Off-line correction for excessive constant-fraction-discriminator walk in neutron time-of-flight experiments

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Abstract

A method for reducing excessive constant-fraction-discriminator walk that utilizes experimental data in the off-line analysis stage is introduced. Excessive walk is defined here as any walk that leads to an overall timing resolution that is much greater than the intrinsic timing resolution of the detection system. The method is able to reduce the contribution to the overall timing resolution from the walk that is equal to or less than the intrinsic timing resolution of the detectors. Although the method is explained in the context of a neutron time-of-flight experiment, it is applicable to any data set that satisfies two conditions. (1) A measure of the signal amplitude for each event must be recorded on an event-by-event basis; and (2) There must be a distinguishable class of events present where the timing information is known a priori.

Introduction

Accelerator-based experiments that require precise timing information typically employ discriminators to provide that information. Upon receipt of an analog signal from a detector, the discriminator will generate a logic signal whose start time is dependent on some property of the input analog signal. For leading-edge discriminators, the output logic signal is triggered when the amplitude of the analog signal exceeds a threshold set by the user. Because the rise time from scintillator signals is independent of signal amplitude, however, the timing of the logic signal's trigger in a leading-edge discriminator will vary with the amplitude of the input signal. The variation of the output signal's timing with input signal's amplitude is commonly referred to as walk.

Reducing the amount of walk improves the overall timing resolution in an experiment, especially where there is a large dynamic range of signals into the discriminator. The walk in leading-edge discriminators can be reduced using methods that measure the walk prior to running an experiment [1-3]. In two cases [1,2] beam particles were used to produce a range of pulse heights, and the walk was then measured as a function of pulse height. In another case [3], ^{60}Co was used to produce a range of pulse heights, which were then used to measure the dependence of walk on pulse height. In all three cases, the dynamic range of pulse heights was on the order of 5:1. It was found that the walk varied with the inverse of the square root of the pulse height, although there was some slight variation in the exact functional form used to fit the walk data in each case. In addition to being dependent on pulse height, the walk is also a function of the discriminator threshold and the gain setting of the detector (such as the high voltage applied to a photomultiplier tube). As such, care must be taken during the walk "calibration" to use thresholds and gains that are close, if not identical, to the settings used in the actual experiment.

Another method for minimizing time walk is to use constant-fraction discriminators (CFDs) instead of leading-edge discriminators. CFDs are designed to provide a reliable timing signal from analog pulses that have the same rise time, with little variation of the timing on the amplitude of the input signal [4-6]. This property of CFDs is accomplished by triggering a timing signal at a specific fraction of the input signal, thus avoiding the threshold problem of leading-edge discriminators that leads to walk. The reported walk in most commercial NIM-module CFDs is on the order of 100 ps over an input-signal dynamic range of 100:1 [4,5]. Over a dynamic range of 1000:1, which most CFDs accept, the walk will be worse. In addition, the operation of CFDs usually requires the user to adjust the delay time and the DC level of the internally attenuated signal (walk adjust). Any improper adjustment by the user can worsen the walk, and as such care must be taken during the operation of the CFD to ensure that the timing resolution resulting from the CFD stays within the overall timing requirements of the experiment. Even if the user-adjustments are set to their optimum values, a large dynamic range of input signals may result in a walk that is too large to use for some timing experiments.

In this paper we present an off-line analysis technique that was used to correct data from a neutron time-of-flight experiment where CFD walk in one of the data channels initially rendered that data unusable. The method is similar to methods described above for leading-edge discriminators except here the method utilizes experimental data, not calibration data taken prior to running the experiment. One result of using experimental data is that the method here measures the walk over a larger dynamic range of pulse heights than those reported in refs. 1-3. In addition, using experimental data eliminates any uncertainty in the walk correction that may arise if settings used in the pre-experiment calibration are not identical to the settings used in the experiment. In many cases, the walk-adjust setting in CFDs is set during the initial stages of the experiment, making it impractical to know beforehand what settings to use in a pre-run calibration. In those instances, being able to use experimental data to "self-correct" excessive walk is a great advantage.

The success of the method relies on meeting two conditions: (1) A measure of the amplitude of the pulse from the scintillator is recorded on an event-by-event basis along with the timing information, and (2) There is a class of events in the data stream that has a wide dynamic range of signal amplitudes and has its timing information known a priori. Although the technique will be described in the context of a neutron time-of-flight experiment, any experiment that satisfies those two conditions should be able to apply this method.

Experimental Method and Results

A. Experiment Description

The data shown here come from an experiment conducted at the Heavy Ion Medical Accelerator in Chiba of the National Institute of Radiological Sciences in Chiba, Japan. The purpose of the experiment was to measure secondary-neutron production cross-sections using the time-of-flight method. A total of seven neutron detectors, each a 12.7-cm diameter by 12.7-cm long cylinder of liquid scintillator (NE-213), was used. One detector each was placed at 5°, 10°, 20°, 30°, 40°, 60° and 80° in the lab, with flight paths

3 to 5 meters from target center to the front face of the detectors. Directly in front of each neutron detector was a solid plastic scintillator (5-mm thick and 12.7cm-by-12.7-cm square) that was used to detect charged particles incident upon the neutron detector. A thin (0.1 mm or 0.5 mm) scintillator was placed 5 cm upstream from the target position to detect beam particles incident upon the target and to provide the stop signal in the time-of-flight measurement. A valid event was defined by a coincidence between a signal in any of the neutron detectors with a signal from the beam-scintillator. Each valid event generates a logic signal, called the "event coincidence gate", that is used to start acquisition processing. Data was recorded on an event-by-event basis, with the following information recorded for each valid event: (1) the magnitude of the signal from the beam scintillator, as measured by a charge-integrating analog-to-digital converter (QDC); the magnitudes of the (2) total and (3) slow components of the pulse from the neutron detector's photomultiplier tubes, as measured by a charge-to-amplitude converter (QDC); (4) the time difference between the signal from the beam scintillator and the event coincidence-gate, as measured with a time-to-digital converter (TDC); (5) the "self" time difference between the signal from neutron detector and the event coincidence-gate; and (6) the magnitude of the signal from the veto detector, as measured by a QDC. Additional details about the experiment may be found in Ref. 7.

B. Experimental data and evidence of problem due to CFD walk

The event coincidence-gate is used as the start in the TDC module, and a delayed signal from the beam scintillator is used to generate the stop signal. Figure 1 shows a TDC spectrum for the detector placed at 30°. The data comes from 600 MeV/nucleon Ne ions incident upon a 5 g/cm^2 target composed of C, H, Si, O, Mg, Ca and Fe. Charged-particle events have already been removed from the spectrum, so the only events present in Fig. 1 are gamma-ray and neutron events. Time increases from right to left in Fig. 1. Background events have not been subtracted from the spectrum. Each TDC channel is equal to 250 picoseconds.

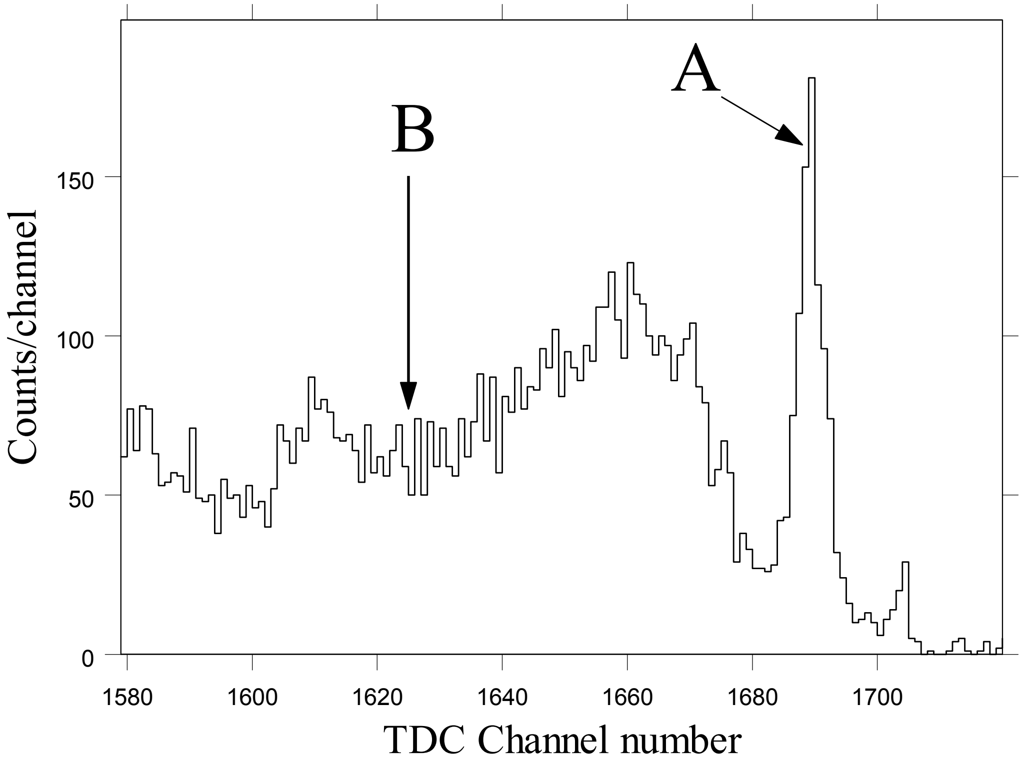

Figure 1. TDC spectrum for both neutrons and gamma rays detected at 30°. One histogram channel is equal to 250 ps. The peak labeled "A" comes from prompt gamma rays created in the target. Neutron events from the target are in the region to the left of the prompt gamma-ray peak, such as the event located at "B".

The peak labeled "A" in Fig. 1 comes from prompt gamma-ray events created by direct interactions between the beam and target nuclei. Valid neutron events are to the left of the prompt gamma-ray peak. Because all gamma rays travel at the speed of light regardless of their energy, they should show up at the same channel number in the TDC spectrum. Experimentally, there is some width in the observed prompt gamma-ray peak due to the finite timing resolution of the neutron detector and beam scintillator. In this particular experimental design, the location of the prompt gamma-ray peak is critical in determining the neutron time of flight between the target and the neutron detector. Considering the neutron event located in the TDC channel marked by "B" in Fig. 1, the neutron time of flight is the time difference between the prompt gamma-ray peak channel and channel "B", plus the time it takes for a gamma ray to go from the target to the detector.

Figure 2 shows the TDC spectrum for neutron and gamma-ray events in the detector at 20°. Unlike the TDC spectrum at 30° shown in Fig. 1, there is no evidence of a prompt gamma-ray peak at 20°, although there should be. Eliminating neutron events and background events from the spectrum shown in Fig. 2 does not help; no prompt gamma-ray peak is observed, even in those conditions. The lack of a prompt gamma-ray peak renders the data at 20° useless; there is no way to measure the neutron time of flight without knowing the peak location of prompt gamma-ray events.

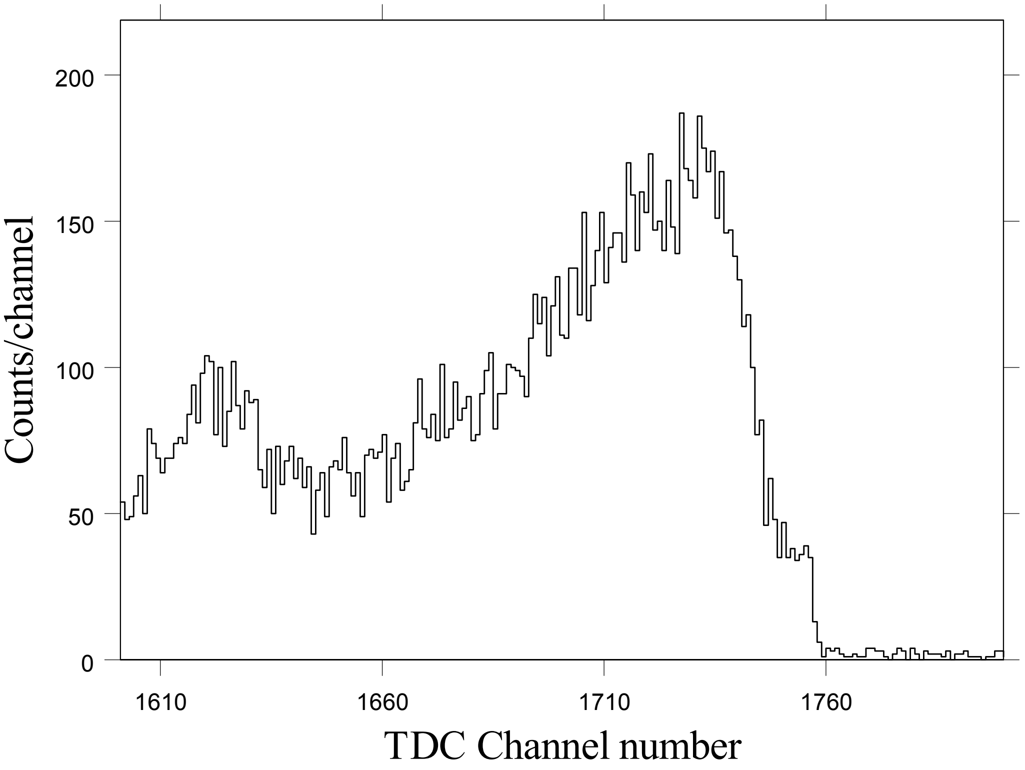

Figure 2. The TDC spectrum for neutron and gamma-ray events in the detector at 20° (compare with Fig. 1). Note the lack of a prompt gamma-ray peak due to poor timing resolution resulting from excessive CFD walk.

One possible reason for the lack of a prompt gamma-ray peak at 20° may be excessive CFD walk that results in poor timing resolution. A large dynamic range of input pulse amplitudes into the CFD or possible user error in setting the walk adjust on the CFD module (or a combination of the two) may lead to the problem observed in Fig. 2. There is an appreciable dynamic range of signal amplitudes into the CFD used for the 20° detector, as can be seen in Figure 3. Figure 3 shows the amount of charge in the pulse for gamma-ray events in the 20° detector as measured with a QDC. Although most of the events are contained in the first 100 QDC channels above threshold, the QDC values extend out to the maximum range available in the 11-bit QDC module. With the threshold set approximately at channel 60, this corresponds roughly to a signal dynamic range of 34:1, which is within the operating limits of the CFD.

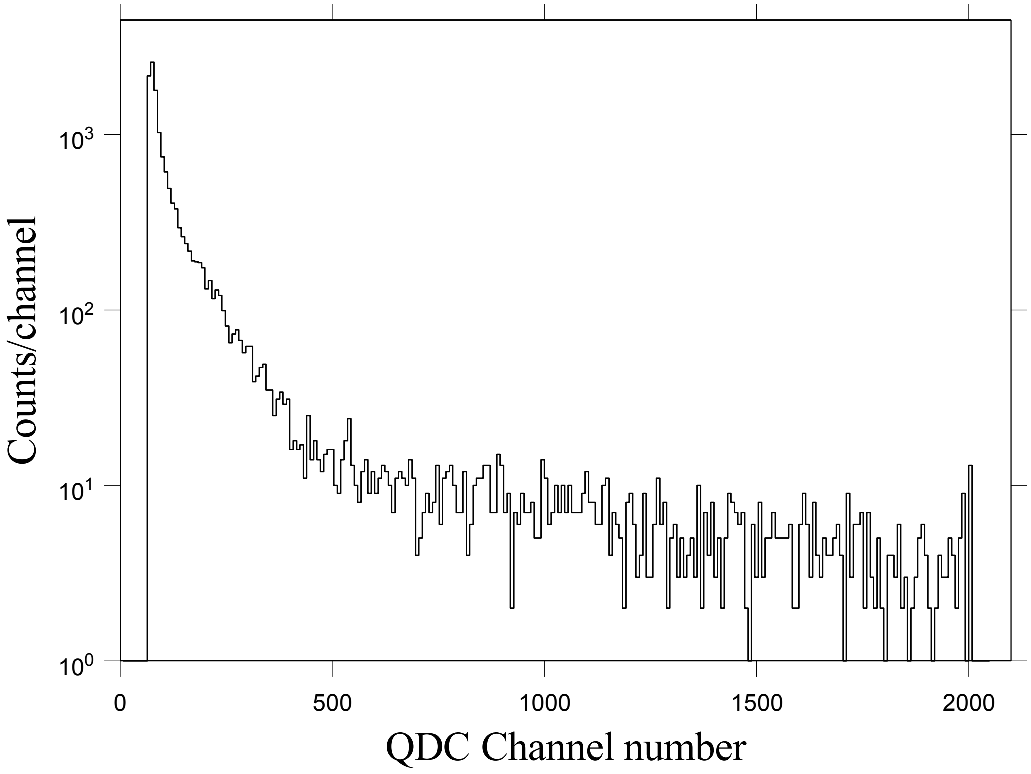

Figure 3. Charge-to-digital converter (QDC) values for gamma-ray events in the 20° detector.

If there is excessive CFD walk present in the spectrum in Fig. 2, and if that walk presents itself as a variation in timing with signal amplitude, then it may be possible to minimize the effects of CFD walk by selecting a narrow range of signal amplitudes. Figure 4 shows the same TDC spectrum that was shown in Fig. 2, except in this case the data has been selected with QDC values between channels 80 and 100. The presence of a prompt gamma-ray peak in Fig. 4 (labeled "A") not seen in Fig. 2 indicates that there may be a signal-amplitude dependent CFD walk.

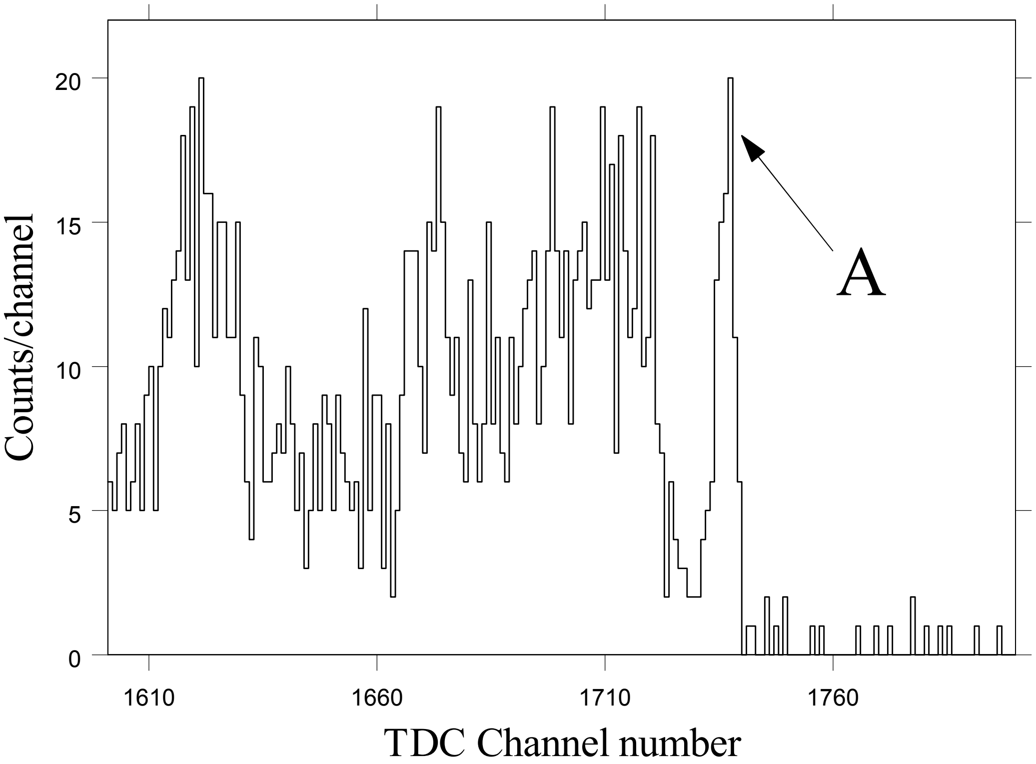

Figure 4. The TDC spectrum for neutron and gamma-ray events in the detector at 20° gated on a narrow range in signal amplitude (compare with Fig. 2). Note the appearance of a prompt gamma-ray peak ("A") that was missing in Fig. 2.

C. Method for correction of excessive CFD walk

The presence of prompt gamma rays in the TDC spectra provides a way to correct those spectra for excessive CFD walk. Although the prompt gamma rays are produced with a large range of energies and signal amplitudes, every prompt gamma-ray event should be in the same TDC channel, within detector timing resolution. If there is a significant amount of CDF walk, however, the position of the prompt gamma-ray peak may vary with signal amplitude. Thus, by measuring the position of the prompt gamma-ray peak (TDC channel number) as a function of the signal amplitude (QDC channel number), a measure of the amount of CFD walk present in a TDC spectrum can be obtained. Table I lists the measured prompt gamma-ray peak positions as a function of signal amplitude in the 20º detector. The first column shows the range of QDC values used to gate the data, and the second column shows the peak position in TDC channel number. Figure 5 shows a plot of that data, with the abscissa values equal to the midpoints of the ranges given in Table I. There is a clear dependence of the prompt gamma-ray peak position on the QDC value of the signal. As the signal amplitude increases, the peak position shifts to higher TDC values. From QDC channel number 90 to QDC channel number 1650, there is a shift in peak position of 21.5 TDC channels, which corresponds to a shift of 5.4 ns (250 picoseconds per TDC channel). That is a significant amount of CFD walk, especially considering the intrinsic timing resolution of the neutron detectors is on the order of 1 ns.

Table I. Values of the prompt gamma-ray peak position in the TDC spectrum as a function of the range of QDC values used to gate the data in producing the spectrum. QDC values are given in QDC channel number.

QDC range (channel number)	Peak position (TDC channel)
70-90	1732.8
80-100	1734.9
90-110	1736.4
100-120	1738.4
110-130	1738.9
120-140	1739.9
130-150	1740.8
140-160	1741.3
150-170	1742.7
160-200	1743.3
180-220	1743.7
200-240	1745.0
220-300	1745.5
260-340	1746.5
300-400	1747.7
350-450	1747.8
400-600	1749.2
500-1000	1750.2
750-1250	1752.7
1000-1500	1753.5
1250-1750	1754.3

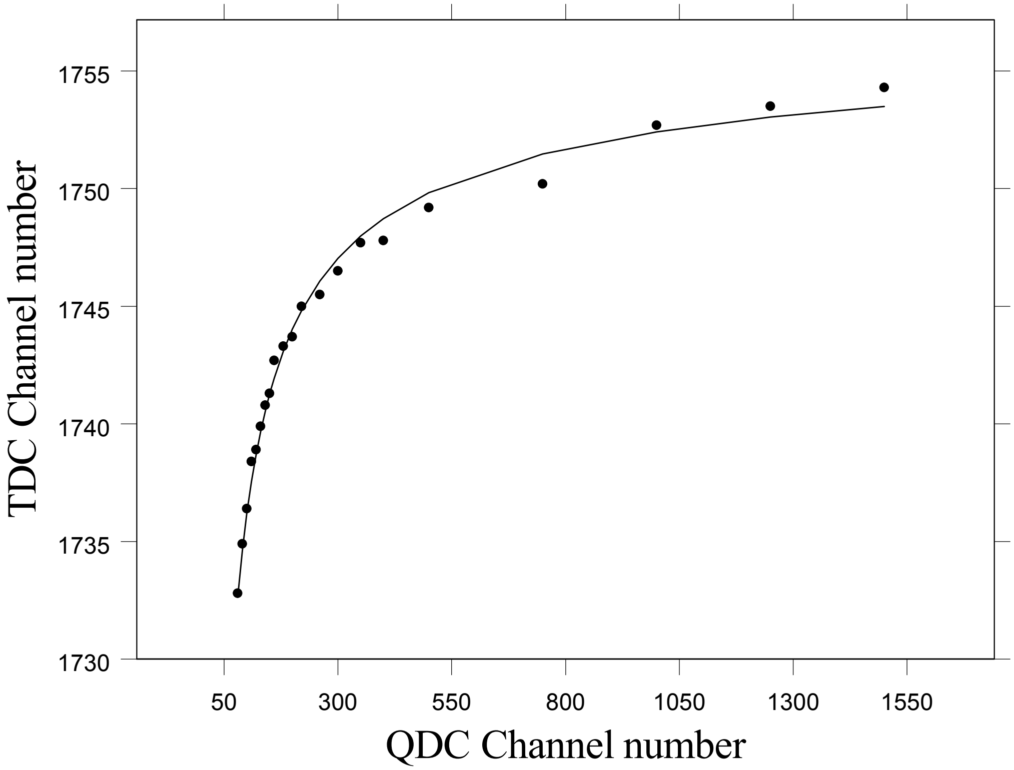

Figure 5. Plot of the data from Table I. The values used for QDC channel number are the midpoints of the QDC ranges reported in Table I. Each TDC channel is equal to 250 ps. The solid line is a fit to the data using Eqn. 1.

With the data shown in Table I and in Fig. 5, it is possible to correct the TDC data for CFD walk. One method is to shift an event's TDC value relative to an arbitrarily determined standard, based on its corresponding QDC value. For example, the TDC values for the data at 20° will be shifted such that prompt gamma-ray peak should be at channel 1740 (the choice of 1740 for the channel number is not important – it can be any channel number as long as the prompt gamma-ray peaks are shifted to that value). Using the information from Table I, any event with QDC values between channels 90 and 110 will add 3.6 channels (=1740 – 1736.4) to its TDC value. Any event with QDC values between channels 260 and 340 will add –6.5 channels (=1740-1746.5) to its corresponding TDC value. Alternatively, instead of using the raw data from Table I, that data can be fitted with a functional form, and that function can then be used to determine the amount of shift in TDC value based on the corresponding QDC value. The following function was used to fit the TDC peak shift data listed in Table I:

$$TDC = a_1 - a_2 \times \exp\left({a_3}\Big/{\sqrt{QDC}} \right), \tag{1}$$

where a_1, a_2, and a_3 are fit parameters, T_{peak} is TDC channel number of the prompt-gamma-ray peak, and Q is the corresponding QDC channel number. Note that eqn. 1 is slightly different in form than eqn. 3 of Ref. 1 and the equation in section 4.1 of Ref. 2, where they found the walk in leading-edge discriminators varied with the inverse of the square root of the pulse height. For the data in Table I, values of 1782.23, 24.3937, and 6.3472 were used for a_1, a_2, and a_3, respectively.

Figure 6 shows the corrected TDC spectrum at 20° for the entire range of signal amplitudes. Comparing with Fig. 2, which is for the same data set as in Fig. 6 except for the lack of a correction in TDC value, a prompt gamma-ray peak is now evident after applying the correction for CFD walk. The FWHM of the prompt gamma-ray peak in Fig. 6 is 1.3 ns. Given that the intrinsic timing resolution of the neutron detector is about 1.0 ns, the FWHM value indicates that the CFD walk over the entire dynamic range of signals has been reduced to about 0.83 ns, assuming that the walk and the intrinsic timing resolution can be added in quadrature to yield the FWHM value. Most importantly, neutron time-of-flight information can now be extracted from the data at 20°, which was not possible before the correction.

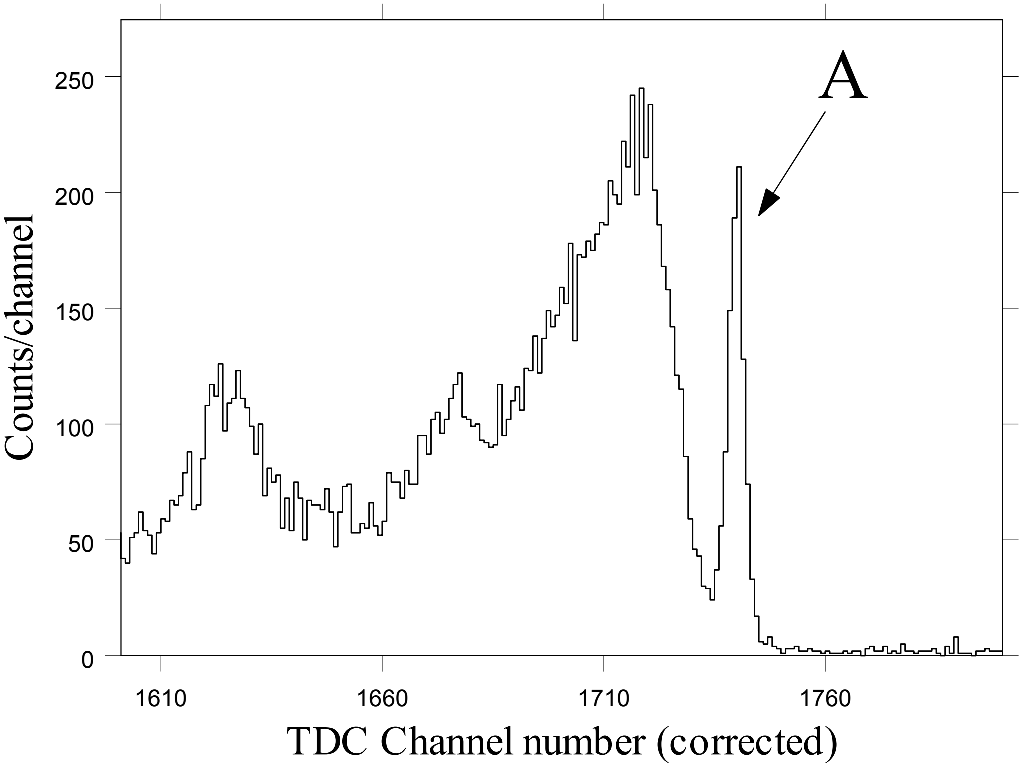

Figure 6. The TDC spectrum for neutron and gamma-ray events in the 20° detector, after applying a correction for CFD walk to the TDC value based on its corresponding QDC value. Figure 2 shows the same data before correction. Note the presence of a prompt gamma-ray peak ("A") not seen in Fig. 2.

The degree to which the magnitude of the walk can be reduced is limited by the intrinsic timing resolution of the detection system. In this case, although the walk can be limited to 100 picoseconds in theory, the walk most likely cannot be reduced lower than a few hundred picoseconds because the ability to locate the prompt gamma-ray peak position is limited by the 1-nanosecond timing resolution of the neutron detectors. However, the walk can be reduced to a level where its contribution to the overall timing resolution is equal to or less than the intrinsic timing resolution of the detectors.

Summary

Constant Fraction Discriminators (CFDs) are designed to provide a timing signal with a minimal amount of variation in the timing with signal amplitude. The amount of variation in timing is commonly referred to as "walk." Ideally, the timing of a signal should be independent of signal amplitude; however, there is some walk present in CFDs, especially when a large range of signal amplitudes is used as input. User error in setting the CFD time delay and walk adjust can worsen the problem of CFD walk. An off-line analysis technique has been presented that can correct timing information that is distorted by CFD walk. It is similar in nature to corrections applied to leading-edge-discriminator walk, with the main difference being that experimental data is used here instead of beam calibration data. As a result, discriminator walk is measured over a large dynamic range of signal amplitudes under the same experimental settings used to acquire the data. In order for the method to be applied, two conditions must be met: (1) A measure of the signal amplitude for each event must be recorded on an event-by-event basis, and (2) There must be a distinguishable class of events present where the timing information is known a priori. These two conditions are readily met in neutron time-of-flight measurements where gamma-ray events are also recorded in the data stream. By applying the technique to data presented here, the problems in that data due to CFD walk were corrected to the point where the contribution to the overall timing resolution from walk was less than the intrinsic timing resolution of the detector.

Acknowledgements

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