TOWARDS DIGITAL γ-RAY AND PARTICLE SPECTROSCOPY *

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Digital spectroscopy is an experimental technique for directly processing of detector signals without analog signal shaping. Digital spectrometers capture the detailed shape of preamplifier signals with high speed ADCs, and then process captured waveforms in real time with field-programmable gate arrays and digital signal processors, that perform digitally all essential data processing functions, including precise energy measurement and event timing, ballistic deficit correction, pulse shape analysis, and time stamping the output data for offline analysis. Applications of this novel technology include position sensitive γ-ray spectroscopy with arrays of Ge detectors and high-speed particle emission spectroscopy. In both applications digital spectrometers process signals from semiconductor detectors in order to measure the interaction energy, time, and location within the detector volume. Excellent energy resolution and essentially zero dead time can be easily obtained with XIA digital spectrometer devices, even when time separation between consecutive events in a decay chain is shorter than 1μs. These and other applications of digital spectroscopy are at the frontier of experimental nuclear chemistry and nuclear physics.

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1. Introduction

Researchers in the field of Nuclear Physics have traditionally been mainly interested in obtaining the best possible energy and timing information with a given detector. While it is known [1] that more information can be obtained from the precise shapes of the detector signal pulses, the required analysis

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is commonly considered to be an advanced experimental technique due to the complexity of the required analog circuitry. The advent of digital data acquisition with fast analog to digital converters (flash ADC's) and digital filtering, however, has recently [2] changed this situation by placing pulse shape analysis within reach of an experimental nuclear physicist.

The new technology can be used advantagously in a number of applications. In multielectrode γ-ray detectors, pulse shape information can be used to find the photon conversion point with a precision much better than the size of individual electrodes. In phoswich detectors, the relative contributions of various time components of the light output pulse can be determined, yielding a particle identification signal (*i.e.*, neutron *versus* γ discrimination, or the charge and mass of the incident particle). In gas [1] and silicon [3] detectors, information on the ionization density profile can be used to determine the charge and mass of the ionizing particle. The list of such applications goes on and on, clearly pointing to the benefits that pulse shape analysis could bring if used routinely in nuclear physics experiments.

In this paper we will first explain in general terms how energy and timing information is obtained from the digitized preamplifier output signal, and how analysing the shape of the digitized ADC trace can yield additional information, such as making a ballistic deficit correction to the measured energy values. We will then describe the concrete digital spectroscopic pulse processor DGF-4C manufactured by XIA. Two novel applications of this processor will be discussed: the *position-sensitive γ-ray spectroscopy* and *fast particle emission spectroscopy.* We will then discuss a few data acquisition issues such as time stamping and event building. Finally, we will conclude by discussing some of the features of the digital processing electronics that can specifically benefit experimental nuclear physicists.

2. Digital pulse processing

Each analog stage in a conventional signal processing chain introduces irreversible signal deterioration that cannot be removed by further processing stages. On the other hand, once digitized, signal information is preserved during transmission and storage as digital data. The principle of digital spectroscopy can thus be summarized as follows: *digitize as soon as possible in order to preserve fidelity.* The earliest location in the processing chain where the signals can be digitized is immediately after the preamplifier. Until recently, the resulting volume of digital data was difficult to handle, thus severely limiting practical applications of the early digitization scheme. For example, a 40 MHz sampling rate at 12 bit precision yields 60 MB/s of raw data *per single detector channel.* Such huge data rates are difficult merely to transmit over practically available data links, let alone process. A remedy to the problem of high data rate glut was patented by X-ray Instrumentation Associates in about 1993 in the form of *Real Time Processing Units (RTPUs)* whose role was to reduce the raw data stream to manageable level by digitally filtering the raw ADC data. The RTPUs were first introduced in a *Digital X-Ray Processor (DXP)* geared towards high count rate X-ray applications [5]. Recently a *Digital Gamma Finder (DGF)* [2, 5], whose main applications are high-precision γ-ray and particle spectroscopy, has brought the power of digital spectroscopy to the Nuclear Physics community.

2.1. Obtaining energy and timing information from digital data

In all XIA digital pulse processors, RTPUs continously extract "running energy values" Φ from the ADC sample stream X_i by a trapezoidal finite-impulse response (FIR) filter [6] having a peaking time L and gap G [1]. The energy value E for a given event is determined by the peak value of the filter response Φ at the time $L + \frac{1}{2}G$ after the event, *cf.* figure 1. The difference between two sums over L samples reduces the noise of a single sample by a factor $\sqrt{L/2}$, while the separation G reduces the sensitivity to signal rise time variations.

$$\Phi = \sum_{i=L+G}^{i=2L+G} X_i - \sum_{i=0}^{i=L} X_i \, . \qquad (1)$$

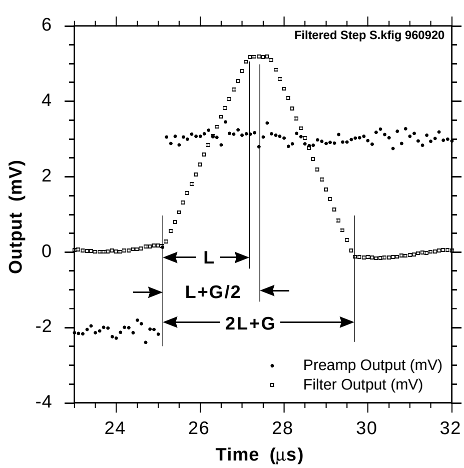

Fig. 1. Trapezoidal finite-impulse response (FIR) energy filter with peaking time L and gap G. The energy value is sampled at the peak of the filter response, that occurs at the time $L + \frac{1}{2}G$ after the event.

[1] The FIR peaking time L is related to the familiar "shaping time" t_s as $t_s = \frac{1}{2}L$.

Because the calculation (1) must be repeated by RTPUs each clock cycle, *i.e.*, every 25 ns in the case of the XIA's DGF-4C signal processor, the RTPUs are implemented using the field-programmable gate array (FPGA) technology capable of performing calculations at this speed. In addition to energy calculations, RTPUs also perform event triggering and pileup inspection, *cf.* [5] for details.

Time of arrival of each pulse is extracted by the on-board digital signal processor (DSP) with the digital constant fraction (CFD) method by interpolating between the ADC samples, yielding FWHM $\approx$ 4 ns for pulser signals, much below the ADC sampling period (25 ns). Timing resolution with large coaxial Ge detectors is usually limited by the detectors themselves to about three times that value.

2.2. Ballistic deficit correction

The energy resolution of γ-ray detectors can be dominated by ballistic deficit effects, particularly when short processing times are needed to permit high rate operation [1, 7]. Even though ballistic deficit is diminished by the trapezoidal energy filter (1), it nevertheless adversely effects energy resolution when resistive feedback preamplifiers are used to process signals with large rise time variations, as is the case with coaxial Ge detectors [8]. XIA recently patented a ballistic deficit correction algorithm which uses pulse shape analysis to achieve good energy resolution. The ballistic deficit cal-

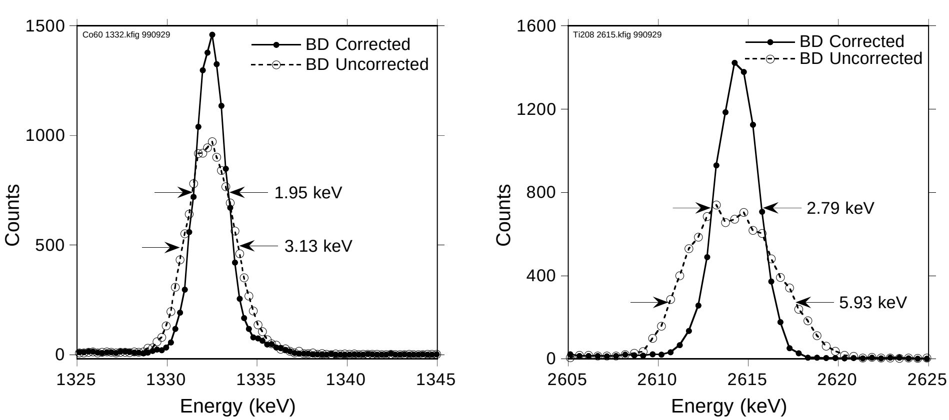

Fig. 2. Accurate ballistic deficit correction calculated by the on-board DSP allows for excellent energy resolution for shaping time as short as $t_s = 1\mu$s. Energy values calculated with formula (1) (open points) show an inferior energy resolution caused by the rise time variations, that are corrected for when the ballistic deficit correction is applied to the data (full points).

culations are performed by the DSP, that processes raw filter results (1) supplied by the RTPUs. Figure 2 shows the improvement in spectroscopic energy resolution obtained by this method for a particular coaxial Ge detector for peaking times as short as 2μs, *i.e.*, an equivalent RC shaping time t_s as short as $t_s = 1\mu$s. Excellent results provided by the new correction algorithm allow the throughput of the digital spectroscopy system to be significantly improved relative to its analog equivalent. In some applications, such as obtaining particle ID directly from planar Si detectors [3], ballistic deficit correction is necessary in order to accomodate the large pulse shape variations characteristic of that method [4].

2.3. Pulse shape analysis

The ballistic deficit correction was a special case of pulse shape analysis, where the waveform of the preamp pulse was used to derive specific corrections to the measured energy value. In the general case, information such as position in the detector [2] or mass and charge of the detected particle [3] is encoded in the entire shape of the pulse. In order to access this information, the consequtive ADC samples are stored in a fast first-in, first-out memory (FIFO) and subsequently processed by the on-board DSP. The DSP code can be extended by users with application-specific algorithms to extract pulse shape information of specific interest. User algorithms can be implemented in a high-level language such as C, or in DSP assembly language if processing speed is important.

2.4. The Digital Gamma Finder DGF-4C

Several types of digital signal processors are manufactured by XIA for various applications. The four-channel CAMAC module DGF-4C [2, 5] was designed for nuclear physics experiments involving large-volume Ge detectors with resistive-feedback preamplifiers, but it is flexible enough to be used in many other applications as well. The module consists of four independent acquisition channels driven by a 40 MHz clock, serving as a common time reference. Each channel features a high-fidelity amplifier with computer-controlled gain and offset, whose function is to match an amplitude and DC offset between a module input and an internal flash ADC. The amplifier performs no signal shaping, other than the necessary "minimal filtering" of high-frequency signal components above the Nyquist frequency of the ADC. The ADC is followed by an RTPU that performs digital filtering (1) and pileup inspection, where both L and G are programmable from 25 ns to 49.6 μs. All four channels are served by a single DSP, responsible for calculating ballistic deficit corrections and other user-programmable pulse shape analysis, as well as for internal bookkeeping functions. The DSP also performs output data formatting and buffering.

Every event that is accepted by the module is time-stamped with an internal reference clock of 25 ns granularity before being placed in the output buffer. If the noise of the input signal permits for good timing, the digital constant-fraction calculation is performed by interpolation between ADC samples to improve timing precision, down to about FWHM $\approx$ 4 ns, as discussed earlier.

The DGF-4C modules feature several auxillary input and output connectors such as trigger and multiplicity input and output, as well as event validation and clock synchronization, designed to connect several modules together into a large composite data acqusition system. The detailed description of the DGF-4C module is available at the XIA web site [5].

3. Position-sensitive γ-ray spectroscopy

The primary aim of *position-sensitive γ-ray spectroscopy,* to be used with newly proposed high-efficiency γ-ray detector arrays [9], is to reconstruct full photopeak energies of all γ-quanta from measured positions and energies of Compton-scattered γ-rays. In other applications, such as medical imaging, it is also essential to reconstruct all three coordinates of a photon interaction within the detector volume. The complexity of the reconstruction problem depends on the detector geometry. Coaxial Ge detectors with segmented outer electrodes will require solving a complex 3D problem to find the positions of the γ-ray interactions [9]. Preliminary measurements [2] of the signal waveforms from a prototype coaxial segmented Ge detector indicate feasibility of the approach.

On the other hand, a double-sided striped planar Ge detector allows the 3D reconstruction problem to be decomposed into three independent 1D problems [10], thanks to a combination of three effects: (A) each γ-ray produces a point-like charge deposition with no plasma delay. Charge clouds thus move almost like point charges within the detector volume. (B) The "small pixel effect" makes a point-like charge cloud visible only when it is close to a detector electrode. (C) A detector thickness of ≈ 1 cm translates to ≈ 100 ns time difference between front and back signals that is easy to measure with the DGF-4C.

Under these conditions, a striped planar Ge detector is effectively turned into a "solid state drift chamber", whose data is easy to measure and to interpret. Figure 3 shows the measured [10] time differences between the pulses collected by the front and back strips of the 1 cm-thick detector, compared with the known distribution of interaction depths of the 122 keV γ-rays. An excellent agreement is observed in this figure between the measured and expected distributions.

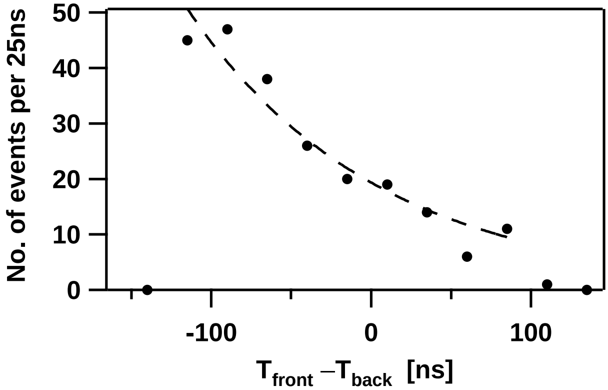

Fig. 3. The measured distribution of interaction points in planar Ge detector (points) is compared with known attenuation of 122 keV γ-rays in germanium (dashed line).

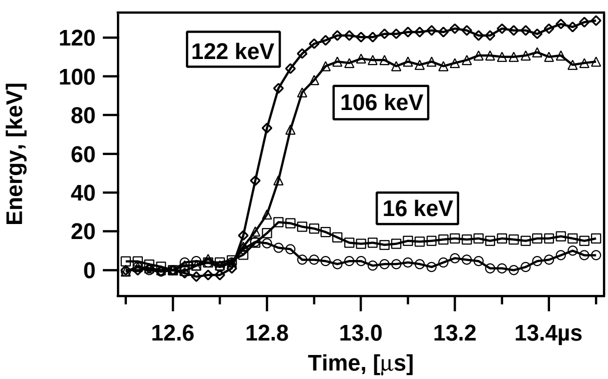

Fig. 4. Compton scattering event, as measured with the DGF-4C in a planar Ge detector. The full energy of an incident γ-ray (122 keV) was partitioned between initial Compton-scattering close to the detector surface (16 keV) and absorption of the scattered γ-ray deeper in the detector (106 keV). The bottom ADC trace with a transient excursion from zero voltage was caused by the induced transient charge in the neighboring strip electrode.

Position resolution in a Ge strip detector also enables one to disentangle Compton scattering events within the detector volume, making it possible to trace complex Compton cascades of γ-rays through a stack of Ge detectors. Figure 4 shows a set of waveforms from a Compton-scattering event, where an incident 122 keV γ-ray was first Compton-scattered close to the detector surface depositing 16 keV, and then was absorbed deeper in the detector depositing the remaining 106 keV. The positions of both events in the depth direction (perpendicular to the detector face) could be calculated from the time difference between the pulses. Small pulses induced in the neighboring strips can in principle be used to improve the in-plane position resolution to a fraction of the strip pitch. This work [10], while still preliminary, clearly demonstrates the potential of the approach.

4. Pulse shape analysis and particle identification

Deriving particle identification from recorded pulse shapes is a very promising application of digital pulse processors such as the DGF-4C. It is well known [1] that, in response to different ionizing radiation, scintillators such as CsI(Tl) emit different light components whose decay time (microseconds) is ideally suited to analysis with digital electronics. It is relatively less known that semiconductor detectors exibit similar time variations of their response on a somewhat shorter time scale (tens of nanoseconds) [3], also well matched to digital pulse processor sampling rate. The rise time variations are made more pronounced and shifted to longer times (hundreds of nanoseconds) when a planar Si detector is irradiated from its back side [4], thus making such Si detectors ideally suited for digital pulse processing. It is worth pointing out that digital pulse processors such as the DGF-4C can obtain not only the time and energy from the input signals, but can also calculate the ballistic deficit correction, that was shown [4] to be necessary in the case of back-irradiated Si detectors.

5. Fast particle emission spectroscopy

A traditional analog method to measure radioactive decay by proton emission leads to a dead time of $\approx 7\mu$s, primarily due to overloading the analog electronics by the large pulse caused by implanting the emitting ion into the silicon detector [11]. This dead time severely limits one's ability to investigate proton emitters in the μs time range. In order to overcome the limitation, DGF-4C modules were used [12] to take advantage of their large dynamic range, and ability to record and process pulses with almost no dead time. Figure 5 shows an example of such a sequence of pulses, *i.e.*, a weak ≈ 0.5 MeV proton emission pulse occuring about 1.5 μs after the large-amplitude (≈ 18 MeV) ion implantation pulse. [The amplitude of the weak pulse was somewhat smaller than expected (≈ 1 MeV for proton emission) due to partial escape from the detector.] Further experiments utilizing the DGF-4C electronics are in progress to investigate proton emitters in μs and even sub-μs decay time ranges.

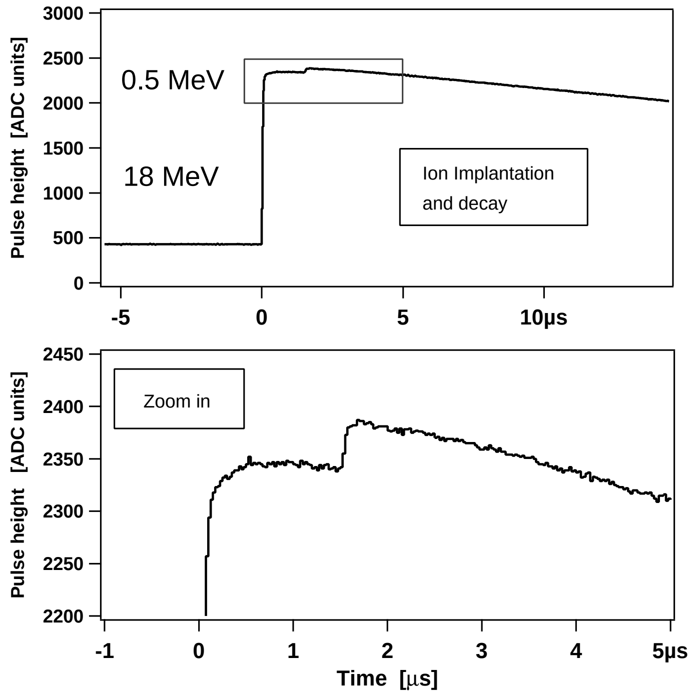

Fig. 5. Proton emission (a small $\approx$ 0.5 MeV pulse) occured about 1.5μs after a ^{113}Cs ion was implanted into a silicon detector (a large $\approx$ 18 MeV pulse). Both events were clearly resolved by the DGF-4C pulse processor.

6. Data acquisition with digital electronics

Data acquisition (DAQ) using digital electronics differs from event-driven DAQ using analog electronics and traditional ADC's. The digital electronic modules continuously sample input signal and extract quantities of interest (amplitude and shape parameters) for every detected pulse. Event processing is internally initiated whenever the signal meets certain criteria, such as the occurence of a steep rise in the sampled data due to incident radiation, *cf.* figures 1 and 5. The data processing in a given module can also be externally triggered, thus allowing many modules to be synchronised among themselves. Every packet of information is time stamped with an internal clock value, formatted, and put into an output buffer for a delayed readout. The data buffers are retrieved by a main DAQ computer over a FastCAMAC bus (optionally: FERA bus [13]), and global event building is performed by the main DAQ computer based on time stamps provided by every module. The main computer can also retrieve ADC waveforms recorded by each module in order to perform offline user-programmed pulse shape analysis.

(Sophisticated users can program the module's DSP to perform such analysis in-situ, as noted earlier.)

Because of the relative complexity of the digital electronics and many numerical parameters pertinent to their operation, the modules are typically controlled using dedicated PC-based software with an intuitive graphical user interface.

7. Conclusion: the merits of digital spectroscopy

Digitizing early and processing digital rather than analog data makes it possible to implement the whole processing chain in a single electronic unit that implements all essential data processing functions, including:

1. Precise energy measurement.
2. Variable filtering time.
3. Timing to within a small fraction of the data sampling period.
4. Ballistic deficit correction.
5. In-situ analysis of the ADC traces (*i.e.*, pulse shape analysis).
6. Time stamping of every datum for offline analysis.
7. Buffering and formatting the output data.

Because of high integration, digital electronics is very cost effective when compared to the analog alternative. The electronics has no mechanical moving parts such as potentiometers, and thus all the internal module settings can be easily recorded in a disk file. The same hardware unit can therefore serve many diverse applications and is easily changed from one to another by changing appropriate parameter values. Example applications include:

1. Radioactive recoil decay tagging.
2. Fast particle emission spectroscopy.
3. Position sensitive gamma spectroscopy.
4. Simultaneously measuring particle energy and ID.
5. Pulse shape investigations for detector R&D.

6. Other applications can be developed by the end user by either programming the main DAQ computer to analyse captured ADC waveforms, or by programming the internal DSP to perform in-situ pulse shape analysis.

In conclusion, digital pulse processing is a well developed technology that has become available to the nuclear physics community and will soon change the way nuclear physics experiments are performed.

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