Three-detector setup for PAL spectrometer based on DRS4 waveform digitizing board (Postprint)

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Abstract

A digital three-detector positron lifetime spectrometer was developed. It consists of a DRS4 waveform digitizing board and three LaBr3 scintillation detectors coupled to XP2020Q photomultiplier tubes. DRS4 waveform digitizing allows data sampling at up to 5 GSPS with high amplitude resolution, with good time scale linearity and stability. In the triple-coincidence, the new system could reach a 195 ps time resolution, which is better than the conventional analog apparatus with the same detectors. This spectrometer can be applied to the other scintillation timing measurements with picoseconds accuracy.

Full Text

Preamble

Three-Detector Setup for PAL Spectrometer Based on DRS4 Waveform Digitizing Board

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Abstract
A digital three-detector positron lifetime spectrometer was developed, consisting of a DRS4 waveform digitizing board and three $LaBr_3$ scintillation detectors coupled to XP2020Q photomultiplier tubes. DRS4 waveform digitizing enables data sampling at up to 5 GSPS with high amplitude resolution, excellent time scale linearity, and stability. In triple-coincidence mode, the new system achieves a time resolution of 195 ps, surpassing conventional analog apparatus using the same detectors. This spectrometer can be applied to other scintillation timing measurements requiring picosecond accuracy.

Keywords: Digital lifetime spectrometer, Timing, Triple-coincidence, Waveform sampling, DRS4 chip
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Introduction

Positron annihilation lifetime (PAL) spectroscopy is a valuable technique for studying defects in condensed matter [1-3], where time resolution represents a critical performance parameter. Significant efforts have been devoted to improving time resolution through advances in scintillator materials, data acquisition systems, and timing technologies [4-7]. A conventional PAL spectrometer typically comprises a pair of scintillation detectors, two constant fraction timing discriminators (CFD), a time-to-amplitude converter (TAC), and a multi-channel analyzer (MCA), achieving a time resolution of approximately 200 ps or slightly better [8]. However, the performance of conventional PAL spectrometers is fundamentally limited by analog electronic components.

With the rapid development of electronics and digital signal processing technology [9, 10], researchers have employed fast digitizers or digital oscilloscopes to construct a new class of instruments known as digital positron lifetime spectrometers (DPLS) [11-14], which offer superior time resolution and simplified architecture. The DRS4 chip, developed at the Paul Scherrer Institute in Switzerland [15, 16], is a switched capacitor array (SCA) capable of sampling nine differential input channels at rates of 0.7-5 GSPS. Its high channel density, 950 MHz analog bandwidth, and low noise of 0.35 mV make it ideally suited for high-precision waveform digitization. To simplify integration of the DRS4 chip into custom electronics, an evaluation board has been designed at the University of Science and Technology of China (USTC), functionally equivalent to a 4-channel 5 GSPS digital oscilloscope.

This paper presents the design and testing of a simplified DPLS based on the DRS4 evaluation board.

Experimental and Analysis Methods

The detectors consisted of $LaBr_3$ cylindrical crystals wrapped with Teflon tape, coupled to XP2020Q photomultiplier tubes (PMTs) and encapsulated in duralumin housings. The start detector measured Φ36 mm × 20 mm, while the two stop detectors measured 36 mm × 15 mm (configured for 1275 keV and 511 keV γ-rays, respectively). The PMTs were biased at -1.8 kV, substantially lower than the maximum rated voltage of -3 kV. A ^{22}Na source with an activity of approximately 93 kBq ($ $25 µCi) was employed [FIGURE:1].

The start and stop detectors were positioned at a 90° angle, while the two stop detectors were placed opposite each other at 180°. Compared with a two-detector system, the three-detector configuration incorporates a double-stop system that enables detection of the flight time of paired annihilation photons traveling in opposite directions, thereby obtaining an accurate "stop time" (averaged from the two stop detectors). This improvement yields lifetime spectra that more closely reflect physical reality and provides better time resolution than two-detector systems. A lead shielding plate was placed between the start and stop detectors to reduce Compton scattering effects among the three detectors and to absorb backscattered γ-rays. The count rate for the given source activity depends on the measurement geometry; in this experiment, the actual count rate reached 25 s^{-1}.

As shown in [FIGURE:1], the DPLS comprises three detectors and a DRS4 evaluation board. The anode pulses from the PMTs are fed into channels 2, 3, and 4 of the DRS4 evaluation board. Input signals are converted to discrete waveform data, which are stored in the board' s memory after triggering conditions are satisfied, then transferred to a PC via USB 2.0 bus at a maximum rate of approximately 20 MB/s. The waveform data are subsequently analyzed to construct positron lifetime spectra. The DRS4 evaluation board operates in fulfilled triggering mode on channels 2, 3, and 4, acquiring signals only when voltages exceed the threshold amplitude simultaneously on all three channels. Pulses from the two stop detectors are delayed by 4-8 ns using delay cables. Several digital waveform processing methods are employed to construct the positron lifetime spectrum by histogramming the time interval between start and stop detector pulses following pulse discrimination.

A. Pulse Discrimination Methods

The first step in data processing involves discriminating eligible waveform pulses and removing deformed or distorted waveforms. Several pulse discrimination algorithms are implemented to select suitable pulses for timing analysis.

1. Methods to Eliminate Bad Waveforms Distorted waveforms (where multiple waveforms accumulate in a single channel) are eliminated using pulse shape discrimination algorithms based on peak searching and baseline discrimination methods. The peak searching algorithm identifies the peak position and amplitude in the waveform, while the baseline discrimination method selects an appropriate baseline level. These two approaches effectively filter suitable waveforms.

2. Pulse Area Discriminator Methods In many applications, the total energy of a measured pulse is proportional to the sum of all scintillation photons produced, and the pulse area between the digitized waveform and baseline corresponds to the γ-ray energy. The pulse area is calculated by summing the amplitude of each sample over the entire waveform range. The energy spectrum of the ^{22}Na source measured by the digital PAL spectrometer is shown in FIGURE:2, exhibiting energy resolutions of 3.7% at 0.511 MeV and 3.2% at 1.275 MeV. For comparison, FIGURE:2 shows the energy spectrum obtained using an analog system with identical detectors, yielding energy resolutions of 5.85% at 0.511 MeV and 4.73% at 1.275 MeV. The digital system demonstrates superior performance, and the pulse area discriminator is used to select pulse pairs corresponding to 1.275 MeV and 0.511 MeV events.

B. Digital Constant Fraction Timing Analysis Methods

After confirming that anode pulses fall within predetermined energy (pulse area) windows, timing analysis extracts temporal information from the digitized pulse groups. The standard timing algorithm for scintillation detectors is constant fraction timing, which analyzes numerous leading-edge timing measurements to identify the moment representing minimum time jitter when the pulse crosses a specific constant fraction level f_{cf} of its full amplitude. The optimum fraction is characteristic of the specific detectors, scintillators, and PMT types employed.

A Gaussian function provides an excellent description of a pulse’ s leading edge [11, 18]. Since Gaussian fitting involves non-linear interpolation, a logarithmic transformation is applied to the waveform amplitudes to obtain new waveform data, which are then fitted with second-order polynomial interpolation as an alternative to direct Gaussian fitting. The fitting range comprises 40 samples on the leading edge of the pulses. The dependence of time resolution on both fitting range and timing fraction is investigated by varying the fraction for one detector while keeping it constant for the other. The optimum constant fraction is approximately 30% for both detectors [11, 17].

C. Building Positron Annihilation Lifetime Spectra

Triple-coincidence measurements require a reliable double-stop system. The DRS4 evaluation board’s performance was tested using two signals with identical pulse parameters but different time delays from a signal generator. Subsequently, signals from the two stop detectors were used to test the double-stop system.

shows a typical waveform of two signals from the signal generator recorded by the DRS4 evaluation board. With the sampling rate set to 5.12 GS/s, the two identical-parameter signals exhibited a time delay of 10 ns, with minimum and maximum measured delays of 9.917 ns and 9.947 ns, respectively, and a mean standard deviation of 2.5 ps. The system demonstrates excellent timing synchronization and is suitable for triple-coincidence PALS applications.

The same delay cable was used for both stop detectors. The two stop signals

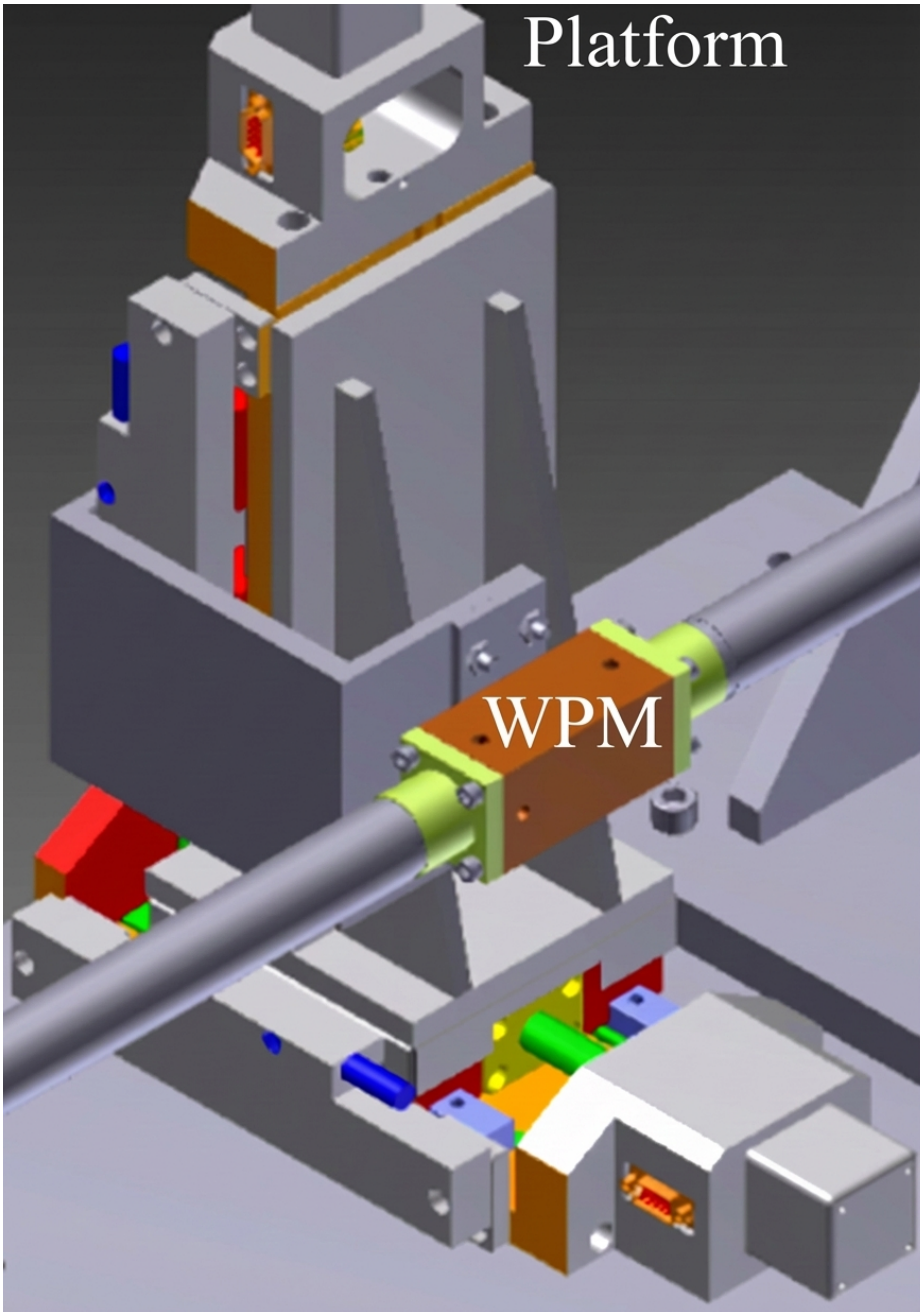
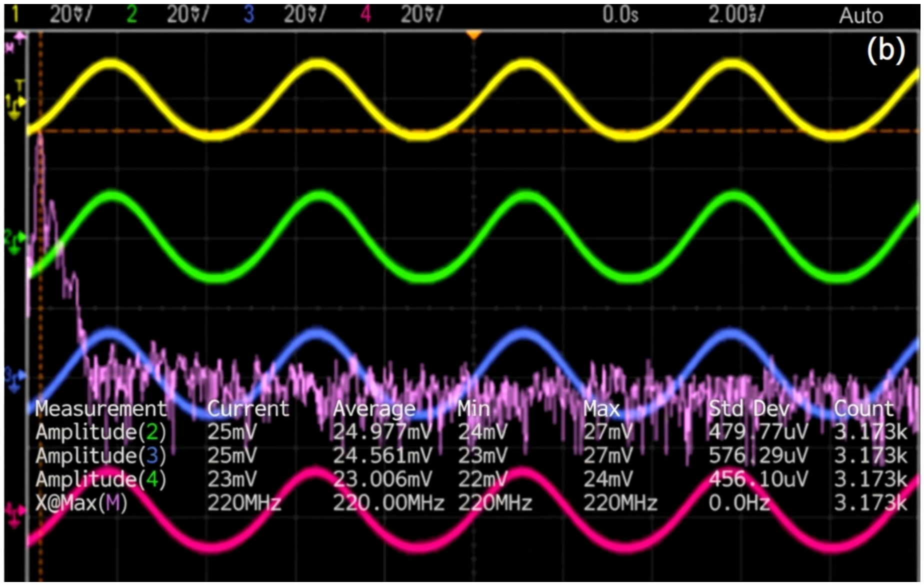


Figure 1: Figure 3

recorded by the DRS4 are shown in [FIGURE:4], with a sampling rate of 5.12 GS/s. The black trace represents the signal from PMT1 and the red trace from PMT2. The two signals exhibit identical rise times and time delays, demonstrating excellent signal synchronization.

After γ-ray energy selection via pulse amplitude discrimination, the frequency distribution of Δt is calculated as $\Delta t = t_{\text{stop}} - t_{\text{start}}$, where $t_{\text{stop}} = [t_{\text{CF}}(\text{PMT2}, 0.511\,\text{MeV}) + t_{\text{CF}}(\text{PMT3}, 0.511\,\text{MeV})]/2$ and $t_{\text{start}} = t_{\text{CF}}(\text{PMT1}, 1.28\,\text{MeV})$. Additionally, only events satisfying $|t_{\text{CF}}(\text{PMT2}, 0.511\,\text{MeV}) - t_{\text{CF}}(\text{PMT3}, 0.511\,\text{MeV})| < 450\,\text{ps}$ are accepted. The PAL spectra are constructed from the frequency distribution of Δt.



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Measurement   Current   Average     Min      Max      Std Dev    Count
Amplitude(2)  25mV      24.977mV    24mV     27mV     479.77uV   3.173k
Amplitude(3)  25mV      24.561mV    23mV     27mV     576.29uV   3.173k
Amplitude(4)  23mV      23.006mV    22mV     24mV     456.10uV   3.173k
X@Max(M)      220MHz    220.00MHz   220MHz   220MHz   0.0Hz      3.173k
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Figure 2: Figure 5

shows two PAL spectra collected using single-stop and double-stop systems, each containing approximately 1 million counts. Only about 500 channels around the spectral peak are presented for comparison.

Results and Discussion

PAL spectra for bulk silicon were measured to evaluate spectrometer performance. Analysis of the PAL spectra reveals that τ_1 ((220.0 ± 2.8) ps) corresponds to free positrons in the sample, consistent with Ref. [19], while τ_2 ((495.0 ± 8.7) ps) and τ_3 ((2235.0 ± 46.3) ps) originate from source components. The double-stop system achieves a time resolution of 192 ps (FWHM), superior to the single-stop system, which employs a face-to-face detector geometry with a symmetry axis passing through both detectors. The background of the double-stop system is also lower than that of the single-stop configuration.

The dependence of time resolution on incident γ-ray energy was measured over 11 days using ^{60}Co (1.33 MeV and 1.17 MeV) with 2.6×10^4 counts. The time resolution for ^{60}Co cascade radiations was (175.0 ± 1.4) ps. The energy window was set to $1.0\,\mathrm{MeV} < E < 1.5\,\mathrm{MeV}$, and the time spectrum is shown in [FIGURE:6]. Improved time resolution can be obtained with narrower energy window settings at the cost of reduced counting rate.

lists time resolutions for different conditions of double-stop PAL, single-stop PAL, and ^{60}Co measurements.

Conclusion

A digital positron annihilation lifetime spectrometer comprising three $LaBr_3$ scintillation detectors and a DRS4 evaluation board has been developed. For ^{60}Co spectra, the DPLS with double-stop achieves a time resolution of approximately 175 ps. With its excellent performance and stability, the DPLS offers significant advantages over conventional positron annihilation spectrometers.

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