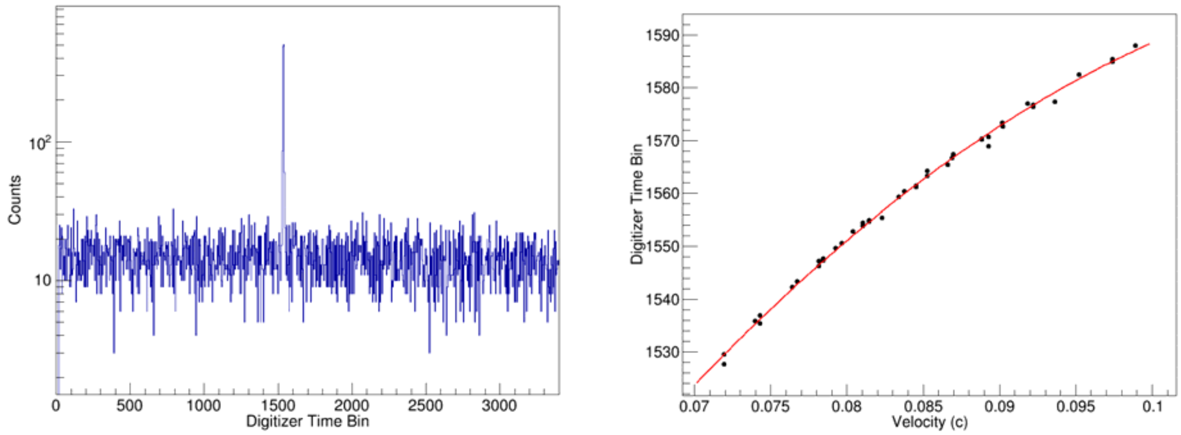

FIG. 2. (a) The distribution of phoswich signal times within the digitization window when the phoswiches are recorded as slaves when a ^{7}Li particle is detected at the MARS focal plane. The horizontal axis is the time bin where the signal begins and the time bins are 4 ns wide. The sharp peak corresponds to phoswich signals which come from the same event as the detected ^{7}Li. (b) After extracting the peak locations for all MARS-identified particles, the time bin location of the phoswich signals can be correlated with the velocity of the particle at the back of MARS. This calibration can then be used to determine on an event-by-event basis whether a phoswich signal is from the same event as the MARS particle.

During the pionic fusion experiment, the phoswiches were also allowed to trigger events according to a muon decay trigger which was developed to selectively identify pion candidate events. The muon decay trigger works by searching for a second instance of a signal passing the CFD threshold within a single digitization window. Fig. 3 (a) shows an example of an experimental signal which passes the muon decay trigger conditions. For a pion primary event, the second pulse corresponds to the decay of the muon daughter of the implanted pion. However, a common background process is true pile up of events within the 8 μs window. Fig. 3 (b) shows the distribution of the times of the first phoswich response within the digitization window. The figure's time axis has been zoomed in so that the structure can be observed. As a feature of the trigger, the second pulse is always located at the same time bin location. The distribution, therefore, is effectively a distribution of the time difference between the first and second phoswich response. The periodic peaks in Fig. 3 (b) correspond to the RF frequency of the cyclotron. Thus, events within these peaks are more likely to be pile up. Pion primary events which are followed by muon decays are not correlated with the cyclotron frequency, though, so one can selectively look for pion candidates by considering only events which populate the valleys between the RF peaks. This reduction of background candidates greatly increases the sensitivity of the search for true pion events.

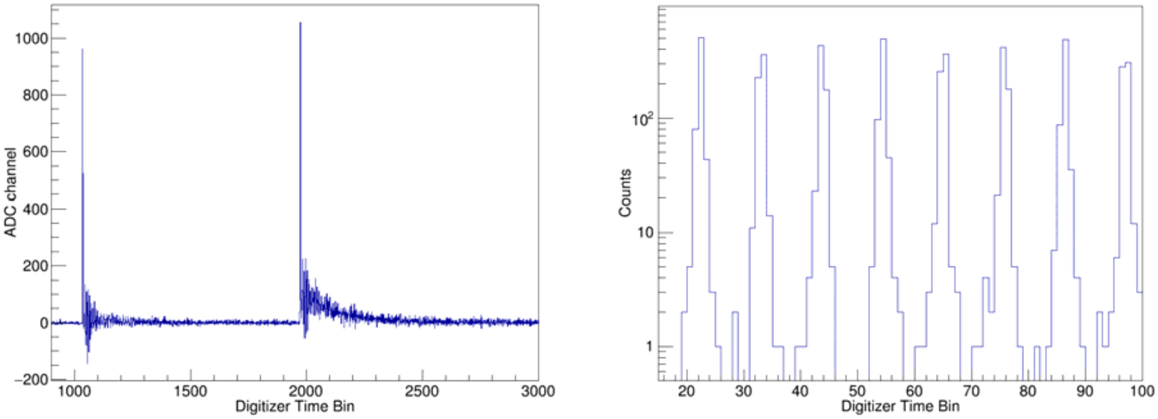

FIG. 3. (a) An example of a phoswich signal recorded during the pionic fusion experiment which satisfied the muon decay trigger conditions. The horizontal axis is in units of the 4 ns digitizer time bins. (b) The distribution of time bin locations of the first phoswich peak in events that satisfy the muon decay trigger zoomed in on an arbitrarily chosen section of the distribution so that the structure can be observed. The peaks in the distribution are due to true pile up events coming from different beam bursts and the frequency in the data corresponds to the cyclotron RF frequency.

Future work regarding the ParTI array will include a detailed publication describing the instrument and its observed pion and light charged particle detection capabilities. Analysis of the data collected in the PSI and pionic fusion experiments is also still ongoing.

[1] A. Zarrella, *et al*. Physics Procedia. **90**, 463 (2017).