Development of signal processing methods for a high-rate timing detector of the charmed baryon spectroscopy experiment

K. Shirotori[1], T. Akaishi[2] and for the J-PARC E50 collaboration
[1] *Research Center for Nuclear Physics (RCNP), Osaka University, Ibaraki, Osaka 567-0047, Japan*
[2] *Department of Physics, Osaka University, Toyonaka 560-0043, Japan*

1 Introduction

One of main subjects in the hadron physics is to understand how hadrons are originated by quarks. The constituent quark model doesn't work for understanding the properties of the excited states although the model well describes those of the ground state hadrons. It is necessary to investigate effective degrees of freedoms of hadrons with extended constituents such as the diquark correlation as well as the hadron molecular picture. The diquark correlation is expected to be an effective degree of freedom to describe hadrons. In the case of light baryons, three diquark pairs are correlated each other in an equal weight so that the extraction of the diquark correlation cannot be emerged. When one quark in a baryon is replaced to a heavy quark, charm, the diquark correlation is expected to be isolated and developed in the excited states of charmed baryon. We plan a charmed baryon spectroscopy experiment (J-PARC E50 [1]) at the high-momentum beam line of the J-PARC hadron experimental facility. In the experiment, the excited states of charmed baryons are produced via the $\pi^- \ p \rightarrow Y_c^{*+} \ D^{*-}$ reaction using the π^- beam of 20 GeV/c. Production rates and decay branching ratios of the excited states are measured in a wide mass region by the missing mass method. The diquark correlation which is supposed to be an essential degree of freedom to describe the hadron structure can be established by the systematic measurements of production rates and decay branching ratios. For measuring the missing mass and decay events of charmed baryons, we are constructing the spectrometer system [2].

A high-intensity secondary beam of 30 MHz for the 2-second extraction is used for sufficient yield of charmed baryons. The beam timing detector has to be operated under a high-counting rate environment. In the high-rate beam condition of 3 MHz/segment, the time resolution of 60–80 ps (σ) is required to identify a forward scattered particle from the target by Time-of-Flight with TOF detector in the spectrometer. We have developed a Cherenkov timing detector for the high-intensity beam timing measurement. The developed detector is comprised of an X-shaped acrylic Cherenkov radiator and a multi-pixel photon counter (MPPC) [3]. To use in a high-counting rate environment, we have employed a narrow width of 3 mm for a fine segmentation, and an amplifier for shaping signal into a narrow width of 10 ns(FWHM).

2 Improvement items for signal processes

From the test experiment with a high-counting rate [4], we have achieved the time resolution of 54(1) ps(σ). However, we found that a pile-up effect made the time resolution worse from the best resolution of 43 ps(σ) in the low-counting rate condition. A signal from the MPPC amplifier had small pulses following the main pulse which is caused by the ringing of the signal pulse. It was found that the ringing affected the time resolution by deteriorating timings from the baseline changes. Since the affected time range after signal pules was $\sim$200 ns, the suppression of the ringing is crucial to obtain a better time resolution.

Since a streaming DAQ system without a dead time is used, a normal ADC with a dead time of several μs cannot be used in the charmed-baryon spectroscopy experiment. In addition, if a flash ADC is used, the amount of data becomes enormous and data transfer becomes difficult. For these reason, we have to use a fast signal digitalization without ADC so that we consider to use the Time-over-Threshold method in which the signal width from both leading and trailing timings measured by TDC is used instead of ADC. Since the shaping circuit is designed to shape signals to be narrow by using a simple differentiation circuit, the width of the signal saturated and lost linearity with pulse height information when the pulse height becomes high. It is not sufficient to correct the pulse height from the signal width. We should improve the shaping circuit having the correlation between signal width and pulse height.

3 Suppression of ringing effect by using Schottky Barrier Diode

For suppressing the ringing effect, we adopt a Schottky Barrier Diode (SBD). SBD was used for realizing a narrow signal readout of MPPC as [5]. By connecting SBD to a subtraction circuit with a series connection at the end of circuit, an input pulse was filtered to be narrower one. SBD which has a quick time response and a small forward voltage can be used as a kind of a rectifier diode. Reversed and smaller pulses are suppressed

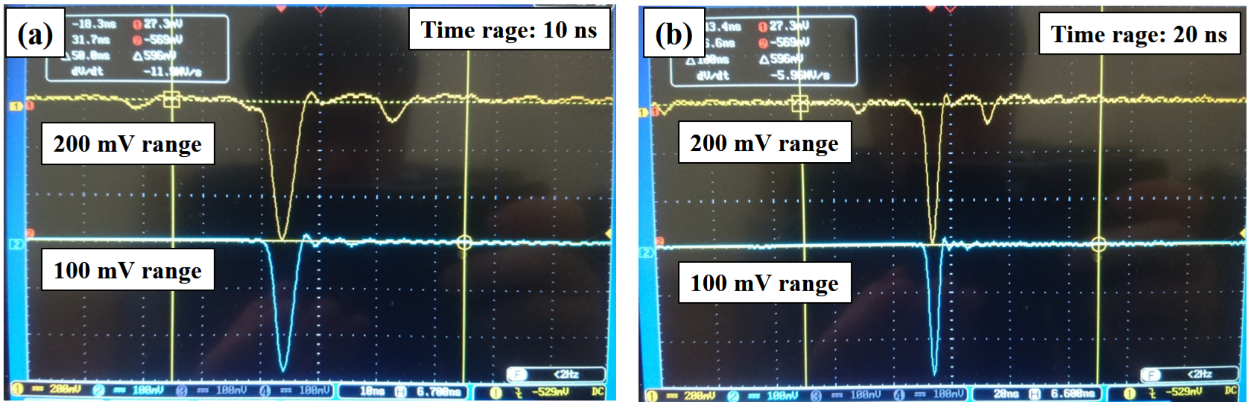

Figure 1: Oscilloscope snapshots of output signals before and after filtered by SBD. Channel 1 (yellow line) and channel 2 (blue line) show output signals before and after processed by SBD, respectively. (a) and (b) show different time ranges of 10 ns and 20 ns, respectively.

by the rectification and the Schottky barrier of SBD, respectively. Both elimination of reversed pulses and the threshold function to suppress small pulses following the main pulse can be performed by using SBD with a series connection at the end of circuit. For an actual SBD to connect the amplifier, BAT63 [6] which has forward voltage of ∼120 mV is satisfied. BAT63 has enough properties of its forward current and reverse voltage for filtering signals from the MPPC amplifier.

For the signal readout test, BAT63 was serially connected to the end to the MPPC amplifier. The ringing signal was obviously suppressed while the leading edge and a narrow width of the main pulse were kept as shown in Fig. 1. On the other hand, the pulse height filtered by SBD was decreased to be half of the input signal. For evaluating the performance of the amplifier with SBD, we test a Cherenkov timing detector by using a β ray from a ^{90}Sr source as shown in Fig. 2. The time difference between both edge of the detector was measured by the HUL high-resolution TDC modules [7]. By triggering the central region of the Cherenkov radiator with a 3-mm plastic scintillation detector, a time spread by hitting other positions of the radiator can be eliminated. Then, the time-walk correction was performed by using a pulse height information which was measured by a waveform of the DRS4 module [8]. From the previous study [3], the time resolution of one edge showed the resolution of 50 ps(σ) so that the expected resolution of the subtraction timing is 70 ps(σ) which is a root mean square of that of both edge. In this measurement, the over-voltage of MPPC and a discriminator threshold value is +7V and 3.5 photoelectrons, respectively.

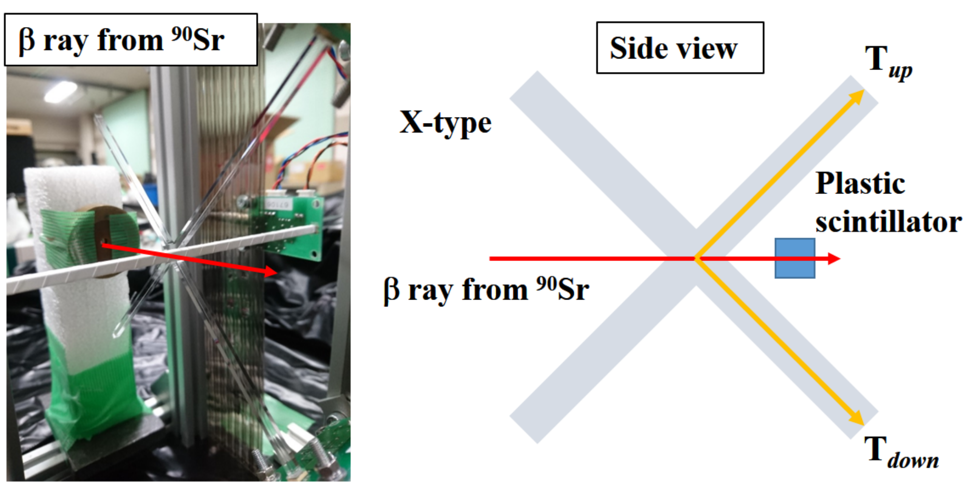

Figure 2: Photograph of the test Cherenkov timing detector (left). Time resolution of the detector was evaluated by using a β ray from a ^{90}Sr source. The time difference between both edge (T_{up} and T_{down}) of the detector was measured.

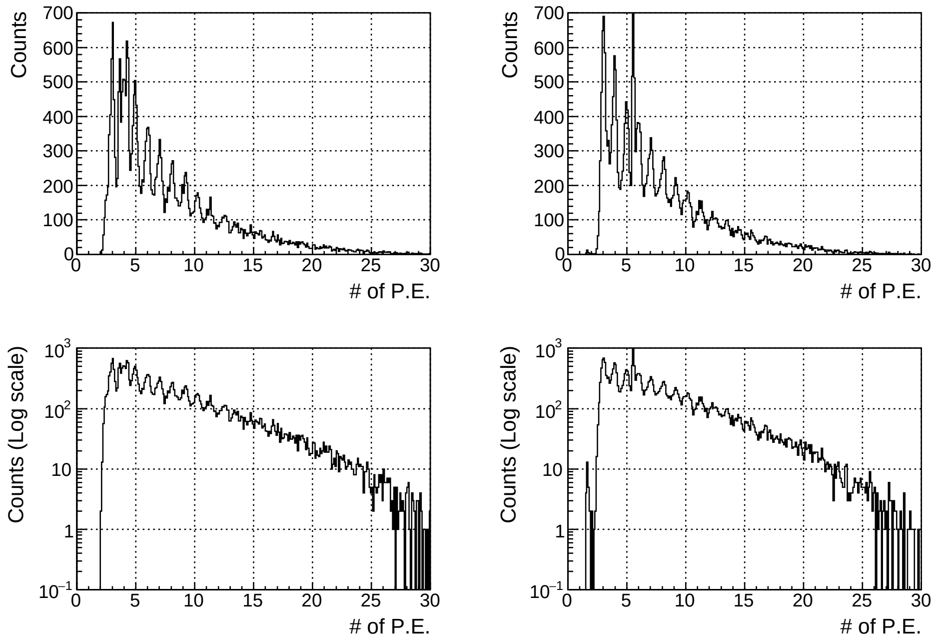

Figure 3: Distributions of number of p.e. of both top (left) and bottom (right) edge of the test Cherenkov timing detector with SBD. Top and bottom figure show normal and logarithmic scale of the vertical axis, respectively. Spike noises on the DRS4 waveform data are shown as a peak structure around number of p.e. of 5.

Figure 3 shows distributions of number of photoelectrons(p.e.) of both top and bottom edge of the test Cherenkov timing detector with SBD. Maximum number of p.e. is ∼30 with mean values of the distributions of ∼8.5. The distributions of number of p.e. were not affected by whether SBD was used. For evaluating the time resolution, we selected events by cutting number of p.e.. Figure 4 shows the time resolutions by selecting number of p.e. after the time-walk correction. Horizontal axis shows the mean value of number of p.e. in the selected events. By selecting larger number of p.e., the time resolution became better because the number of fast photons which are arrived to MPPC are increased. Data of more than 20 p.e. are corresponded to that of the minimum ionization particle. Figure 4(a) and (b) show the time resolutions with and without SBD, respectively. Both results show the same time-resolution around 20 p.e.. Therefore, we found that SBD can be used as a filtering device without any deterioration of the time resolution. In addition, BAT63 is a suitable Schottky Barrier Diode with a forward voltage of ∼120 mV which can be used for many cases such as signal shaping of MPPC, PMT and so on.

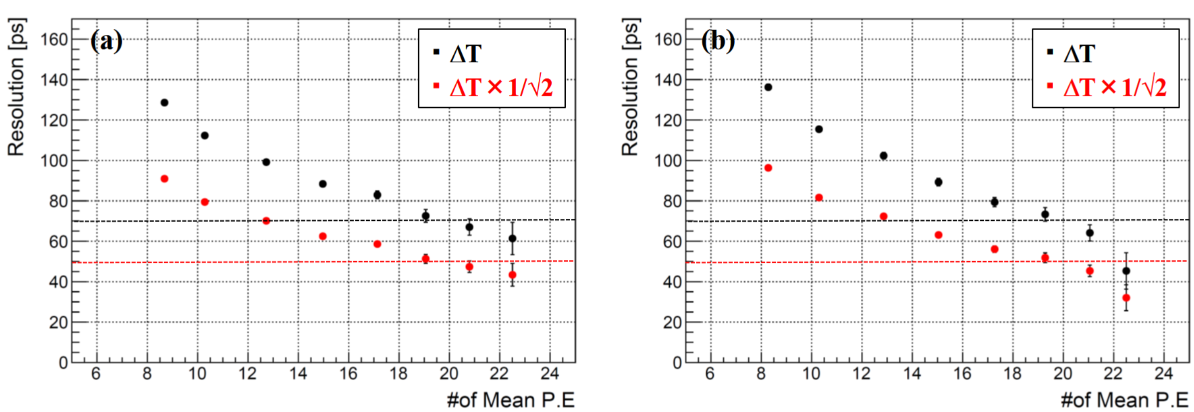

Figure 4: Time resolutions by selecting number of p.e.. (a) and (b) show the resolutions without and with SBD, respectively. Black and red points show the measured and estimated (divided by $\sqrt{2}$ of measured values) time resolutions, respectively. Time resolution of 70 ps and 50 ps are indicated by black and red dashed lines, respectively.

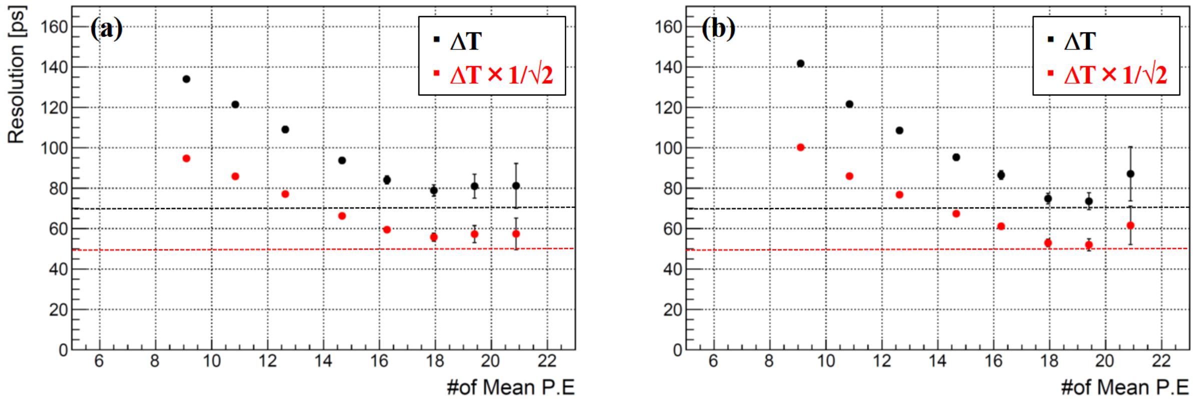

Figure 5: Time resolutions by selecting number of p.e.. (a) and (b) show the resolutions by correcting the time-walk by information of the pulse height with filtering by SBD and the signal width with both filtering by SBD and the integration, respectively. Black and red points show the measured and estimated (divided by $\sqrt{2}$ of measured values) time resolutions, respectively. Time resolution of 70 ps and 50 ps are indicated by black and red dashed lines, respectively.

4 Time-over-Threshold method

Because the width of the signal saturates and lose linearity with the pulse height information, Time-over-Threshold method didn't work by just using a raw signal from the MPPC amplifier. In addition, the small pulses following the main pulse which is caused by the ringing of the signal pulse disturb a measurement of the trailing edge timing. For overcoming those effects on the signal from the MPPC amplifier, we found that it is essential for both filtering by SBD and integration of the output signal with a small time constant. SBD which suppresses the small pulses following the main pulse by the ringing makes the measurement of the trailing edge timing better. Then, by integrating the signal with a small time constant, the signal width can have the information of the pulse height. For this measurement. we used a simple integration circuit (just RC integration circuit) with a time constant of 2.4 ns by a resistance and a capacitance of 51 Ω and 47 pF, respectively. Finally, by combining both filtering by SBD and signal integration, we can extract the information of the pulse height from the signal width. Although the integrated signal has a longer tail of ∼15 ns than the raw signal of ∼15 ns, it is acceptable for the experimental condition of the E50 experiment.

The time resolutions were evaluated by the same method as of SBD. Figure 5(a) and (b) show the time resolutions after the time-walk correction by using the information of the pulse height with filtering by SBD and the signal width with both filtering by SBD and the integration, respectively. Data of all p.e. regions showed the same time resolution between both measurements. Therefore, we found that the Time-over-Threshold method was achieved by using SBD and the signal integration.

5 Summary and future prospects

We plan a charmed baryon spectroscopy experiment at the high-momentum beam line of the J-PARC hadron experimental facility. A high-intensity secondary beam of 30 MHz for the 2-second extraction is used in the experiment. We have developed a beam-timing detector comprised of an X-shaped acrylic Cherenkov radiator and MPPC. Although we have achieved the goal of the time resolution from the test experiment with a high-counting rate, we found that the small pulses following the main pulse caused by the ringing of the signal pulse deteriorated the time resolution. For solving the problem by the ringing effect, a Schottky Barrier Diode was used as a filter. By using SBD, we found that the ringing was suppressed and the time resolution was kept. The time-walk correction by the Time-over-Threshold method in which the signal width from both leading and trailing timings measured by TDC is necessary instead of ADC because a streaming DAQ system without a dead time is used in the experiment. We used both filtering by SBD and signal integration for obtaining pulse height information from the signal width. By combining the filtering by SBD and integration by a RC circuit with time constant of 2.4 ns, we achieved the same time resolution from the time-walk correction by the Time-over-Threshold method as of the pulse height information.

It is necessary for the further studies because the performance evaluations by SBD and the Time-over-Threshold method were performed by only a β ray from a ^{90}Sr source. The number of p.e which is strongly related to the time resolution was different from the actual experiment in which we measure the minimum ionization particles. Therefore, a test experiment with the same beam conditions is necessary. The test experiment with an enough particle energy was performed at the LEPS beam line in the SPring-8 facility. We tested the Cherenkov timing detector by using the filtering by SBD and the RC circuit. The data analysis are on-going and it will be reported in the next annual report. The final test experiment with a high-counting rate condition is also planned at the ELPH facility in Tohoku university. After finishing the high-rate experiment, we expect that the development of the Cherenkov timing detector will be completed.

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