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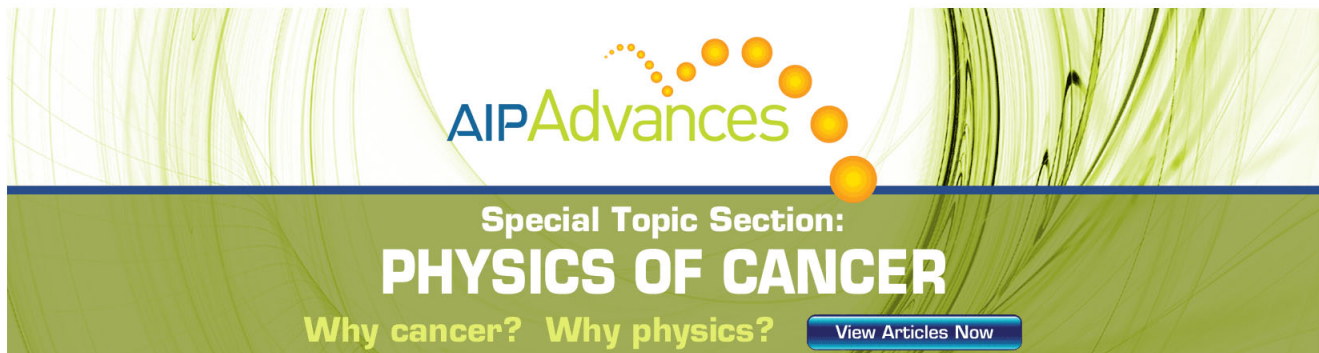
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Extending the dynamic range of nuclear pulse spectrometers

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Using an innovative time-varying front-end electronics in conjunction with a bulky coaxial high-purity germanium detector, we were able to extend the range of the radionuclide spectra well beyond the analog to digital converter (ADC) saturation point. The electronics automatically conditions the signal for digital-filtering optimization if it is in the ADC voltage range and for time-over-threshold analysis if it exceeds the ADC range. A high spectroscopic resolution has been achieved in both operation ranges. An unprecedented wide energy range from 5 keV to 150 MeV of equivalent energy, or 90 dB, has been obtained using a single acquisition chain, while maintaining a high-energy resolution in the whole spectrum. For example, with an ADC range of 3 MeV a resolution has been obtained of 1.3/2.2 keV full width at half maximum on the 122/1332 keV gamma-ray lines of ^{57}Co and ^{60}Co, and of <0.4% in the time-over-threshold region, or for energy deposits beyond 3 MeV. © *2008 American Institute of Physics.* [DOI: 10.1063/1.2894305]

In this Note we suggest that high-resolution spectroscopy of ionizing radiations (X and gamma photons, charged particles, ions) is possible even beyond the ADC range, by using a proper time-varying preamplifier and switching to a time-over-threshold (TOT) measurement technique for the over-range pulses. The typical case in which such an approach can be fully exploited is with thick high-purity semiconductor detectors such as Ge, Si(Li), CdTe, etc., where the measurement range is typically limited by the ADC itself or by the output stages of the analog electronics, rather than by the detector. Normally such cases are addressed by reducing the gain of the electronic chain or by using two or more electronic chains in parallel with different gain values. The former approach typically yields a poor resolution at the lower energies and suffers from noise and disturbances picked up at the circuit output, while the latter requires a complex multichannel acquisition architecture for each individual detector channel. The proposed approach overcomes these issues and provides through a single acquisition channel a high resolution and an excellent noise immunity over the full dynamic range of the detector. The technique is demonstrated using a HPGe capsule of the AGATA detector[1] and an ^{241}Am+Be source with Ni/Fe target setups.[2]

In Fig. 1 the structure of the used front-end electronics is shown. It consists of a charge-sensitive preamplifier ac coupled to the detector anode (c_{ac}), connected to a passive pole-zero cancellation stage with a fast-reset circuitry, comprising a Schmitt-trigger comparator (T) and a switched constant-current sink (I_R). The higher threshold (T_H) of the comparator is set at or slightly below the ADC maximum input voltage. The lower threshold (T_L) is set at 0 V. A gain/ antialiasing (GAA) stage is used to pass the signal along to a 14 bit 100 MHz flash ADC. The sampled signals are stored into a personal computer hard disk through a universal serial bus interface and processed off line using either standard digital-filtering techniques,[3–5] or the TOT algorithm described next, depending on whether their amplitude is under or over T_H.

The charge-sensitive preamplifier itself has a very large voltage range of 11 V, with a linear range of 8 V or of more than 150 MeV of equivalent energy. However, after the GAA stages, the ADC can cover only a little fraction of this range or 3 MeV of equivalent energy. Reduction of the circuit gain would remarkably spoil the energy resolution at the lower energies because of second-stage and pickup noises and therefore is not envisaged. A question arises: how to measure the large signals yielding ADC saturation ? Here is the idea: when the signal overcomes the ADC range, switch S is turned on by comparator T and current I_R is continuously flown through capacitance C until the output voltage reaches its baseline at 0 V. At that point switch S is automatically turned off by T. The time needed to complete this process, or TOT for the shake of brevity, depends on the amplitude of the input signal. So a measurement of the TOT yields a measurement of the signal amplitude. Note that the working principle of this circuit is similar to that of Wilkinson ADCs.[6] In order to accurately measure the reset time, we sampled the signal provided by the comparator using one more 14 bit 100 MHz ADC channel and interpolated the leading and trailing edges of the sampled waveform so as to derive its width at half amplitude with a subsampling-time resolution. In Fig. 2 one such acquired large signals is shown along with the corresponding comparator signal. We accurately calculated the expression of the reset transient, and we found an exponential relation between the reset time and the total equivalent energy that is subject to reset. This energy is given by the sum of the energy of the large overthreshold event and the energy of the tail due to previous sub-threshold events. By expanding the exponential time-to-energy relation to second order, while also including the tail contribution and an offset term, the following relation is found:
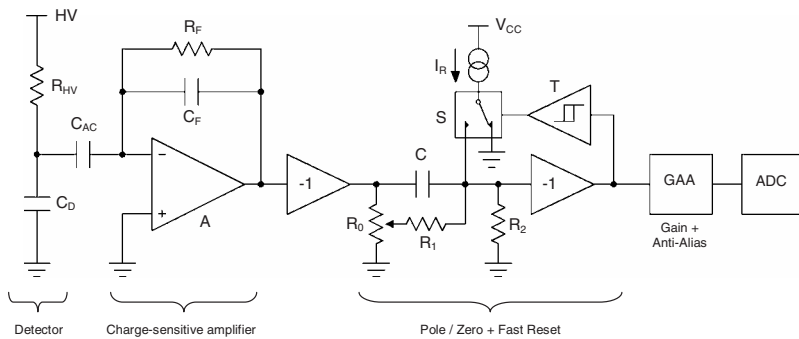
FIG. 1. Structure of the used front-end electronics. HV is the +4 kV high voltage used for detector biasing and C_{AC} is the ac coupling capacitor.

$$E = b_1 T + b_2 T^2 - k_1(V_1 - V_2) + E_0, \qquad (1)$$

where E is the unknown energy of the event, T is the reset time, and V_1 and V_2 are the pre- and postevent baselines. b_1, b_2, k_1, and E_0 are constant parameters that can be easily derived once for all through a least-mean-square fitting procedure run on a calibration dataset. The first term on the right hand of Eq. (1) dominates over the second, so parameter b_1 well represents the "reset velocity" which, in our case, is of ~ 4.2 MeV/μs.

We tested the new measurement technique using an HPGe detector of AGATA (core electrode) as irradiated with an ^{241}Am+Be source housed in a cylindrical box with thick paraffine walls for fast-neutron thermalization and we used a Ni powder or Fe target for neutron capture production of gamma photons in the 3–9 MeV energy range. We also used a few other simpler calibration sources (^{57}Co, ^{60}Co). In Fig. 3 a spectrum is shown of this source as acquired beyond the ADC range with our front-end electronics working in the TOT mode. The energy of the events is derived from the reset time through relation (1). The overall count rate of the events was ~ 3.5 kHz. The part of the spectrum at energies <3 MeV has been also acquired in normal pulse-height mode, but is not shown here.

For comparison we also show in Fig. 4 the same spectrum as acquired in amplitude mode only, after reducing the

electronic chain gain in such a way that the ADC range reached 9.4 MeV. Note that in this case the false line at 9.4 MeV is due to ADC saturation and not to physical events. Note also that gain reduction yielded a worsening of ~ 0.2 keV full width at half maximum (FWHM) in the energy resolution at low energy, i.e., on the ^{57}Co line, as caused by the higher impact of second stage and pickup noises.

The excellent correspondence of the spectra of Figs. 3 and 4 is evident, which proves the effectiveness of the TOT-mode measurement technique.

In Table I the energy resolution obtained with the new setup of Fig. 1 is shown as evaluated on the various spectral lines of the spectrum. It is worth observing that the width of the carbon line at 4.440 MeV region is intrinsically broadened by the Doppler effect. In fact, the line comes from the capture reaction involving the light nuclei of Be and the α
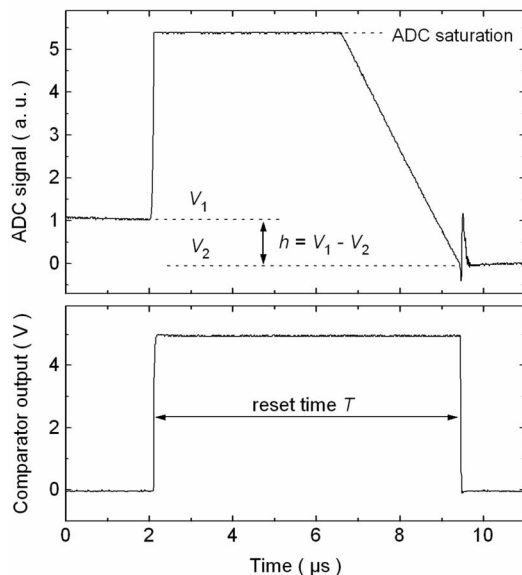

FIG. 2. Top: large signal waveform superposed to the tail of a previous event. The flat top is caused by ADC saturation. Bottom: corresponding signal provided by the comparator.
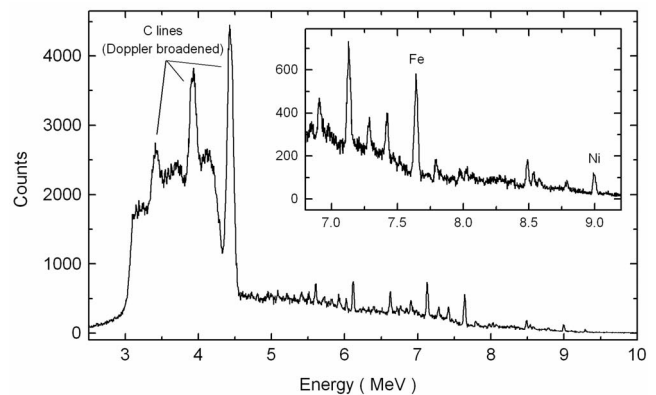

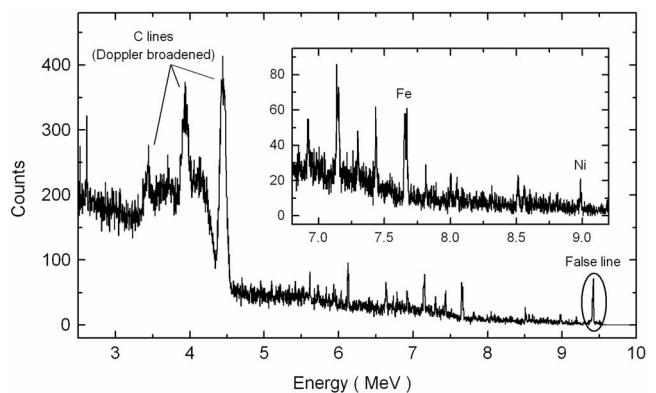FIG. 3. Spectrum acquired beyond the ADC range of ~ 3 MeV using the TOT mode technique.

FIG. 4. Spectrum acquired in amplitude mode after reduction of the electronic chain gain. The peak at 9.4 MeV is false and due to ADC saturation.

TABLE I. Energy resolution.

Energy	Resolution FWHM	Mode
122 keV (^{57}Co)	1.3 keV	Standard filtering
1.33 MeV (^{60}Co)	2.2 keV	Standard filtering
4.440 MeV (C)	2.34%[a]	TOT
~5.6 MeV	0.34%	TOT
~6.1 MeV	0.28%	TOT
7.6312 MeV (Fe)	0.21%	TOT
7.6456 MeV (Fe)	0.21%	TOT
8.9984 MeV (Ni)	0.21%	TOT
~19 MeV (pulser)	0.10%	TOT
~33 MeV (pulser)	0.081%	TOT
~50 MeV (pulser)	0.086%	TOT

[a]Dictated mainly by the Doppler effect (see text).

particles emitted by the ^{241}Am source. The resulting ^{12}C nuclei emit γ photons while moving after absorption of the α particle momentum. The random angle of the emitting nucleus trajectory yields a remarkable Doppler-effect broadening. All the other lines acquired in the TOT mode show an excellent energy resolution better than 0.4%. Even if the physical line of largest energy is that of Ni at about 9 MeV, we could test the system for equivalent energies >9 MeV using a high-precision pulser to simulate large detector signals. As can be seen in Table I the pulser lines are in the 19–50 MeV. We had no possibility to inject larger test signals with the pulser available in the used experimental setup. However, in testbench measurements we measured a circuit range of >150 MeV, i.e., an output voltage swing >8 V as seen at the charge-sensing stage output.

We believe that this new approach opens the way to all those applications where high-energy deposits (from charged particles, ions, gammas) are to be measured while maintaining at the same time the highest possible energy resolution in the typical lower-energy range.

In conclusion, a new time-variant circuit technique has been proposed for nuclear pulse spectroscopy, which permits a substantial improvement of the energy measurements dynamic range. The technique has been successfully tested using a capsule of the AGATA detector array, an advanced front-end electronics, and an ^{241}Am+Be neutron source with Ni/Fe targets generating high-energy gamma photons by neutron capture reactions. The AGATA preamplifiers fully support the shown technology, which will therefore be available for the next-generation nuclear physics experiments.

The limiting factor of the shown technique is ADC blindness to pileup along the reset transients. Increasing the reset velocity or reducing the gain can help in this regard.

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