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Nuclear Instruments and Methods in Physics Research A 538 (2005) 778–789

NUCLEAR INSTRUMENTS & METHODS IN PHYSICS RESEARCH Section A

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# Performance analysis of a digital positron lifetime spectrometer

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Received 14 October 2003; received in revised form 10 August 2004; accepted 10 August 2004
Available online 16 September 2004

**Abstract**

A digital positron lifetime spectrometer has been set up and tested comprehensively. The system consists of a fast commercial digitizer connected to a computer, a simple coincidence circuit and software to extract the timing from the collected detector pulses. The digital system has the same time resolution as a conventional analog apparatus using the same detectors. The pulse processing part of the spectrometer is able to analyze and store in real-time several thousands of events per second, which is an order of magnitude more than the count rates in typical positron lifetime experiments. The data acquisition can handle small pulses, down to a few tens of millivolts, and its time-scale linearity and stability are very good. We discuss the advantages of timing with software, e.g. simple setup, use of different timing algorithms and possibility of an offline analysis of lifetime events. The idea is generally applicable to direct measurement of time intervals with picosecond accuracy.


*PACS:* 06.60.Jn; 07.35.Hd; 78.70.Bj; 07.85.Nc

*Keywords:* Digital; Timing; Time spectroscopy; Positron annihilation; Fast digitizer

## 1. Introduction

Digital data readout techniques applied to nuclear radiation detectors have recently become viable as a result of the development of fast analog-to-digital converters (ADC). An early conversion to digital form both simplifies the measurement setup and enables various corrections to the data with software. Digital data collection methods have already been used in both pulse-height (see, e.g. Ref. [1] and references therein) and time-interval spectroscopies [2–6]. In this work, we have set up and tested a digital positron lifetime spectrometer. Basically, the pulse processing part of the apparatus measures time intervals, from nanoseconds up to microseconds, with an accuracy of about 20 ps.

Positron lifetime spectroscopy yields information, e.g. on open-volume type defects in solids.

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0168-9002/$ - see front matter 
doi:10.1016/j.nima.2004.08.102

The positron lifetime is sensitive to the average electron density around the positron which leads to longer lifetimes in vacancies than in the lattice [7–9]. The positron lifetime is measured as the time difference between two γ-quanta, the first one emitted simultaneously with the positron from the $^{22}Na$ source and the second emitted from the annihilation with an electron. Fast scintillation detectors are used to detect the photons. Conventionally, time information is extracted from the detector pulses using constant-fraction discriminators (CFD) and a time-to-amplitude converter (TAC) whose output pulses are collected in a multi-channel analyzer (MCA) to form the lifetime spectrum. This chain of analog electronics may require time-consuming adjustments and may exhibit long-term instability. With proper adjustments, however, the contribution of the electronics to the time resolution can usually be diminished to a negligible level. See, e.g. Ref. [10] for a description of a state-of-the-art analog spectrometer.

The digital positron lifetime spectrometer consists, in principle, only of the two scintillation detectors and a fast digitizer connected to a computer. In order to achieve the time resolution determined purely by the detectors, the sampling rate has to be sufficiently high to capture the leading edges of the detector pulses. In two recent studies, it has been shown with fast digital oscilloscopes that sampling rates of 5 and 4 GS/s enable accurate timing of anode pulses with rise times in the nanosecond range [4,5]. The time resolutions achieved in these studies were either excellent (144 ps [5]) or moderate (297 ps [4]) and, moreover, close to those obtained by using similar detectors with analog electronics. However, the data throughput was a problem due to limitations set by the oscilloscopes, especially in Ref. [4]. Very fast sampling ADCs were also recently used to record silicon-strip detector pulses in time-of-flight measurements [6]. In that case, the time resolution of the instrument was of the same order ($\approx 200$ ps) as in positron lifetime spectrometers.

The aim of this paper is to investigate in detail how the replacement of the conventional analog timing instruments by a fast digitizer influences the performance of a lifetime spectrometer. This research was done with a detector setup giving a reasonable counting rate ($\approx 200\,s^{-1}$) and time resolution of about 200 ps (full-width at half-maximum, FWHM).

A commercial digitizer with a sampling rate of 2 GS/s, 8 bit amplitude resolution and an analog bandwidth of 500 MHz turns out to be a good recording apparatus for the positron lifetime spectrometer. The optimum resolution, determined by the detector properties is achieved. The maximum data storage and analysis rate of $\geqslant 3000$ events per second was reached, which solves the bottleneck of data throughput encountered when using digital oscilloscopes [4]. Digital processing of detector pulses is found to offer significant advantages. For instance, the integral linearity of the time scale is inherently better than that in conventional analog equipment. The long-term stability of the apparatus is improved, as the digitizer can work with much smaller detector pulses. A major advantage of the digital positron lifetime spectrometer is that it is very simple to set up compared to an analog one. Furthermore, the possibility to store all the raw data allows various off-line corrections to be done.

## 2. Setup and methods

### 2.1. Hardware

The essential hardware components of a digital positron lifetime spectrometer are shown in Fig. 1. Two fast scintillation detectors capture the γ-quanta which are emitted at the time of the birth and the annihilation of the positron. The anode

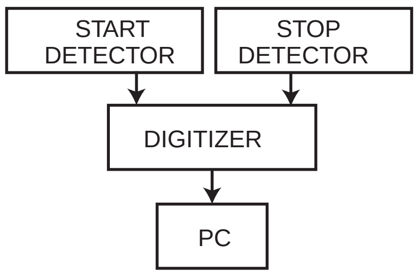


Fig. 1. Schematic diagram of a digital positron lifetime spectrometer.

pulses from the photomultiplier tubes (PMT) are led to a digitizer unit. The time information is then analyzed from the voltage sample sequences with software.

Fig. 2 depicts in detail the system that was used in this study. The anode pulses are fed into a combiner and led via a single cable to the digitizer. This is a reasonable approach even in case the digitizer had two channels. In this way the possible time spread related to the synchronization of the channels is not introduced between the start and stop pulses. To avoid timing errors arising from the ringing of the baseline after the first pulse, a proper minimum delay (in our case about 50 ns) must be set between the pulses with a cable.

In a typical positron lifetime spectrometer, the ratio of the true coincidence rate to the singles rate is only a couple of percent. From the point of view of the data transfer into the computer, it is important to eliminate most of the non-coincident pulses. A sufficiently flexible triggering function has not yet been implemented in commercial fast digitizers. Hence, we designed and constructed an external gate module to provide a triggering signal to the digitizer in case of a useful event (see Figs. 2 and 3). In the following, the devices used in this paper are presented in more detail.

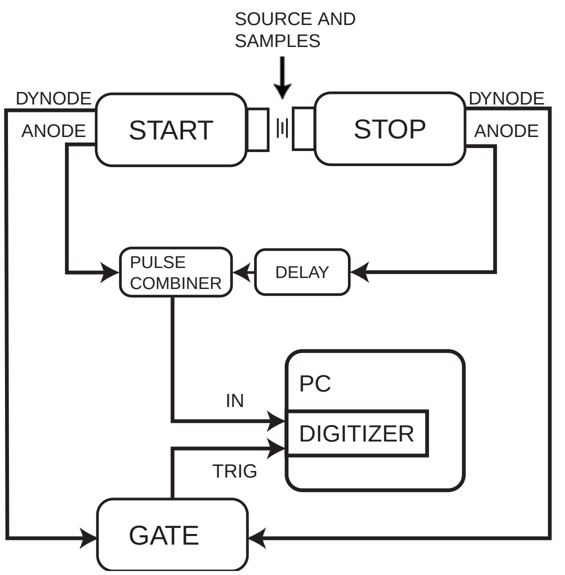


Fig. 2. A detailed block diagram of the digital positron lifetime spectrometer tested in this work. START and STOP are fast scintillation detectors, GATE a triggering module for detecting coincidences, DELAY a $\approx 50$ ns cable delay and PULSE COMBINER an impedance matched power splitter.

### 2.1.1. Detectors

The detectors were composed of fast plastic cylindrical scintillators (NE-111) and XP2020 photomultipliers (by Photonis). The sizes of the scintillators were $\varnothing 30 \times 20\,\mathrm{mm}^3$ in both the start and stop detector (set for the capture of the 1275 and 511 keV $\gamma$-quanta, respectively). The PMT bases were slightly modified from the B′ divider suggested by the manufacturer: the voltages between the cathode and the first dynodes were increased to ensure good photoelectron collection efficiency at the applied supply voltages of the order of 1800 V [11]. With these dividers the anode pulse rise times were about 3 ns (from 10% to 90% level). Note that, besides the PMT operation, also the scintillation decay time and the light collection time of the scintillators affect the anode pulse rise times.

With these detectors a typical count rate at $\approx$ 1 cm interdetector distance (configuration allowing, e.g. the use of a cryostat for sample cooling) is $200\,\mathrm{s}^{-1}$ with a customary 1 MBq $^{22}$Na source. The count rate at a given source activity naturally

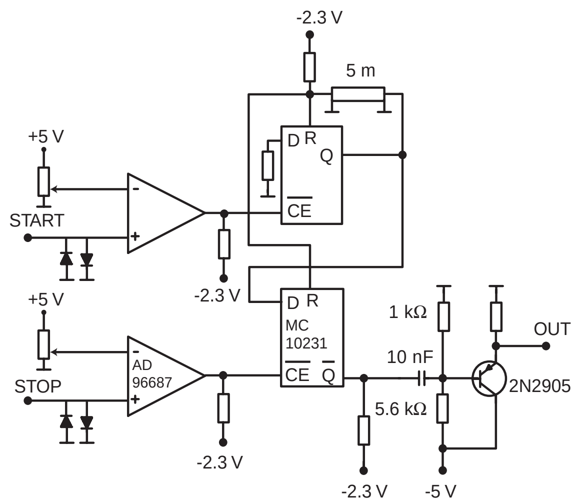


Fig. 3. Circuit diagram of the gate module used for detecting the coincidences and triggering the digitizer. Unmarked resistors are 50 Ω.

depends strongly on the measurement geometry. In the tests described below, the count rate has typically been 50–200 $s^{-1}$ using 0.1–1 MBq sources.

### 2.1.2. Digitizer

The digitizer used in this study was an 8-bit digitizer card DP210 by Acqiris connected to the PCI-bus of the measurement computer. The bandwidth of the card is 500 MHz and its maximum sampling rate 2 GS/s. It allows fast transfer of data from the buffer memory (up to 8000 events in on-board extended memory) to the computer memory. The price of the digitizer is already now lower than that of the analog electronics chain.

According to the specifications, the aperture uncertainty of the digitizer is $\pm 1$ ps and clock accuracy better than $\pm 2$ ppm. The differential amplitude/voltage non-linearity of the ADC is specified to be better than $\pm 0.7$ LSB (least significant bits) and integral non-linearity less than $\pm 1\%$. The noise performance of the DP210 is given by an effective number of significant bits. This figure is more than 6 bits above 20 MHz (specified up to 200 MHz).

### 2.1.3. Gate module

The gate module presented in Fig. 3 gives an output signal if two negative pulses exceeding chosen amplitudes appear at the unit inputs within a selected time interval. The circuit consists of two fast comparators and two D flip-flops. The start pulse exceeding the start threshold sets the start flip-flop, which again arms the stop flip-flop for the desired time. If there is a stop pulse exceeding the stop threshold during this time, a 'coincidence' pulse is generated, which signals the digitizer to store the event.

## 2.2. Software

### 2.2.1. Data acquisition

The program for the Acqiris DP210 digitizer control and data collection was written in C++ using Microsoft Visual C++ 5.0. The software could be well run in a computer with a 500 MHz Pentium III Processor, 128 MB system RAM and 20 GB of disk space.[2] The multi-tasking program simultaneously controls the data acquisition and analyzes the data. This solution reduces the dead time in a usual positron lifetime measurement to a negligible level ($<1\%$), where it is determined only by the transfer time of the data and the triggering rate of the digitizer.

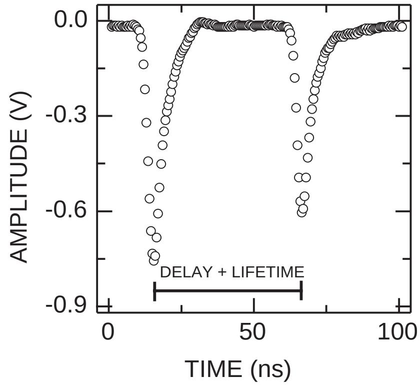


Fig. 4. A typical positron lifetime event as registered by the digital apparatus at 2 GS/s sampling rate. The two pulses are separated by the cable delay and the positron lifetime.

### 2.2.2. Data analysis: extracting the time information

The data analysis of the digital positron lifetime spectrometer consists of: (i) checking that the anode pulses fit in predetermined energy (amplitude) windows, (ii) extraction of the time information from the digitized pulse pairs, (iii) histogramming the time intervals to form a conventional lifetime spectrum, and (iv) analyzing the exponential lifetime components. Once the timing information has been determined, the histogramming is trivial and the bin width (i.e. time channel width, typically 10–30 ps) can be arbitrarily chosen. The analysis of the lifetime spectrum is performed here by conventional multi-Gaussian fitting [8,9]. The extraction of the time information, however, is non-trivial and is discussed in more detail below.

A typical positron lifetime event is shown in Fig. 4. This sample sequence has been acquired

[2]Storing a typical positron lifetime spectrum of $10^6$ counts requires $>500$ MB disk space.

with the Acqiris DP210 digitizer operating at a sampling rate of 2 GS/s. The first pulse originates from the 1.275 MeV $\gamma$-quantum and the second from the 511 keV annihilation photon. Before extracting the time information from a pulse pair, one has to make sure that the pulses fit into the selected pulse-height (or energy) windows.

It is generally believed that the best timing algorithm for scintillation detector pulses is constant fraction CF timing. The method was discovered as a result of numerous leading-edge-timing measurements according to which the moment that represents the capture of the $\gamma$-quantum with minimum time jitter is when the pulse crosses a certain constant fraction level $f_{CF}$ of its full amplitude [12,13]. The optimum fraction is characteristic of the detectors, i.e. the scintillator and the PMT types.

Not unexpectedly, we found that the best method of obtaining the time information from the sampled pulses is CF timing. Other methods which were technically simpler but not making use of the CF principle were also tested. These, including algorithms based on determining the center of mass of the pulse, the peak position of a moving average over the pulse and the cross-correlation of the pulse with an average-shaped pulse, all resulted in time resolutions about 25–35 ps worse than that obtained with CF timing. In the following, the CF procedures we used are discussed in more detail.

The basic idea for finding the timing instant (and reducing the effect of noise) is to fit a curve to the leading edge of the anode pulse and to calculate the time corresponding to the desired fraction from the fit. We tried three different numerical algorithms:

- fitting a Gaussian function,
- calculating a weighted moving average of the data and interpolating the result with splines (as presented in Ref. [5]) and
- fitting a smoothing spline.

The methods were compared by testing them with a single set of data.

A Gaussian was noticed to describe the leading edge of a detector pulse rather well. As an example, Fig. 5 presents pulses from detectors with plastic and $BaF_2$ scintillator, and corresponding Gaussian fits ($BaF_2$ pulse is presented to show that the 2 GS/s sampling rate is sufficient to capture its leading edge). We investigated the dependence of the time resolution on both the fitting range and the timing fraction. Best results concerning the fitting range were obtained when the fit was applied to the range shown in Fig. 5. In Fig. 6 we show the effect of the timing fraction on the time resolution of the spectrometer. The curves were obtained by varying the fraction in one detector and by keeping the fraction constant in the other. As seen, the optimum fraction is about 25% with both detectors.

*Cubic smoothing spline* fitting is a method of fitting a curve to a set of noisy data without using prior knowledge on the functional form of the data. It has recently been applied to reduce the effect of noise in pulse-height spectroscopy [14]. *Full cubic splines* are piecewise cubic polynomials which go exactly through the data points. In the method of cubic smoothing splines, one searches for a piecewise cubic polynomial which attempts to minimize the residuals between the data and the model while keeping the model function smoother than with full cubic splines. The degree of smoothing is a variable parameter. The cubic

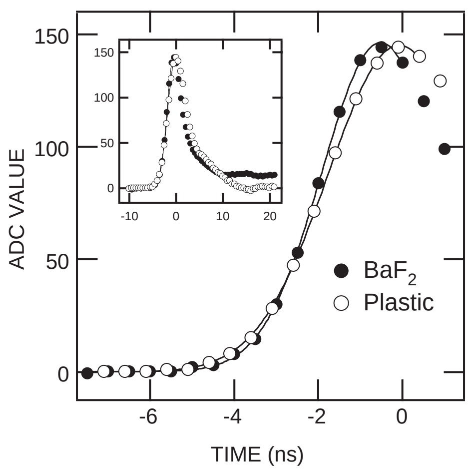


Fig. 5. Fast scintillation detector anode pulses with a plastic and a $BaF_2$ scintillator. The effect of the scintillation decay time and the light collection time of the scintillators is visible in the figure. The high voltage has been 1800 V in both cases. The solid lines depict Gaussian functions fitted to the leading edges.

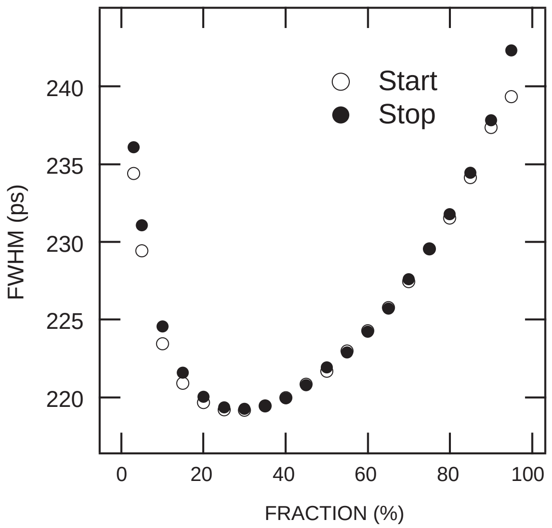


Fig. 6. The time resolution of a test spectrometer as a function of the fraction $f_{CF}$ used in the CF timing.

smoothing spline $f_p(t)$ is the piecewise cubic polynomial $f(t)$ which minimizes the function

$$S(f(t), \mathbf{y}) = p\sum_{i=1}^{N}\{y_i - f(t_i)\}^2 + (1-p)\int_{t_1}^{t_N} f''(t)^2\,\mathrm{d}t, \qquad (1)$$

where $\mathbf{y}$ is the sampled data and $p$ is the parameter which determines the relative importance between minimizing the sum of the residuals and maximizing the smoothness [15]. Lowering $p$ leads into smoothing of pulses somewhat similarly as in low-pass filtering (moving average), which has also been used in a realization of a digital positron lifetime spectrometer [5].

We studied the time resolution obtained with cubic smoothing spline analysis by varying the parameter $p$, the range to which the smoothing spline was fitted, and the fraction $f_{CF}$. The best time resolution was obtained with $p = 0.3$ and $f_{CF} = 0.2$, and it was a few picoseconds better than the best values obtained from Gauss fitting or the method of a moving average followed with spline interpolation [5]. The similarity of the obtained resolutions and the results from the simultaneous measurements with an analog set-up (see Section 3.2.3) suggest that all three timing algorithms are near the optimum for CF methods.

The timing performance of the spectrometer and the functioning of the analysis procedure are demonstrated in Fig. 7. One is able to perceive the time spread associated to the detectors when the pulse pairs are normalized and shifted so that the start pulses coincide.

## 3. Performance of the system

### 3.1. Data throughput

The DP210 digitizer with extended memory (16 Mpoints) can store up to 8000 events at a time (maximum 2000 points per sweep). These data can be transferred to computer main memory with a sufficient rate. Recently, transfer rate measurements were made with a new computer with dual AMD Athlon MP 1900+ processors. In a test in which pulses were fed to the digitizer from a pulse generator, up to 30,000 unprocessed events per second could be recorded to main memory. This rate is limited by the hardware. When performing an online analysis to the data, the computing power of the processor limits the maximum rate of true analyzed events to $3000\,\mathrm{s}^{-1}$ (using cubic smoothing spline fitting). This rate is clearly high enough for routine positron lifetime measurements.

### 3.2. Time resolution

The most prominent performance characteristic of a positron lifetime spectrometer is, besides the count rate, the time resolution. In analog systems it is widely accepted that the electronics degrades the total resolution only marginally, by around 10 ps or less at the 200 ps level. In other words, the resolution of a spectrometer with properly optimized electronics is determined by the detectors. In a digital spectrometer the ‘electronic resolution’ is influenced by several factors, e.g. the sampling rate (or the number of samples in the pulse), the noise added to the voltage pulse by the digitizer and the amplitude linearity of the digitizer. In this section we investigate the role of these factors. In addition, the method used to analyze the voltage pulse plays a role, as discussed in Section 2.2.2. All the following data in this section are analyzed using the Gauss-fit procedure. Considering only the ADC specifications given for the digitizer, it is by no means a priori clear that the time spread contribution of the digitizer would be competitive with that obtained with analog instruments.

As a preliminary test, we measured the 'electronic resolution' (or actually its lower limit) of the digital spectrometer with constant amplitude pulses divided in two unequal cable delays. We obtained a value of about 20 ps, which corresponds to an effect of 1 or 2 ps on the total resolution.

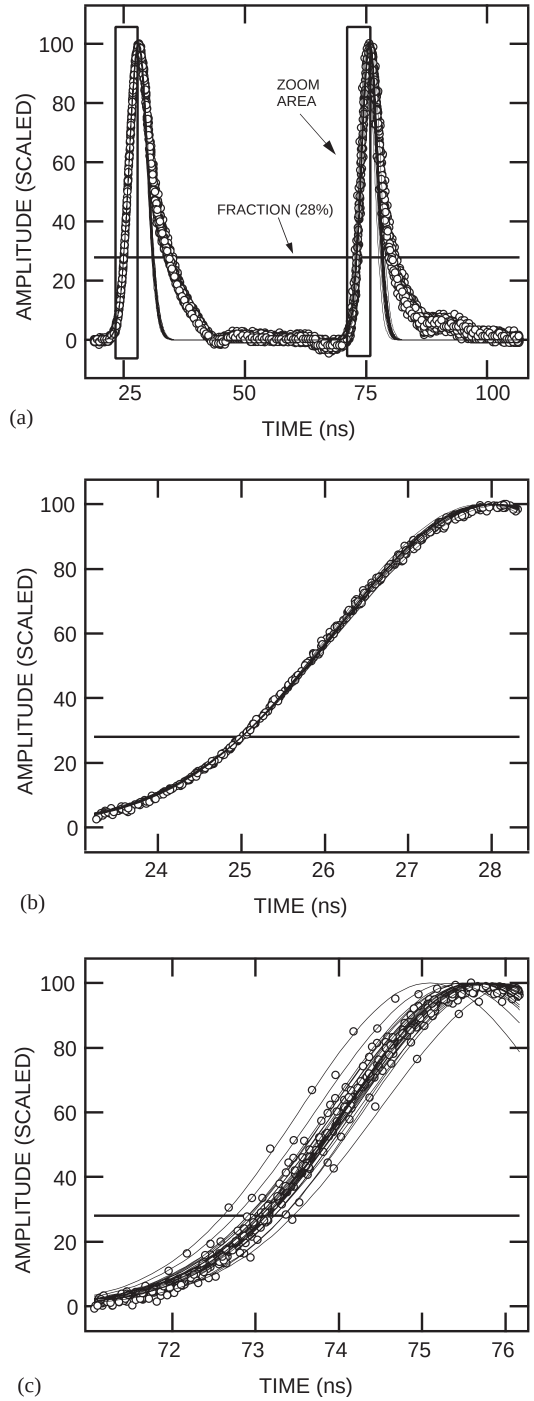

Fig. 7. A timing demonstration. The pulse pairs are obtained by measuring an ideal coincidence source (panel a). A Gaussian fit has been used for timing. Pairs have been shifted and pulse heights normalized so that the timing instants of *start* pulses coincide (panel b). The time resolution can then be observed as the jitter of the positions of normalized *stop* pulses (panel c).

### 3.2.1. Effect of sampling rate and noise

The influence of sampling rate and noise on the time resolution of the digital positron lifetime spectrometer was studied by using a $^{60}Co$ source. It emits two simultaneous photons with energies 1.17 and 1.33 MeV acting thereby as a nearly ideal source for resolution studies. To make the study more comprehensive, we used also our previous digital positron lifetime spectrometer setup based on the Tektronix TDS 3052 oscilloscope [4] with the data-analysis procedures presented in the present paper.

The detector conditions were kept constant during the data-acquisition period. Data were acquired at sampling rates 1 and 2 GS/s with DP210, and at 2.5 and 5 GS/s with TDS 3052. The time resolution value (FWHM) obtained with DP210 was 204 ps at 1 GS/s and 201 ps at 2 GS/s. For the TDS 3052, results were 208 ps at both sampling rates.

Contrary to expectation, the time resolution values obtained with TDS 3052 are, in spite of the larger number of samples in the leading edge, slightly worse than those measured with DP210. A potential explanation could be the larger amount of noise in the Tektronix data. A visual comparison of the pulses recorded with the two digitizers reveals that the noise level of TDS 3052 is about two times that of DP210. No significant difference in the pulse shapes at least up to 1 V level can be observed. This comparison was done with pulses sampled at 2 GS/s (DP210) and 2.5 GS/s (TDS 3052).

To evaluate the effect of random noise in the digitized pulses we added different amounts of simulated white noise with software to the data sampled with DP210 at 2 GS/s. To quantify the results, we calculated the average magnitude of the deviation between a voltage sample and the (Gaussian) fit. Without any extra noise added to the pulse the average deviation was found to be about 1.0 LSB. Adding noise so that the deviation equals 1.1 LSB results in a degradation of resolution by 3 ps. Further, an average deviation of 1.5 LSB leads to FWHM = 221 ps, i.e. worsening of time resolution by 20 ps. This simulation clearly suggests that the time resolution is sensitive to random noise in the digitized pulse. This may well explain the poorer time resolution obtained from the data measured with TDS 3052.

To obtain a better understanding on the importance of the number of points on the leading edge, we manipulated the sample sequences collected with DP 210 at the 2 GS/s sampling rate to imitate acquisitions at 1 GS/s and at 667 MS/s. This was done simply by selecting every second or third sample for 1 GS/s and 667 MS/s, respectively. The time analysis of these data results in a resolution about 3 ps at 1 GS/s and 30 ps at 667 MS/s worse than that obtained at 2 GS/s. The third highest 'hardwired' sampling rate 500 MS/s does not enable successful timing: at this rate the resolution function splits into separate Gaussian-like peaks. This result is easily understandable since there are only two samples on the leading edge.

The small difference between the 1 and 2 GS/s resolution results suggests that a further increase in the sampling rate at this noise level may not lead to significant enhancement in the resolution. Thus, with a digitizer whose noise properties are like those of the Acqiris DP210, the minimum number of samples on the leading edge required for a close-to-optimum timing is about four (1 GS/s). Eight samples (2 GS/s) appear to give the full time resolution in the present case.

### 3.2.2. *Amplitude linearity of pulses: walk*

The voltage pulse shape sampled by the digitizer ADC may vary as a function of pulse height for two reasons. The detector pulses themselves can be non-linear or the amplitude non-linearity of the digitizer may result in distortion of sampled pulse shapes. Extraction of the timing instant with the CF principle then leads to variation of the timing instant as a function of pulse height. This phenomenon is known as the walk effect.

To study the magnitude of walk in our digital positron lifetime spectrometer, we analyzed data acquired using a $^{60}Co$ source with narrow energy windows. A Gaussian fit with a 28% fraction was used for timing. In Fig. 8 we present the peak position of the resolution curve as a function of the position of a narrow window in the stop detector. The window in the reference detector is constant at 50%. The pulse amplitude at the upper level of the full window is 1.0 V in both detectors. As seen, the peak position varies by only about 7 ps when the narrow window is moved across the full 50% window. In the start detector the results are similar. These values are very low compared to those typically observed with analog instruments (often tens of picoseconds within a 50% energy window and usually attributed to the finite charge sensitivity of the discriminator [16,17]). This indicates

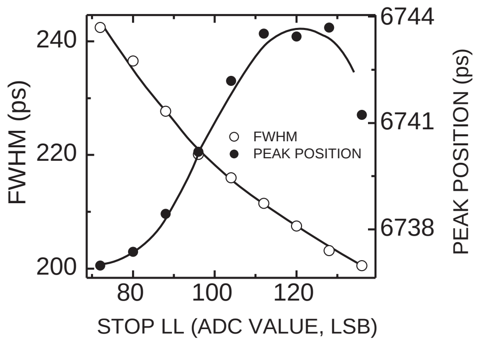


Fig. 8. Resolution function peak position (walk) and FWHM as a function of the lower limit of a narrow (8 LSB) energy window in stop detector. The horizontal range of the figure corresponds to a 50% $^{22}Na$ stop window. The lines are for guiding the eye. The results are similar for the start detector.

two things: firstly, the anode pulses seem to be linear in this anode current range, and secondly, the amplitude linearity of the digitizers is well sufficient for positron lifetime measurements. The magnitude of walk may, of course, depend somewhat on the fitting method.

### 3.2.3. Performance compared to an analog spectrometer

As a final test of the timing performance of the digital positron lifetime spectrometer we compared it to an analog spectrometer. The analog electronics was composed of units which were known to work well (Ortec Model 583 differential CFDs, Ortec 566 TAC). The CFD walk setting and CF delay were adjusted to the optimum values (smallest FWHM). The supply voltages over the PMTs were set such that 60% Co energy windows corresponded to anode pulse amplitudes of 0.4–1.0 V in both the start and the stop detector. The full-scale range of the digitizer was set at 1.0 V so that the pulses in the energy windows are sampled at maximum resolution. The digitally collected pulses, sampled at 2 GS/s, were analyzed using the smoothing spline method with $p = 0.3$ and $f_{CF} = 0.2$.

To assure reliable comparison, the same events were handled by both systems. This was accomplished by dividing the anode pulses with impedance matched power splitters to the discriminators and the pulse combiner. The discriminator pulse-height windows were set for 60% Co windows. Once a successful conversion was performed by the TAC, the 'Valid Conversion' output supplied a triggering pulse to the digitizer. With this setup, at a rather low count rate, more than 98% of the coincidences processed by the analog system were also registered by the digitizer. The digital system discards events with more than two pulses.

The data acquired with the two systems are shown in Fig. 9. Closed markers represent the data processed with analog timing electronics and open ones the digitally processed data. No difference is noticeable. The FWHM is 212 ps for both sets of data. The line presents a Gaussian fit. Evidently, the contribution of the electronic resolution is negligible in both cases.

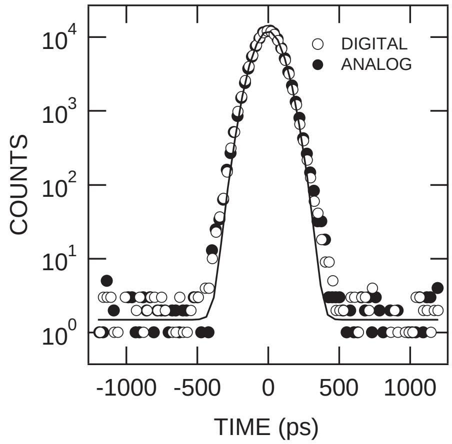


Fig. 9. Resolution functions obtained with analog timing electronics and digital data collection apparatus. Both spectra contain $\approx 110,000$ counts. The number of coincidences in the digitally measured spectrum is more than 98% of the coincidences processed by the analog system. The digital system discards events with more than two pulses. The bin width of the digital system has on purpose been chosen to be equal to that of the analog apparatus (25.65 ps/ch).

### 3.3. Linearity of the time base

The integral linearity of the apparatus is inherently extremely good, because the conversions are timed by a continuously running crystal calibrated clock. The linearity was tested by using a detector for providing the start signal and a pulser the stop. The produced time intervals are uniformly distributed. In Fig. 10 we present the results from the basic linearity measurement without using the gate module. No deviations from uniformity are detected, as expected. With the gate module we have observed small effects, of the order of a few tenths of a percent, in the differential and intermediate linearity [18]. These effects, due to, e.g. ringing, periodical noise and digitization errors are so small that their contribution is barely discernible in a lifetime measurement and is of the same order as normal variations in an analog apparatus, i.e. less than a picosecond.

### 3.4. Performance with small pulse amplitudes

In positron lifetime spectrometers it is important to keep the average anode current in the PMTs as

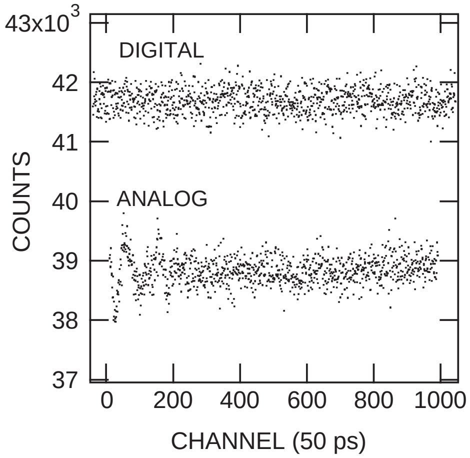


Fig. 10. Linearity measurements with digital and analog lifetime spectrometers. The linearity measurement of the digital apparatus has been performed without the gate module. The oscillations observable in the beginning of the analog spectrum are a normal artifact and pose no problem in positron lifetime measurements.

low as possible for good long-term stability of the system [11]. Therefore, operation of the spectrometer at low pulse amplitudes is advantageous. With modern CFDs the smallest pulses that can reliably be handled are some hundreds of mV in amplitude. Below this the operation may become unstable. The lowest full-scale range of DP210 is 50 mV which suggests that the internal noise level in the digitizer is much lower than this. We studied how much the pulse amplitude can be decreased without loss in time resolution. It is evident that when decreasing the signal-to-noise ratio of the pulses, the resolution ultimately starts to degrade due to both increasing relative quantization errors and the analog noise in the digitizer electronics.

The anode pulse heights were reduced by using attenuators between the pulse combiner and the digitizer. The full-scale range of the digitizer was chosen in each case such that the anode pulses are digitized with maximum amplitude resolution. Fig. 11 illustrates the time resolution of the spectrometer as a function of the attenuation. The pulse amplitudes at the lower edge of the energy window of the stop detector are also marked in the figure. The resolution is constant at 218 ps until the LL amplitude decreases below 25 mV. With attenuation less than or equal to

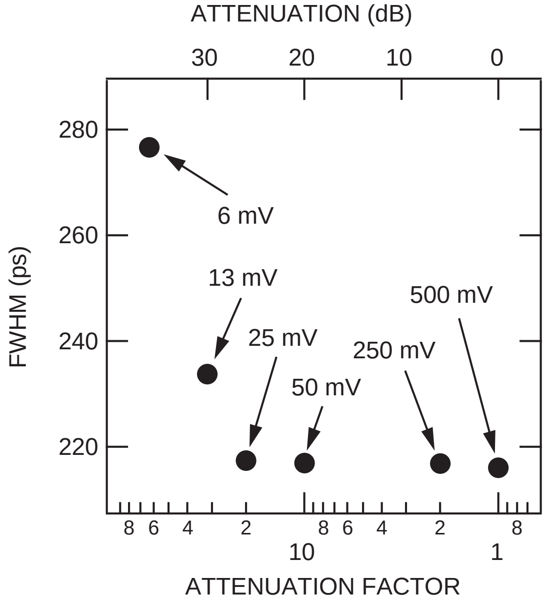


Fig. 11. The time resolution as a function of anode pulse height at the digitizer input. The measurement has been performed by attenuating both the *start* and *stop* pulses. The voltages presented in the figure represent the lower level of the *stop* window. Only at the highest attenuations (⩾26 dB) the full-scale range of the digitizer is not fully utilized. The width of the amplitude windows (50% $^{22}$Na) has been kept constant in all measurements.

26 dB, the anode pulses fill the whole full-scale range of the digitizer. At higher attenuations, the quantization error increases and contributes to the worsening of the time resolution.

We simulated the effect of increasing the quantization error by truncating samples to artificially increase the quantization error. The results show that dividing the full-scale range into 64 levels (6 bits) instead of 256 levels (8 bits), leads only to a 10-ps increase in the resolution. This effect is small compared to the increase from 218 ps (at 0 dB) to 275 ps at 36 dB attenuation corresponding to a similar decrease of the number of utilized voltage levels. Thus, the degradation of the resolution is mainly due to the noise in the variable gain amplifier of the digitizer card.

The fact that the time resolution is close to optimum even when the smallest anode pulses are only 25 mV of amplitude means that the PMTs can be driven at average currents one-tenth of those usually required with analog CFDs (usable pulses $>250\,\text{mV}$). This decreases the degradation rate of the gain of the PMTs by the same factor, which again enhances the long-term stability of the spectrometer. When applying lower supply voltages over the PMTs, one just has to take care that the voltages at the input electron optics of the tubes are sufficiently high [11]. This usually means that one has to modify the voltage divider chain from the suggestions given by the manufacturer.

## 4. Other tests

### 4.1. Intermediate-term stability of the spectrometer

The stability of the digital positron lifetime spectrometer was investigated by collecting Co-spectra with about $2 \times 10^5$ counts each for 10 days. An overall drift of about 10 ps in the centra of mass was observed. This magnitude is also typical of conventional analog spectrometers. This drift can mostly be attributed to the variation of the transit time and gain of PMTs as a function of laboratory temperature [19]. During the measurement the internal thermometer of the digitizer was used to register the temperature, which varied by about 2 °C. The correlation between the temperature and the peak position is apparent. To reduce the effect of the drift, a normal software compensation is applicable, whereby the spectrum is saved in smaller parts and the drift is compensated by shifting the partial spectra into a fixed position with software.

### 4.2. Lifetime measurement

As a final test of the digital spectrometer we measured positron lifetime spectra in bulk Si (Fig. 12). After subtraction of the source components, a single exponential convoluted with a Gaussian resolution function fits the data very well. The fitted lifetime equals 219 ps in agreement with previous experiments [7–9]. The time resolution obtained from the fit is 220 ps (FWHM). We have already used the system in a positron lifetime study of the semi-insulating properties of SiC [20].

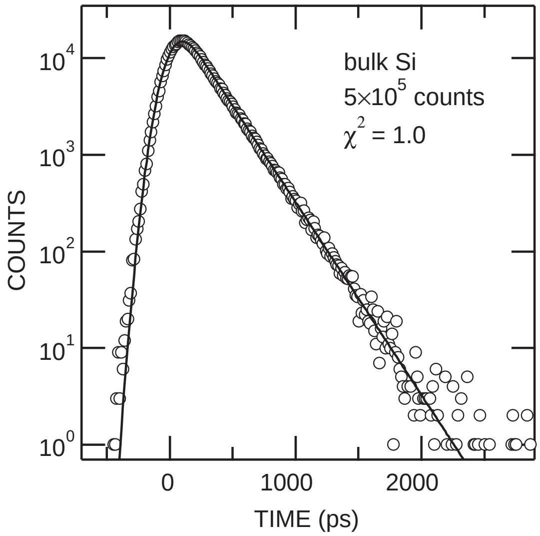


Fig. 12. Positron lifetime spectrum measured in bulk Si. The spectrum is source and background corrected. The average positron lifetime from the fit is $\tau = 219\,\text{ps}$ and the time resolution FWHM $= 220\,\text{ps}$. A detector–source distance of a few centimeters and a rather small number of counts explain the exceptionally good fit at the beginning of the spectrum.

## 5. Conclusions

A fully operational digital positron lifetime spectrometer has been set up and its performance investigated. The system is composed of two fast scintillation detectors, a pulse combiner, a triggering unit and a digitizer connected to a computer.

The performance of the digital spectrometer was studied comprehensively by applying common basic tests used for characterizing a positron lifetime spectrometer. The results show that the performance of the digital approach is equal to or better than that of the analog. The time resolution of the system ($\approx 200\,\text{ps}$) is similar to that achieved with analog devices, and is primarily determined by the scintillation detectors. The data processing and storage capacity achieved with the system, $\geqslant 3000$ events per second, is sufficient for positron lifetime measurements. Compared to conventional equipment, the linearity of the time scale was found to be good, as the conversions are timed by a continuously running crystal calibrated clock. We also demonstrate another important advantage—the possibility to use smaller pulses from the detectors, which slows down the aging of the PMTs. According to our tests the digitizer is able to handle as small pulses as 25 mV without significant contribution to the time spread. The quality of the digitizer is also demonstrated by the small amplitude walk, less than 10 ps in a 0.5–1 V pulse-height window.

Various timing methods with software were tested and the best results were obtained with CF timing. Software can also be implemented to perform offline corrections to compensate, e.g. residual amplitude walk and drifts in the spectrum position, and to reject pile-up pulses. These possibilities along with easy setup and good stability represent significant advantages over conventional positron lifetime spectrometers.

## Acknowledgements

We thank Prof. K. Kalliomäki for useful discussions.

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