

A new positron annihilation lifetime spectrometer based on DRS4 waveform digitizing board^{*}

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Abstract: A new simple digital positron lifetime spectrometer has been developed. It includes a DRS4 waveform digitizing board and two scintillation detectors based on the XP2020Q photomultiplier tubes and LaBr₃ scintillators. The DRS4 waveform digitizing can handle small pulses, down to few tens of millivolts, and its time scale linearity and stability are very good. The new system has reached a 206 ps time resolution, which is better than the conventional analog apparatus using the same detectors. These improvements make this spectrometer more simple and convenient in comparison with other spectrometers, and it can be applied to the other scintillation timing measurements with picosecond accuracy.

Key words: digital lifetime spectrometer, timing, waveform sampling, DRS4 chip

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1 Introduction

The positron annihilation lifetime (PAL) spectrometer has been proved to be a useful technology for studying crystal lattice defects and open-volume cavities in the range from single atoms to several nanometers [1–3]. The conventional PAL spectrometer consists of a pair of scintillation detectors, two constant fraction timing discriminators (CFD), a time-to-amplitude converter (TAC) and a multi-channel analyzer (MCA). Its time resolution is about 200 ps [4]. Numerous works to improve the time resolution, stability, and count rate have been reported [5–8]. However, the performance of the conventional PAL spectrometer is limited by the analog electronic devices that it uses. With the rapid development of electronics and digital data readout technology [9], some researchers have used a fast digitizer or digital oscilloscope to set up a new type of PAL spectrometer-digital positron lifetime spectrometer (DPLS) [10–13]. The digital positron lifetime spectrometer has a better time resolution than the analog system and its composition is simple.

Although digital positron lifetime spectrometer (DPLS) has an important advantage in terms of its time resolution, the digitizer or digital oscilloscope (which is part of the DPLS) is very expensive. The DRS4 chip,

which has been designed at the Paul Scherrer Institute, Switzerland [14, 15] is a cheap, switched capacitor array (SCA) that is capable of sampling nine differential input channels at a sampling speed of 700MSPS to 5GSPS. The characteristics of the high channel density, high analog bandwidth of 950 MHz, and low noise of 0.35 mV make this chip ideally suited for high precision waveform digitization. In order to simplify the design process to integrate the DRS4 chip into custom electronics, an evaluation board has been designed. It is basically equivalent to a four channel 5GSPS digital oscilloscope. In this work, we present a new simplified digital positron lifetime spectrometer using a DRS4 Evaluation Board that has been tested in an experiment.

2 Experimental and analysis methods

Detectors were composed of LaBr₃ scintillators coupled to XP2020Q photomultiplier tubes (PMT) with silicon grease. The LaBr₃ scintillators were covered with Teflon tapes. The sizes of the scintillators were $\phi 36 \times 20$ mm in the start detector and $\phi 36 \times 15$ mm in the stop detector (set for the acquired the 1275 and 511 keV-quanta, respectively). The voltages between the anode and cathode were increased to get a linearity photoelec-

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tric signal output with the applied supply voltages of 1600 V. A ^{22}Na source with ~ 93 kBq (~ 2.4 μCi) activity was used in the experiment. Monocrystalline Si was chosen to test the performance of the digital devices. The angle between the Start and Stop Detectors is 120 degrees. A lead shielding plate was positioned at the center of the Start and Stop Detectors. This geometry reduced the Compton scattering effects between the two detectors and the lead shielding plate could absorb the back scattered gamma rays. The count rate with a given source activity depends on the measurement geometry. In the experiment described below, the actual count rate could reach $50\text{--}70$ s^{-1} .

Figure 1 shows a schematic diagram of a new digital positron lifetime spectrometer (DPLS), which simply consists of two scintillator detectors and a DRS4 evaluation board. The anode pulses of the PMTs were directly sent to ch2 and ch3 of the DRS4 evaluation board. The continuous pulses of the input signal were digitally converted to discrete waveform data and stored in the memories of the DRS4 evaluation board after the triggering condition is fulfilled. The waveform data were then transferred to the PC through a USB 2.0 bus. The maximum transfer rate is about 20 MB/s. After that, we analysed the waveform data and constructed the positron lifetime spectra. The DRS4 evaluation board is in the qualified triggering mode on both chn2 and chn3 received the signals at which the voltage exceeded the rated amplitude at the same time. The pulse of the stop detector was delayed for 4–8 ns using a delay cable. A picture of the start and stop waveforms in the DRS4 evaluation board

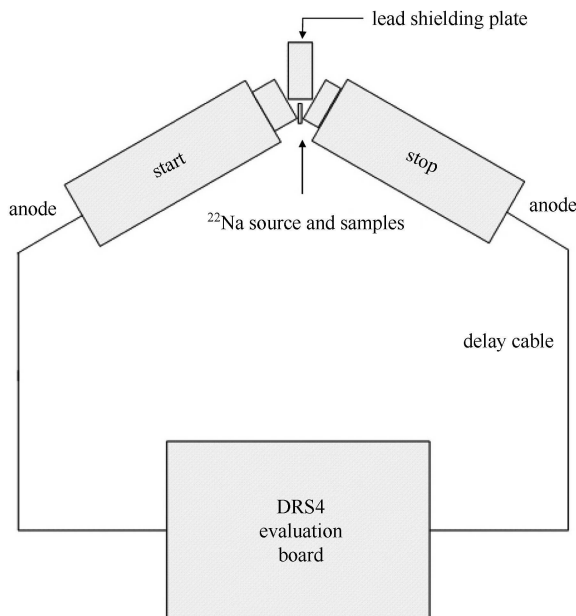


Fig. 1. Schematic diagram of the simple digital positron lifetime spectrometer (DPLS).

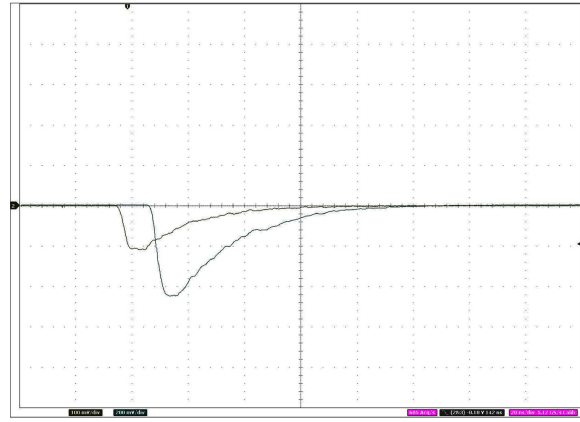


Fig. 2. A pair of output waveforms from the start and stop detectors, as shown on the screen.

is shown in Fig. 2. In this figure, the rise time of the pulses was around 5.6 ns. The peak of the pulse is at the 1/3 of the restricted time range for a full of the waveforms. The waveform data were acquired by the DRS4 evaluation board working at a sampling rate of 5.12 Gs/s, the sampling time interval was 200 ps. The full time scale range of each input channel is about 200 ns. Several methods were used in the waveform digital processing to construct the positron lifetime spectrum by histogramming the time interval between the start and stop detector pulses after pulse discriminator.

2.1 Pulse discrimination methods

The first step of the data analysis is to discriminate the waveform pulses. Some waveforms were deformed and distorted, and they should be eliminated. So, several pulse discrimination algorithms were performed to extract the suitable pulses for timing analysis.

2.1.1 Methods to eliminate bad waveforms

In the experiment, some distorted waveforms that have unstable baseline or more than two waveforms piled up appeared in the same time scale range of one channel. We should eliminate these pulses and choose the qualified pulses by pulse shape discrimination algorithm.

2.1.2 Pulse amplitude discriminator

When the energy of γ rays entering in the LaBr_3 scintillator is not too low, the pulse amplitude is proportional to the energy of γ rays deposited in the detector [16], so the pulse amplitude can represent the energy of 1.28 MeV and 0.511 MeV in the measurements. The pulse amplitude is obtained based on the peak search algorithm [9, 16]. The pulse amplitude discriminator window is dependent on the amplitude distribution. Only those pulses whose height stays in the range of the amplitude window would subsequently be analyzed.

2.1.3 Pulse area discriminator

In some works, the total energy of the measured pulse is proportional to the sum of all created scintillation photons [17], the pulse area between the digitized waveform and the baseline is relevant to γ ray energy. The value of the pulse area is calculated by digital integration method, which is simply to sum the amplitude value of each channel over the whole waveform range. Because the LaBr_3 decay time is about 16 ns, the time range integrated from the leading edge of a pulse to the end sample point is about 132 ns, almost 2/3 of the whole time scale range. The energy spectrum distribution of integrating the pulse area is performed in Fig. 3. The obtained energy resolution at 0.511 MeV and 1.274 MeV is 6.05% and 5.42%. We then used the same detector with the analog system to obtain the energy spectrum, which is shown in Fig. 4. The energy resolution of the analog system is at 0.511 MeV, and 1.274 MeV is 5.85%

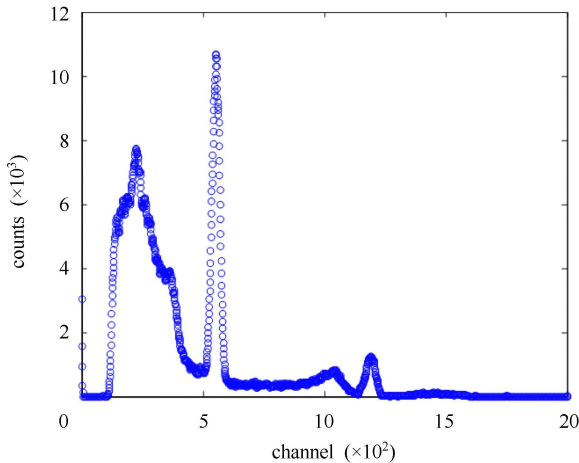


Fig. 3. The energy spectrum of ^{22}Na source measured with the digital positron annihilation spectrometer.

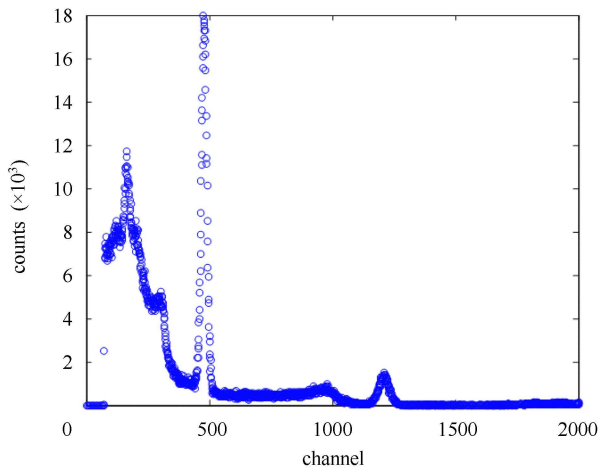


Fig. 4. The energy spectrum of ^{22}Na source measured with the analog positron annihilation spectrometer.

and 4.73%, respectively. The energy spectrum of the digital system is similar to that of the analog system.

Finally, the combination of the pulse amplitude and area discriminator is used to select a pair of pulses, whose energy are 1.28 MeV and 0.511 MeV, respectively.

2.2 Digital constant fraction timing analysis methods

After checking that the anode pulses fit in predetermined energy (pulse amplitude and area) window, timing analysis is planned to extract the time information from the digitized pulse pairs. It is generally believed that the best timing algorithm for scintillation detector pulses is constant fraction timing. This method analyses the result of numerous leading-edge-timing measurements according to the moment that represents the minimum time jitter when the pulse crosses a certain constant fraction level f_{cf} of its full amplitude. The optimum fraction is a characteristic of the detectors, the scintillator, and the PMT types.

2.2.1 Linear interpolation

After the pulses are converted to digital data, at the leading edge of the pulse we find two adjacent sample points (a_1, t_1) , (a_2, t_2) ($t_2 - t_1 = \tau_{\text{clk}}$) whose amplitude satisfy the inequality of $a_1 < fA < a_2$, a linear interpolation is then operated between (a_1, t_1) and (a_2, t_2) , finally t_{DCFT} is calculated with the linear interpolation function.

2.2.2 Cubic smoothing spline

Cubic smoothing spline fitting is a method of fitting a number of data whose function is unknown without prior knowledge, as introduced in Refs. [10, 18]. It has recently been applied to reduce the effect of noise in other spectroscopy studies. Considering only the leading edge of the pulses is useful for DCFT, about 40 sample points around the peak are selected, and t_{DCFT} is calculated by the fitting cubic smoothing spline function.

2.2.3 Gaussian rising edge fitting

A Gaussian function was noticed to describe the leading edge of a pulse very well [10, 16]. Since Gaussian fitting is a non-linear interpolation, we first operate the waveform amplitudes with log transformation, and then the new waveform data is obtained. Finally, we fit the new data with a second-order polynomial interpolation as a replacement of Gaussian fitting. The fitting range is 40 samples in the leading edge of the pulses. We studied the dependent parameters of the time resolution on both the fitting range and the timing fraction. The relationship between the timing fraction and the time resolution of the spectrometer is shown in Fig. 5. The curves were obtained by varying the fraction for one detector and by keeping the fraction constant for the other. As seen, the optimum constant fraction is about 30% with both detectors [10, 16].

2.2.4 Comparison of different digital timing methods

We studied the time resolution and computing speed with linear interpolation, Gaussian rising edge fitting, and the cubic smoothing spline method. The time resolution obtained by using the cubic smoothing spline method is about 202.6 ps, by Gaussian rising edge fitting method it is about 206 ps, using linear interpolation method it is about 218 ps. The precision of the cubic smoothing spline method is better than others, but the speed is opposite: the speed of the linear interpolation is faster. Considering the precision and speed, the Gaussian rising edge fitting method in the digital constant fraction discriminator method is finally adopted.

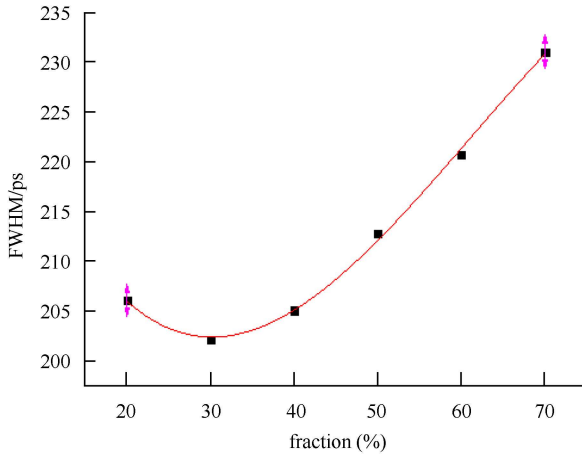


Fig. 5. The time resolution as a function of the fraction using digital constant fraction timing by Gaussian leading edge fit.

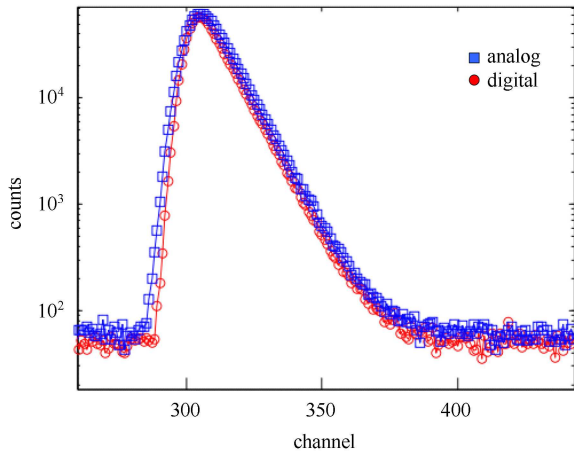


Fig. 6. The positron annihilation lifetime measured for Si sample used the digital lifetime spectrometer compared with the analog system, The peak spectrum is normalized to the analog lifetime spectrum (the channel width is 24.8 ps).

2.3 Building positron annihilation lifetime spectra

After the pulse time-mark has been performed, the PAL spectra is constructed by the frequency distribution of the time-mark difference between the start and stop signals. Fig. 6 shows two positron lifetime spectra collected in the digital and analog systems, each containing about 1 million counts. Only 200 channels around the peak position of the spectra are presented for better visual comparison.

3 Results and discussion

The PAL spectra for bulk Si were measured to test the performance of the present spectrometer. After subtracting the source components, a single exponential convoluted with a Gaussian resolution function fits the data very well. The fitted lifetime is 220 ps, which is in agreement with previous experiments [19, 20]. The time resolution obtained from the fit is 206 ps (FWHM).

Three different intensity of sources (1.6 μCi , 2.4 μCi , 3.2 μCi) are used to test the actual count rate of the spectrometer. The count rate is proportional to the intensity of the source. But if the source intensity is greater than 3.2 μCi , then the actual count rate will not increase. The maximum count rate is about 75 cps. So, we choose the moderate-intensity radioactive sources (2.4 μCi) for the test.

The dependence of the time response on the energy of the incident γ -rays from ^{60}Co (1.33 MeV, 1.17 MeV) with 8×10^4 were each measured for ten days. The time resolution for the ^{60}Co cascade radiations was 182 ps. The time spectrum is shown in Fig. 7. The energy range was set to $1.0 \text{ MeV} < E < 1.5 \text{ MeV}$. Better time

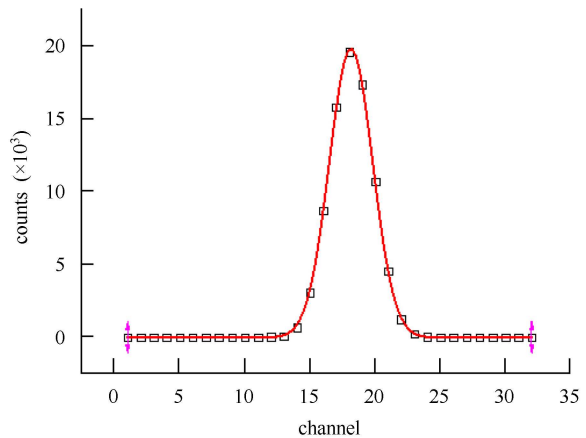


Fig. 7. The time resolution spectrum of ^{60}Co source measured with the digital positron annihilation lifetime spectrometer (the channel width is 24.8 ps).

resolution was obtained with narrower energy window settings at the cost of the counting rate.

4 Conclusions

A new digital positron annihilation lifetime spectrometer consisting of a pair of LaBr₃ scintillator detectors and a DRS4 evaluation board has been set up and tested. The results show that the performance of the digital apparatus is better than that of the analog apparatus. The time resolution of the digital system is about 206 ps, which is better than the analog devices (228 ps). The

time resolution of the for ⁶⁰Co spectra is about 182 ps.

Various software timing methods were tested and the best results were obtained with the DCFT method. Software can also be implemented to perform off-line corrections to compensate for amplitude walk and drifts in the spectrum. The excellent performance demonstrates that the new digital positron annihilation lifetime with easy setup and good stability has prominent advantages over conventional positron annihilation spectrometers. The DRS4 evaluation board can also be applied to the other scintillation timing measurement with picosecond accuracy.

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