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A digital measurement system of 2-detector Doppler broadening

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Abstract

A simple digital measurement system of 2-detector Doppler broadening is presented. We use a data acquisition (DAQ) card to digitalize the pulse from main amplifier, and use software to process the digitalized pulse. We demonstrate that DAQ card with software can replace some conventional analog electronic instruments, such as gate generator, delay and coincidence system. The two-dimensional correlation spectrum shows that this system is as good as a conventional analog measurement system. The system is more convenient and more reliable because of using little analog hardware.

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Keywords: Digital; Positron Doppler broadening; Data acquisition card; Software coincidence

1. Introduction

The Doppler broadening method plays an important role in the application of positron annihilation spectroscopy to the study of defects in materials [1]. The conventional 1-detector Doppler broadening measurement system, which examines only one of the photons from the annihilation process, is distorted by background events. This problem is particularly acute in the energy region where the contributions from high momentum core electrons are dominant.

In 1977 Lynn et al. added a second Ge(Li) detector to the Doppler broadening setup in order to observe the second annihilation photon in coincidence [2]. This resulted in an improvement of the peak to background ratio by two orders of magnitude and of the energy resolution by a factor of $\sim\sqrt{2}$. As a result, it became possible to observe high momentum annihilations with the core electrons. Recently, this method has been revived [3,4]. The new 2-detector setup improves the peak to background ratio in the annihilation spectrum to $\sim 10^5$. It has been shown that the high momentum part of the positron–electron annihilation momentum can be used to identify the chemical environment of the annihilation site [5,6]. This is based on the fact that the tightly bound core

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electrons, owning to high momenta, retain their element-specific properties even in a solid.

Two detectors are used in coincidence and positioned collinearly with the sample. Both annihilation photons are measured. Let E_1 and E_2 be the energies measured by detector 1 and detector 2. The sum energy $E_1 + E_2 = 2m_0c^2 - E_b$, where E_b is the binding energy of the electron and positron in the solid. The difference energy $E_1 - E_2 = cp_x$, where p_x is the momentum component of positron–electron pair in the direction of the detectors. Both photons are detected and the event is stored in a two-dimensional array.

In the present study we have designed a digital measurement system of the 2-detector Doppler broadening. Two signals from amplifiers are directly submit to the computer. Other analog electronic instruments, for example, constant fraction discriminators (CFD), multi-channel analyzers (MCA) and coincidence parts are replaced by a DAQ card with software. The two signals correlation is realized by the software coincidence. The 2-D correlation spectrum shows the system to be as good as a conventional analog measurement system. The system is more convenient and more reliable because of using little analog hardware.

2. New measurement set-up

Two high purity germanium detectors (HPGe, EG&G Ortec, detection efficiencies are 20% and 10%, respectively) face each other, at a distance of 15 cm from ^{22}Na and the sample, which in a sandwich structure. The block diagram of the system is shown as Fig. 1. The 0.511 MeV photon pairs produced by the positron annihilation will be detected by the HPGe detectors, and the signals will be amplified by the pre-amplifier and amplifier and then shaped in the amplifier. Then the signals will be collected by the DAQ card in computer. We use one of the two signal channels to trigger the DAQ card. After A/D converting, the digital signals will be put in memory. Then the online analyzing software will calculate the amplitude of the signals and the time interval between two signals produced by photon pair. The software will record the energy of two photons and time interval between two photons into hard disk, and show the data in a 2-D spectrum on the screen. The data in hard disk will be processed after measurement, for further research.

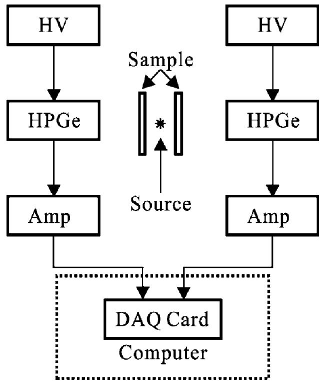

Fig. 1. Block diagram of the system.

The DAQ card we used is ADLINK PCI-9812, 20 M/s sampling rate, 12 bit A/D, four input channels.

A typical signal from amplifier is shown in Fig. 2. The shaping time of the amplifier is 2 μs. In the figure we can see that the ascend slope of the signal is about 2–3 μs, and this signal be collected in 12 μs, 240 sampling points under 20 M samples/s. In the experiment, we collect 512 sampling points for every signal. Because every sampling point occupies 2 bytes, the bandwidth between

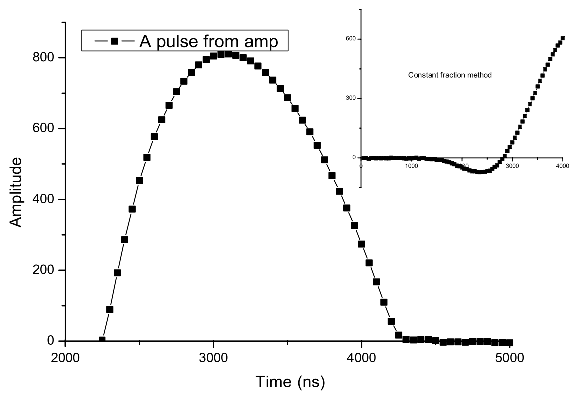

Fig. 2. One signal collected by the DAQ card (UNI), the inlet indicates the constant fraction method.

DAQ card and computer should be greater than 8 M bytes/s when the counting rate is about 5 K in each signal channel. So, there is no problem in bandwidth.

We use software to process these digital signals. First we find the peaks in both two signal channels. If there is one peak in each signal channel, we calculate the height of the peak. The height of peak is the amplitude of the signal, and represents the energy of the photon. Then we calculate the time interval between the two peaks, by which we decide if the two photons are from the same annihilation event.

The sampling deviation of the DAQ card is about 0.1% in 0.511 MeV, not good enough comparing to the resolution of the HPGe (~0.2%). It will cause a big deviation in the final result. If we use the data around the peak, we can reduce the total error. We had try many functions to fit the sampling data around peak, but the functions which have too many parameters (>3) cannot get more accurate results, and will take a long time to calculate, and the two-times polynomial, parabola is a right–left symmetry function, but the signal (shown in Fig. 2) has a rapid ascend slope and relatively slow descend slope. So it cannot get a good result, if we use the two-times polynomial in this experiment. At last, we choose 19 sampling points around the peak, fit them with a three-times polynomial, and get a relatively better result.

The conventional timing method for HPGe signal needs CFD and timing filter amplifier, but in this experiment, since we only use the timing information to coincide, and the counting rate is very low (about 3 K cps) we use the data signal acquired from DAQ card to time with constant fraction method. Because the ascend slope of the signal is not linear, when choose a big fraction constant, we can not get a good timing resolution. So we select 5% as the fraction constant. In fact, because the constant is very small, we first should subtract the base line of the signal. We use the difference of the timing zero point as a criterion of coincidence. The timing resolution is shown in Fig. 3, and the FMHW is about 100 ns.

After all, we record the amplitude and timing of the signal in hard disk and show on the screen. The

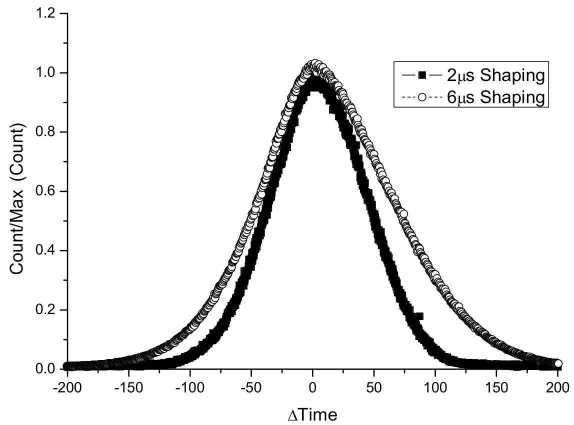

Fig. 3. Timing resolution: the shaping time of two linear amplifiers is 2000 and 6000 ns, respectively. The radioactive source is ^{22}Na, and the counting rate is about 2000 cps in each signal channel.

off-line analyzing program will process the information in hard disk in following steps:

1. Use the position of 0.662 MeV peak of ^{137}Cs and 0.511 MeV annihilation peak to calibrate the system in both signal channels.
2. Cut the whole measurement data into pieces, each segment represents a measurement of 1 h, calculate the peak position in 0.511 MeV, and judge if the system is stable. Because the measurement takes up a long time, and the environment can have effects on the system, so if we find the peak drift much, we should discard the data in one or more hours.
3. Calculate and subtract the background of 2-D spectra. We use the two-dimensional step function to simulate the background [7].
4. Calculate the FMHW of the annihilation peak in sum spectrum [7], and use the FMHW as a criterion to discard the events which

$$|(E_1 + E_2) - 2 \times 0.511 \text{ MeV}| > \delta,$$
$$\text{here} \quad \delta = \text{FMHW}.$$

5. Use $E_1 - E_2$ as coordinates to get difference spectrum.
6. Divide those spectra of different samples by a spectrum of standard sample to get quotient spectra.

3. Experimental results and discussion

For examining the performance of the system we measured some samples. The result of this experiment is shown in Figs. 4 and 5. Fig. 4 is a 2-D spectrum of Si(1 0 0). We can see the Doppler broadening clearly in the direction from top left to bottom right in the figure.

Fig. 5 is quotient spectra to Si. In this figure, we can see the Al_2O_3, MgO and $MgAl_2O_4$ have same peak position, we think it is caused by oxygen [8]. And Ge has no obvious peak, this result is in agreement with the Ge–Al quotient spectra [5]. Al is similar to Si in Doppler broadening.

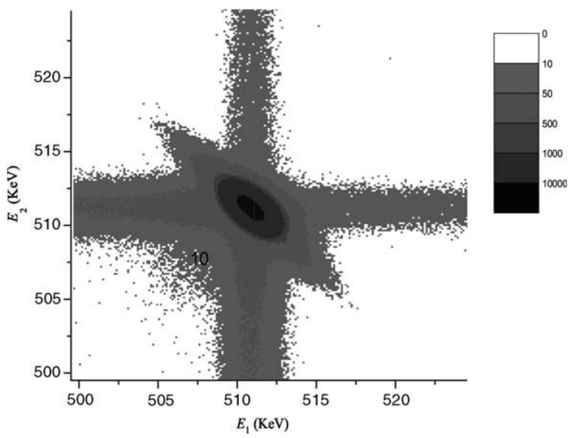

Fig. 4. 2D spectrum of Si(1 0 0) (count is about 1.5×10^6).

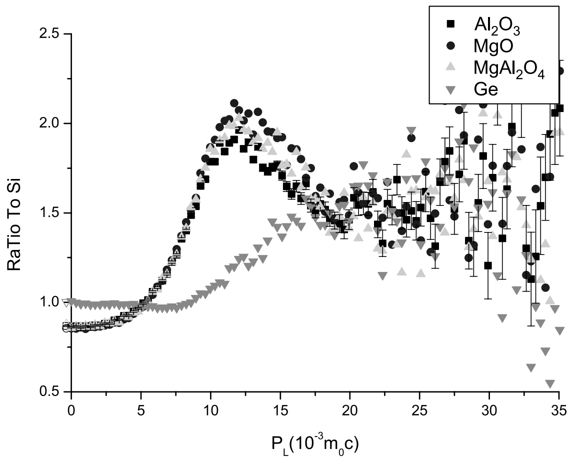

Fig. 5. Quotient spectra to Si. The counts are about 2×10^6, measure time is about 10 h in each sample, and the data are before deconvolution and smooth.

4. Performance of the system

The performance of the system is show in the following.

Timing resolution is about 100 ns. In the experiment the counting rate is no more than 2700 cps, so the incidental coincidence counting rate is no more than 1.5 cps, and far below the total coincidence counting rate (about 300 cps).

The energy resolution is as good as a 4096 channels MCA with same HPGe detector. The resolution of this system as follows:

$$\Delta_{sys} = \sqrt{\Delta^2_{HPGe} + \Delta^2_{Amp} + \Delta^2_{DAQ}}.$$

If we use MCA instead of the DAQ card,

$$\Delta_{sys} = \sqrt{\Delta^2_{HPGe} + \Delta^2_{Amp} + \Delta^2_{MCA}}.$$

The energy resolution of the HPGe detector is about 0.2% in 0.511 MeV, and the resolution of DAQ card in same position is below 0.05%, so the deviation of DAQ card can be ignored.

Every time after the DAQ card collected a set of data, the registers in DAQ card should be reset, and it takes a long time to transfer the data into computer through the PCI bus. So the DAQ card has a longer dead time than MCA. We compare the counting rate of MCA with DAQ card, and find that the DAQ card has about 30% dead time when the counting rate is about 3000.

Only four NIM modules are used in the whole system (two high voltage bias supplies, and two linear amplifiers) so it is cheaper, steady and easy to maintain. This is the reason we use the digital system.

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