Pulse Shape Discrimination of CsI(Tl) with Photomultiplier Tube and MPPCs

N. V. H. Viet, Member, IEEE, K. Takahisa, M. Nomachi, Senior Member, IEEE, T. Shima, B. T. Khai, Member, IEEE, R. Takaishi, and K. Miyamoto

Abstract—To study three-nucleon force in proton ($p$) and deuteron ($d$) channels of muon capture on $^3$He, we use CsI(Tl) scintillator and Multi-Pixel Photon Counters (MPPCs) to obtain energy spectra of $p$ and $d$. We use Pulse Shape Discrimination (PSD) two-gate method to separate these spectra and reject the background mainly from $\beta - \gamma$. In this method, we measure the waveform, integrate charges collected in Short Gate (tail-part) and Long Gate (entire pulse), then take their Ratio to identify different particles. The main contribution of this research is to evaluate and optimize the PSD performance of both MPPCs and photomultiplier tube (PMT). Since the PSD performance of PMT has been studied before, we compare the performance of MPPCs with that of PMT in two test experiments, $\alpha - \beta$ and $p - d$ separations. In the first test, using natural Thorium, we confirm $\alpha - \beta$ separation on both PMT and MPPCs. PSD Figure of Merit (FOM) is about 3 for PMT and 2 for MPPCs. In the second test, we detect $p$ and $d$ from 65 MeV proton beam hits a mixed target of polyethylene and deuterated polyethylene. The $p - d$ separation is only confirmed on PMT. For MPPCs, Long Gate should be increased to give a good PSD performance as PMT does. Thus, we change the digitizer used in two test experiments, the WaveCatcher (digitized waveform $\sim$2.5 $\mu$s), to a new data acquisition system, the $\mu$TCA, with digitized waveform about 9.0 $\mu$s. Using MPPCs and $\mu$TCA, FOM$_{\alpha - \beta}$ is about 3. We expect a good $p - d$ separation with this setup.

Index Terms—pulse shape discrimination, CsI(Tl), photomultiplier tube, MPPC

I. INTRODUCTION

In $\mu$ capture on $^3$He, we focus on channels: $\mu^- + ^3$He $\rightarrow \nu_\mu + n + d$ and $\mu^- + ^3$He $\rightarrow \nu_\mu + n + n + p$. We want to obtain and separate energy spectra of $p$ and $d$ to confirm with theoretical calculations [1] whether a contribution of three-nucleon force (3NF). To separate $p$, $d$ and reject background mainly from $\beta - \gamma$, we use CsI(Tl) scintillator for its ability of pulse shape discrimination (PSD). Using PSD two-gate method, we open two gates: one to collect charges of the entire pulse - Long Gate and the other to collect charges of the tail part - Short Gate (Figure 1). We define Ratio as charges integrated within Short Gate divided by charges integrated within Long Gate. Different values of Ratio identify different types of particles. For photo-sensor, we use Multi-Pixel Photon Counters (MPPCs) instead of photomultiplier tube (PMT) because PMT is vulnerable in He gas and not compact for our He chamber. Preparing for $\mu$ capture experiment, we evaluate and optimize the PSD performance of MPPCs and compare with that PMT in two test experiments, $\alpha - \beta$ and $p - d$ separations. We make this comparison because the performance of PMT has been studied before.

II. PSD PERFORMANCE OF PMT AND MPPCS

A. $\alpha - \beta$ separation

In the first test, $\alpha - \beta$ separation, our source is natural Thorium from lantern mantle. For PMT setup (Figure 2 top), we use $10 \times 10 \times 20$ mm$^3$ CsI(Tl) with Hamamatsu H7415/R6427 PMT $\varnothing$33 mm on the surface of $10 \times 10$ mm$^2$. For MPPCs setup (Figure 2 bottom), we use five Hamamatsu S13360-6075C S$\varnothing$33 mm with H7415/R6427 PMT. We use two experiments.
Fig. 3. Ratio vs. Charge of $\alpha$ and $\beta$ from PMT (top) and MPPCs (bottom), both using WaveCatcher digitizer.

The bias voltage for PMT is $-1000 \text{ V}$. For MPPCs setup, the CsI(Tl) is $10 \times 50 \times 100 \text{ mm}^3$, which we plan for $\mu$ capture experiment. In Figure 2 (bottom), five Hamamatsu S13360-6075CS MPPCs are attached on the surface of $10 \times 50 \text{ mm}^2$ of this CsI(Tl). These MPPCs share the same bias voltage of $-57.4 \text{ V}$. Analog signals from 5 MPPCs are summed up before feeding into a readout channel of WaveCatcher digitizer [2] (maximum length of digitized waveform is 2.56 $\mu$s).

The $\alpha-\beta$ separation is confirmed on both PMT and MPPCs (Figure 3). Project all events in Figure 3 onto Ratio axis, we have the Ratio distribution as showed in Figure 4. To evaluate PSD performance, we use the conventional Figure of Merit (FOM). As in Figure 4, FOM for two types of particles is defined as the Ratio difference divided by the sum of Ratio fluctuations, i.e. the sum of two full widths at half maximum (FWHM). To have a good $\alpha-\beta$ separation, we optimize Long Gate and Short Gate. Since the maximum length of waveform on WaveCatcher is about 2.5 $\mu$s and the decay time of CsI(Tl) is about 1 $\mu$s, we set Long Gate at 2.25 $\mu$s ($t = 0$ to $t = 2.25 \mu$s) for both PMT and MPPCs setups. To optimize Short Gate, we keep the end point of Short Gate at $t = 2.25 \mu$s (same as Long Gate) and vary the start point to find the best FOM$_{\alpha-\beta}$. For PMT, optimized Short Gate is 1.30 $\mu$s (start point at $t = 950 \text{ ns}$). For MPPCs, optimized Short Gate is 1.50 $\mu$s (start point at $t = 750 \text{ ns}$). With these optimization, FOM is 3.26 for PMT and 2.05 for MPPCs. The long decay time of MPPCs for one photo-electron and the analog-sum signal without timing adjustment are possible reasons that lead to long rise time in waveform from MPPCs (Figure 5). This long rise time degrades the FOM of MPPCs.

B. $p-d$ separation

In the second test, $p-d$ separation, we use 65 MeV proton beam from the AVF cyclotron at the Research Center for Nuclear Physics (RCNP), Osaka University. We detect $p$ and $d$ from reactions of the proton beam with a mixed target of polyethylene and deuterated polyethylene. We use the same setups as in $\alpha-\beta$ separation plus an attenuator before signal fed into WaveCatcher due to high-energy events of $p$ and $d$. The bias voltage is also reduced to $-700 \text{ V}$ for PMT. Because we have a reflection at the end of each pulse, we reduce Long Gate to 1.90 $\mu$s ($t = 0$ to $t = 1.90 \mu$s). Optimized Short Gate for PMT is 1.40 $\mu$s (start point at $t = 500 \text{ ns}$). The $p-d$ separation is confirmed on PMT. Figure 6 is the result at scattering angle of 45° with FOM$_{p-d}$ of 0.77. Because the difference in waveform of $p$ and $d$ is not much (Figure 7), thus FOM$_{p-d}$ is lower than FOM$_{\alpha-\beta}$ in previous test. For
III. IMPROVE PSD PERFORMANCE OF MPPCS

In the previous section, the PSD performance of CsI(Tl)+MPPCs is not as good as that of CsI(Tl)+PMT when using WaveCatcher digitizer. Since we use MPPCs instead of PMT for the \( \mu \) capture experiment, we improve the PSD performance of MPPCs by increasing Long Gate. The Long Gate cannot exceed 2.56 \( \mu s \) in WaveCatcher, so we change to a new data acquisition (DAQ) system, the \( \mu TCA \) [3], with a maximum length of digitized waveform up to 8.96 \( \mu s \). We perform another \( \alpha - \beta \) separation test with MPPCs using the \( \mu TCA \) DAQ system. As in Figure 8, with \( \mu TCA \) system, Long Gate can be up to 8.0 \( \mu s \). First, the difference in waveform from 2.5 \( \mu s \) (maximum of WaveCatcher) to 8.0 \( \mu s \) will increase the Ratio difference. Second, a longer gate means an increase in the number of photo-electron collected, thus will reduce the Ratio fluctuation. For Long Gate of 8.0 \( \mu s \), the optimized Short Gate is 7.3 \( \mu s \). As in Figure 9, using \( \mu TCA \) system, the PSD performance of CsI(Tl)+MPPCs is improved with FOM\( _{\alpha-\beta} \) of 3.37. This is better than FOM\( _{\alpha-\beta} \) of CsI(Tl)+PMT when using WaveCatcher. Therefore, using CsI(Tl), MPPCs, and \( \mu TCA \), we expect a good \( p - d \) separation in our future test.

IV. SUMMARY

We have evaluated and optimized the PSD performance for both setups with PMT and MPPCs. In \( \alpha - \beta \) separation, the FOM of PMT is higher than that of MPPCs (3.26 vs. 2.05). The FOM degradation in MPPCs setup possibly comes from the long decay time of MPPCs for single photo-electron and the analog-sum signal without timing adjustment. The optimization of Short Gate also helps confirm the \( p - d \) separation on PMT with FOM of 0.77. To have a good PSD performance for MPPCs, we increase Long Gate length using a new DAQ system, the \( \mu TCA \) with digitized waveform about 9.0 \( \mu s \) (digitized waveform is 2.5 \( \mu s \) for the previous digitizer, WaveCatcher). The \( \mu TCA \) system improves FOM\( _{\alpha-\beta} \) of MPPCs to 3.37. When both scintillator (CsI(Tl)) and photo-sensor (MPPCs) have long decay times, the integration length plays an important role in PSD performance.

In \( \mu \) capture on \( ^3He \), the number of \( d \) is twice the number of \( p \) so FOM about 0.8 of PMT is good enough. We expect with \( \mu TCA \), CsI(Tl)+MPPCs can separate \( p \) and \( d \). To reject \( \beta - \gamma \) background, the FOM of \( \beta(\gamma)-\)hadron must be higher than FOM\( _{p-d} \) since \( \beta - \gamma \) events are much more than \( p, d \) events.

REFERENCES

[1] J. Golak et al., “Break-up channels in muon capture on \(^3\text{He}\),” Physical Review C, vol. 90, no. 2, p. 024001, 2014.
[2] D. Breton et al., “The WaveCatcher family of SCA-based 12-bit 3.2-GS/s fast digitizers,” in 2014 19th IEEE-NPSS Real Time Conference, pp. 1–8, IEEE, 2014.
[3] B. T. Khai et al., “\( \mu TCA \) DAQ system and parallel reading in CANDLES experiment,” IEEE Transactions on Nuclear Science, 2019.