Research on High-Efficiency Measurement Method for Positron Annihilation Based on DRS4 Evaluation Board

Authors: He Zirui, Kuang Peng, Yu Xiaotian, Zhang Hongqiang, Wang Yingjie, Zhang Peng, Liu Fuyan, Wang Baoyi, Shan Jian, Cao Xingzhong

Date: 2025-02-18T00:00:00+00:00

Abstract

The high-performance digital waveform sampling device based on the DRS4 chip with switched-capacitor matrix, leveraging its characteristics of high sampling rate, high integration, and low power consumption, has become the preferred choice for large-scale, multi-channel time measurement systems, and also demonstrates potential application prospects in multi-channel positron annihilation lifetime detection. This paper addresses the main cause of low data processing efficiency in the positron annihilation lifetime measurement system with dual detector channels based on the DRS4 evaluation board, employing a coincidence selection method to precisely identify valid events in the sampling circuit, ensuring efficient utilization of core resources in the circuit to achieve high-efficiency positron annihilation measurement based on the DRS4 evaluation board. Through measurement, the coincidence counting rate of the positron annihilation lifetime measurement system based on the DRS4 evaluation board under the coincidence selection method can reach the processing limit of the DRS4 evaluation board.

Full Text

Efficient Measurement Methods for Positron Annihilation Based on the DRS4 Evaluation Board

Zirui He[1,2], Peng Kuang[2,3], Xiaotian Yu[2,3], Hongqiang Zhang[2,3], Yingjie Wang[2,3], Peng Zhang[2,3], Fuyan Liu[2,3], Baoyi Wang[2,3], Jian Shan[1], Xingzhong Cao[2,3]

[1] School of Electrical Engineering, University of South China, Hengyang 421001, China
[2] Institute of High Energy Physics, Chinese Academy of Sciences, Beijing 100049,

China
[3] Center for High Energy Physics, Henan Academy of Sciences, Zhengzhou 450046, China

Abstract

[**Background**]**:** The high-performance digital waveform sampling device based on the switched-capacitor matrix DRS4 chip has become the preferred choice for large-scale, multi-channel time measurement systems due to its high sampling rate, high integration, and low power consumption, showing promising application prospects in multi-channel positron annihilation lifetime detection.
[**Purpose**]**:** This paper constructs a positron annihilation measurement system with dual detector channels based on the DRS4 evaluation board, systematically analyzes the main factors leading to its low data processing efficiency through experimental studies, and implements improvements to the measurement system.
[**Methods**]**:** To address the system' s low data processing efficiency, an effective event pre-coincidence selection method was adopted in the experiment. By precisely filtering valid events in the DRS4 acquisition circuit, this method ensures efficient utilization of core signal processing resources within the circuit.
[**Results**]**:** Measurement results show that the DRS4 positron annihilation lifetime measurement system based on the new triggering method can reach the processing limit of the DRS4 evaluation board, achieving a coincidence counting rate of 376 cps (counts per second).
[**Conclusion**]**:** By employing the method of valid event coincidence selection, the performance of the positron annihilation lifetime measurement system based on the DRS4 evaluation board has been improved, providing a solution for trigger logic selection in multi-channel positron annihilation lifetime measurement systems.

Keywords: Positron annihilation; DRS4; Coincidence selection; Coincidence count rate

1. Experimental Methods

Positron annihilation lifetime measurement is a non-destructive characterization technique for investigating the internal microstructure of materials, capable of identifying characteristic information such as defect types, sizes, and relative concentrations [1,2]. As one of the most typical nuclear physics time measurement methods, positron lifetime measurement has two critical performance parameters: coincidence count rate and time resolution, which determine the detection efficiency and measurement precision of the spectrometer [3]. Traditional positron annihilation lifetime spectrometers are relatively mature, typically consisting of scintillator detectors, constant-fraction discriminators, time-to-amplitude converters, and multi-channel analyzers as standard modular nuclear electronics systems. Their time resolution and detection efficiency are relatively fixed at approximately 200 ps and 300 cps, respectively [4]. In recent years, with the development of digital sampling and processing technologies, constructing positron lifetime spectrometers using lower-cost and lower-power digital electronics has become a trend, achieving performance parameters comparable to analog electronics systems in terms of time resolution [5,6,7]. Particularly in novel positron annihilation measurement experiments with large channel counts, digital electronics with high integration characteristics can demonstrate greater application potential, such as in high-brightness positron beam burst detection [8].

The DRS4 chip, based on switched-capacitor array waveform sampling, is a high-performance digital sampling device developed by PSI in recent years. With a maximum sampling rate of 5 GS/s and analog input bandwidth of 950 MHz, this chip has been widely applied in positron annihilation lifetime spectroscopy experiments due to its advantages of high sampling rate, low cost, and flexible input channel integration [9]. For example, the University of Science and Technology of China built a positron annihilation lifetime measurement system based on the DRS4 evaluation board, achieving a system time resolution of 206 ps after optimizing digital waveform processing and timing analysis methods, which meets the basic requirements for positron annihilation measurements [10]. The Slovak University of Technology developed the QtPALS software for positron annihilation lifetime measurement based on the DRS4 evaluation board, successfully applying it in both dual-channel and triple-coincidence positron annihilation lifetime measurement scenarios [11,12]. The University of Würzburg in Germany developed the DDRS4PALS software for positron annihilation lifetime spectrum data acquisition and simulation based on the DRS4 evaluation board, improving time measurement accuracy and lifetime spectrum signal-to-noise ratio through research on digital pulse correction and filtering techniques, and has applied it in studies of defects and amorphous structures in materials [13].

Although digital lifetime spectrometers based on the DRS4 chip have achieved relatively high time resolution, their detection efficiency remains low and has not yet reached the level of conventional analog electronics spectrometer systems under equivalent detection conditions. In preliminary experiments, we constructed a positron lifetime measurement system by directly feeding the start and stop detector signals from positron annihilation measurements into the DRS4 evaluation board. Experimental results showed that for a 14.4 Ci positron source, the system' s coincidence counting rate was only 55 cps (counts per second) at maximum, far below the counting rate of traditional positron annihilation lifetime spectrometers (~300 cps) under the same conditions. The research team at the University of Science and Technology of China obtained similar results with their DRS4 evaluation board positron lifetime measurement system, where the coincidence counting rate did not increase with source intensity, reaching a maximum of only 75 cps [10]. Direct application of digital waveform sampling technology to positron annihilation measurement suffers from low measurement efficiency, primarily caused by invalid event-triggered sampling. On one hand, invalid events occupy sampling time during the sampling process, preventing the system from sampling valid events during these periods. On the other hand, the large proportion of invalid events and limited processing capacity during nuclear signal processing results in fewer valid events being acquired per unit time, directly affecting the system' s capture efficiency for valid events. Several international research teams have also recognized the low efficiency problem of digital waveform sampling technology in positron annihilation measurements and proposed corresponding solutions. For improving measurement efficiency, the predominant approach internationally is to use pre-selection methods. For example, the research team at the Slovak University of Technology built a positron annihilation lifetime measurement system based on the DRS4 evaluation board using pre-selection methods [11]. This system employs a pre-selection approach where the DRS4 chip is triggered to sample only when signals in both channels exceed preset energy thresholds. Under this pre-selection mode, the measurement system' s efficiency improved, achieving a coincidence counting rate of 200 cps under a source intensity of 27 Ci. However, the current pre-selection method only performs coarse signal filtering, and invalid events still trigger DRS4 sampling, preventing the system from achieving optimal measurement efficiency. Although the DRS4 chip' s triggering method has been improved, the most reasonable signal filtering scheme has not yet been systematically studied to maximize the measurement system' s efficiency.

To address these issues, this paper systematically investigates the DRS4 chip' s triggering scheme by studying the relationship between effective triggering and coincidence timing signals, thereby achieving high-efficiency positron annihilation measurement based on the DRS4 evaluation board.

1.1 System Configuration

We constructed a positron measurement system based on DRS4, consisting of two BaF_2 detectors (BaF_2 crystal dimensions: $\Phi 30$ mm $\times$ 20 mm, photomultiplier tube model: Hamamatsu R3377), a high-voltage power supply, a DRS4 evaluation board, and a host computer. The anode signals from detectors A and B are fed into channels Ch1 and Ch2 of the DRS4 evaluation board, respectively. After processing by the DRS4 evaluation board, the signals are converted into binary data and transmitted to the host computer via a data cable. In the host computer software, the signals from the two detectors undergo algorithmic reconstruction and amplitude analysis. After identifying the start signal (1.28 MeV γ photon) and stop signal (0.511 MeV γ photon), constant-fraction timing is performed and the time difference between signals is calculated. Finally, after collecting and analyzing sufficient time difference data, the positron annihilation lifetime spectrum of the measured sample is obtained.

Due to limitations in the trigger logic design of the DRS4 evaluation board, invalid events frequently trigger sampling during the acquisition process, resulting in large amounts of invalid data. To ensure efficient transmission of core signals, this paper implements a coincidence selection circuit before signals are fed into the DRS4 evaluation board. By precisely filtering valid events in the DRS4 evaluation board' s acquisition circuit, this approach ensures efficient utilization of core signal processing resources, as shown in Figure 1 [Figure 1: see original paper]. The coincidence selection circuit consists of a constant-fraction discriminator (CFDD) and a coincidence unit. The analog module constant-fraction discriminator (CFDD) discriminates the stop and start signals separately. The constant-fraction discriminator generates two signals for start or stop signals falling within the correct energy window. When the two signals fall within a 100 ns coincidence window, the coincidence unit generates a trigger signal. Once the DRS4 evaluation board receives this trigger signal, it begins sampling the anode signals.

To simplify the sampling circuit, we modified the internal FPGA program of the DRS4 evaluation board, implementing coincidence selection within the board to replace the external coincidence selection circuit. The schematic diagram is shown in Figure 2 [Figure 2: see original paper]. By modifying the FPGA internal program of the DRS4 evaluation board, the discrimination circuit in the board discriminates the start or stop signals, triggering sampling for signals where both channels simultaneously exceed the start signal trigger threshold and the stop signal trigger threshold.

This paper investigates the cause of low counting rates in the positron annihilation lifetime measurement system based on the DRS4 evaluation board, focusing on the triggering method. Improvements were made from both external trigger circuits and internal trigger programs, constructing a positron annihilation lifetime measurement system based on the DRS4 evaluation board using coincidence selection methods. By precisely filtering valid events in the DRS4 sampling circuit, high-efficiency positron annihilation measurement based on the DRS4 evaluation board is achieved.

1.2 System Performance Evaluation

The measurement system was evaluated using a signal generator to produce two pulse signals with a specific delay. The DRS4 evaluation board' s signal acquisition process consists of two sequential stages: sampling and digital readout. The period during which the DRS4 stops sampling and reads out the sampling unit to the ADC for digitization is called dead time. During this period, the next signal cannot trigger DRS4 sampling, causing signal loss and making the signal frequency from the generator inconsistent with the system' s measured count rate. As shown in Figure 3 [Figure 3: see original paper], when the signal frequency is between 2 Hz and 500 Hz, signals can effectively trigger DRS4 sampling, resulting in a linear relationship between signal frequency and system count rate. As the signal frequency increases from 500 Hz to 5000 Hz, the system count rate exhibits a non-linear relationship with signal frequency due to some signals being unable to trigger DRS4 sampling during dead time and limitations in the DRS4 evaluation board' s signal processing capability. The system count rate saturates at 510 cps, which is consistent with the maximum measurement speed limitation of the DRS4 evaluation board caused by USB 2.0 data transmission restrictions mentioned in the literature [9]. The results demonstrate that the system count rate is limited by the DRS4 evaluation board' s signal processing capability, with a maximum achievable count rate of 510 cps.

The experiment employed a pair of standard pure iron (Fe) samples and a ^{22}Na source in a "sandwich" structure placed between two detectors. The system' s coincidence counting rate was measured as the number of positron annihilation events per unit time to evaluate the effect of coincidence selection on the processing performance of the signal time measurement system, with the schematic diagram shown in Figure 1. Figure 4 [Figure 4: see original paper] presents the measurement results of the coincidence selection impact. It can be observed that for the system without coincidence selection, the coincidence counting rate reaches its limit and stabilizes at approximately 50 cps after the ^{22}Na source intensity increases to 5.21 Ci. In contrast, the coincidence counting rate of the system with coincidence selection increases significantly with source intensity, reaching a maximum of 376 cps at a source intensity of 24 Ci. Additionally, the gap in coincidence counting rates between the two systems becomes increasingly pronounced as source intensity grows. Figure 5 [Figure 5: see original paper] shows the growth ratio after adding coincidence selection at the same source intensity (data points represent the growth ratio with/without coincidence selection, dashed line indicates the growth trend). As shown in Figure 5, the growth ratio of the system' s coincidence counting rate after adding coincidence selection increases rapidly as source intensity grows from 0.41 Ci to 10.9 Ci, eventually stabilizing at approximately 7.5 times after the source intensity exceeds 10.9 Ci.

In the system without coincidence selection, invalid events trigger DRS4 evaluation board sampling during the acquisition process, resulting in data containing large amounts of invalid events. After screening for valid events in the host computer, only a small number of valid events can be retained. Therefore, the coincidence counting rate of the system without coincidence selection is affected by invalid event mis-triggering, increasing with source intensity up to a maximum at 5.21 Ci, after which it stabilizes. For the system employing coincidence selection, precise discrimination of valid events before triggering sampling can effectively avoid acquisition of invalid events, improving the DRS4 evaluation board' s processing performance for valid events and enabling high-efficiency data acquisition. Due to limitations in the DRS4 evaluation board' s data transmission circuit design, which restricts data transmission speed, the amount of acquired data can only reach a certain level without achieving higher data transfer rates. Unlike signals from a signal generator, nuclear signals have random characteristics, meaning their generation time intervals are non-uniform. Because of the random nature of nuclear signals, the number of nuclear signals acquired per unit time by the coincidence selection-based system will be lower than the evaluation board' s transmission limit. At a source intensity of 24 Ci, the processing performance of the coincidence selection-based system for nuclear signals reaches its maximum, with a coincidence counting rate of 376 cps. The results demonstrate that employing coincidence selection to precisely filter valid events in the DRS4 evaluation board' s acquisition circuit can effectively ensure efficient utilization of core signal processing resources, enabling high-efficiency positron annihilation measurement based on the DRS4 evaluation board.

To improve system measurement efficiency, reducing DRS4 evaluation board dead time and optimizing data transmission methods are important approaches for enhancing board performance. The DRS4' s serial readout method could be replaced with parallel readout to reduce the impact of dead time and improve system measurement efficiency. The system currently uses a USB 2.0 interface for data interaction with the host computer, which has insufficient transmission bandwidth. Replacing USB 2.0 with Ethernet for data transmission could increase data transfer speed and improve system measurement efficiency. Without considering board transmission limits, higher source intensities could be employed to achieve higher measurement efficiency.

1.3 Efficiency Evaluation of Internal Triggering

To investigate the feasibility of internal triggering in the DRS4-based positron annihilation lifetime measurement system, the experiment similarly employed a pair of standard pure iron (Fe) samples and a ^{22}Na source in a "sandwich" structure placed between two detectors. The system' s coincidence counting rate was measured as the number of positron annihilation events per unit time to evaluate the effect of internal triggering on the processing performance of the DRS4 evaluation board-based positron annihilation lifetime measurement system. Additionally, the time resolution of the DRS4 evaluation board-based positron annihilation measurement system was measured using a ^{60}Co radioactive source within the ^{22}Na energy window.

Figure 6 [Figure 6: see original paper] shows the relationship between source intensity and counting rate measured by the internal triggering-based DRS4 positron annihilation lifetime measurement system. The coincidence counting rate of the internal triggering-based system increases with source intensity, reaching a maximum of 353 cps at a source intensity of 24 Ci. Due to limitations from the evaluation board' s transmission limit and the random nature of nuclear signals, the number of signals acquired per unit time by the internal triggering-based system also remains below the evaluation board' s transmission limit. At a source intensity of 24 Ci, the efficiency of the internal triggering-based system reaches its maximum, with a coincidence counting rate of 353 cps. The internal triggering-based positron annihilation measurement system uses the evaluation board' s internal discrimination circuit to discriminate valid events before triggering the sampling circuit to sample signals. However, the DRS4 evaluation board cannot precisely discriminate valid signals, and a small number of invalid events still trigger DRS4 chip sampling during measurement, resulting in lower measurement efficiency compared to the system using external coincidence selection circuits.

To improve the measurement efficiency of the internal triggering system, precise discrimination of valid signals is the most critical approach. The discrimination circuit of the DRS4 evaluation board could be optimized to precisely discriminate signals in each channel, enabling efficient utilization of core signals and improving system measurement efficiency. The results demonstrate that the internal triggering method for DRS4-based positron annihilation lifetime measurement systems is feasible and can effectively improve the utilization rate of core signal processing resources, but requires optimization of the DRS4 evaluation board' s internal discrimination circuit to precisely discriminate valid events and achieve maximum system measurement efficiency.

The time resolution was measured using a ^{60}Co radioactive source within the ^{22}Na energy window. The ^{60}Co source simultaneously emits two γ photons with energies of 1.17 MeV and 1.33 MeV, respectively. The timing spectrum obtained within the ^{22}Na energy window uses its full width at half maximum (FWHM) as the time resolution parameter. As shown in Figure 7 [Figure 7: see original paper], the time resolution of the DRS4-based positron annihilation measurement system is 186 ps, which meets the basic requirements for positron annihilation measurements.

This paper constructed a positron annihilation lifetime measurement system based on the DRS4 evaluation board. The system' s processing efficiency is primarily limited by the DRS4 evaluation board' s triggering method, which causes invalid events to trigger sampling and results in low valid event counting rates. To address the low measurement efficiency of the DRS4 evaluation board-based positron annihilation system, a coincidence selection method was employed to discriminate valid events and prevent the DRS4 evaluation board from sampling invalid events, enabling the measurement system' s counting rate to reach the DRS4 evaluation board' s processing limit for nuclear signals. Through the method of valid event coincidence selection, the measurement efficiency of the DRS4-based positron annihilation lifetime measurement system has been improved, providing a solution for coincidence logic selection in multi-channel digital positron annihilation lifetime measurement systems.

4. References

[1] 王胜, 杨静, 田丽霞, 等. 用正电子湮没谱学技术表征一种有机-无机杂化膜 [J]. 核技术, 2015, 38(3):
[2] Eldrup M, Singh B N. Study of defect annealing behaviour in neutron irradiated Cu and Fe using positron annihilation and electrical conductivity[J]. Journal of Nuclear Materials, 2000, 276(1-3): 269−277.
[3] 韩振杰, 刘福雁, 张鹏, 等. 基于起始信号触发判选的正电子湮没寿命测量方法 [J]. 核技术,2018,41(06):41-46.
[4] F. Bečvář, J. Čıžek, L. Lešták, I. Novotny, I. Procházka, F. Šebesta, A high- resolution BaF2 positron-lifetime spectrometer and experience with its long-term exploitation, Nucl. Instrum. Methods Phys. Res. A 443 (2-3) (2000)
[5] J. Nissilä, K. Rytsölä, R. Aavikko, A. Laakso, K. Saarinen, P. Hautojärvi,

Performance analysis of a digital positron lifetime spectrometer, Nucl. Instrum. Methods Phys. Res. A 538 (1-3) (2005) 778-789.
[6] N. Djourelov, N. Charvin, C. Bas, J. Viret, V. Samoylenko, D. Sillou, Nucl. Instr. and Meth. B 264 (2007) 165.
[7] Bečvář, František et al. Performance of a High-Resolution Digital Positron-Lifetime Spectrometer[J], Acta Physica Polonica A 113 (2008): 1279-1284.
[8] Wang M, Bian Z , Wang Y ,et al. 2022. A 64-channel high-time resolution digital waveform sampling electronic system based on DRS4 for positron burst annihilation lifetime measurement [J]. Journal of instrumentation: an IOP and SISSA journal, 2022, 17(10), T10001.
[9] DRS4 Evaluation Board Rev. 5.1 manual: https://www.psi.ch/drs/DocumentationEN/manual_{rev51}.pdf
[10] AN Ran, CHEN Bin, LIU Yan-Fen, YE Bang-Jiao, KONG Wei, Stefan Ritt. A new positron annihilation lifetime spectrometer based on DRS4 waveform digitizing board[J]. Chinese Physics C, 2014, 38(5): 056001.
[11] M Petriska, S Sojak, V Slugeň. Positron lifetime setup based on DRS4 evaluation board[J]. Journal of Physics: Conference Series, 2014, 505(1):012044.
[12] Martin Petriska, Stanislav Sojak, Vladimír Kršjak, Vladimír Slugeň; Digital triple coincidence positron lifetime setup with DRS4 and its benefits. AIP Conf. Proc. 2021, 2411 (1): 080009.
[13] Danny Petschke, Torsten E.M. Staab. DDRS4PALS: A software for the acquisition and simulation of lifetime spectra using the DRS4 evaluation board. SoftwareX. 2019, 10, 100261.

Note: Figure translations are in progress. See original paper for figures.