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PILEUP REJECTION IN A DIGITAL PROCESSOR FOR SPECTROSCOPY WITH CRYOGENIC DETECTORS

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PILEUP REJECTION IN A DIGITAL PROCESSOR FOR SPECTROSCOPY WITH CRYOGENIC DETECTORS

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ABSTRACT

The slow response of cryogenic detectors, with a pulse length of a tens of milliseconds, limits the allowable counting rates to a few counts per second and makes easy the analysis with a Digital Signal Processor. Because of the length of the pulses pileup is a serious limit in the measurements that need high statistics because, in order to avoid it, the source activity must be very low. A new efficient method for detecting pileup and reconstructing the original pulses using a digital matched filter is described. We show the spectra obtained using a Beryllium and a Rhenium μ–calorimeters which indicate the possibility of using higher activity sources and reduce the measuring time. The results of test both with simulated pulses and real μ–calorimetric measurements and comparison with traditional derivative methods show the efficiency and the flexibility of the system.

1 – INTRODUCTION

In the experiments where high energy resolution and low energy threshold are requested the effectiveness of cryogenic detectors has already been demonstrated(1). Because of the low counting rate of this kind of detectors it is possible to use a digital signal processor to analyse the pulses(2). In particular the use of an off–line digital filter (in our case a matched filter) can greatly improve the energy resolution of the detector. The length of the pulses (5–100 ms) is also the intrinsic limit of these detectors, therefore the activity of the source must be less then a few Bequerel; higher activities introduce non negligible pileup(3). In the experiments needing high statistics this will result in a very long measuring time. If pileup is high, the traditional methods for reducing these effects (analogue and digital)(2) can introduce a distortion in the spectrum. In particular, when the amplitude of the pulses is comparable to the noise, either the pileup can be undetected or a noise spike due to the electronics can be detected as pileup and then a good pulse will be rejected. In this contest we propose an easy convolutive method that allows a better discrimination between the real pulses and the noise spikes using a matched filter. This method is also more sensitive to the pileup when the second pulse is very small and on the leading edge of the first one. Moreover the interactive use of such a method allows a separation of the two original pulses that can be analysed separately; so we avoid a rejection of the pulses which can change the spectrum. The analysis time with this algorithm, running on a Digital Alpha Station is less than 20 milliseconds per waveform with the 25% of pileup probability. The analysis time is negligible with respect to the actual acquisition time of cryogenic detectors. Here we present the comparison between the traditional digital methods (derivative methods). The spectra obtained from the analysis of a Beryllium–7 electron capture and a Rhenium–187 β–decay with different methods are shown. In the case of the Rhenium–187 μ–calorimeter the tests indicate the possibility of using a higher activity source which could significantly reduce the measuring time.

2 – EXPERIMENTAL APPARATUS

As described in a previous paper(2) a 12 bit CAMAC waveform recorder (Le Croy Model 6820) has been used to digitalize analog pulses into digital data for a successive off–line analysis. The instruments were set to record a file of 1024 12–bit data words at every trigger with the trigger event at channel 256. Data before channel 256 are used to establish a baseline by assuming a constant function for the baseline dependence.

After pileup rejection the pulse energy is determined in two ways: by integration of the pulse or by convolution of the pulse with a reference pulse built averaging "good pulses" which have been selected by eye without pileup and noise spikes. The maximum of the product of convolution is assumed proportional to the pulse energy. For every pulse recorded, a shape factor is evaluated in order to reject spurious pulses, pulses with noise spikes superimposed and eventual pileup not detected before. The algorithm for calculating shape factor is described later.

For each pulse rise time, pre–trigger slope and noise, and decay time are also computed for a successive complete analysis using PAW(4).

3 – DERIVATIVE METHODS FOR DETERMINING

In a derivative(2) method the signal is first smoothed with a low–pass digital filter in order to reduce high frequency oscillations, then it is differentiated and the crossing of a threshold by the resultant signal is searched. When there is only one peak in the registered waveform, or when the time interval between the two adjacent peaks is bigger than the pulse width, the energy of the pulse is evaluated; otherwise the pulse is rejected.

This method is insensitive to the form of the pulses: noise spikes can be detected as real pulses and then a good signal can be discarded. This method is also insensitive to a little pulse superimposed on a larger one, because the negative derivative of the first pulse can compensate the positive derivative of the second one as shown in figure 1.

It is also possible to reject pulses with pileup not identified by the derivative method using a shape factor, m:

$$m = \frac{\overline{\left(\frac{s}{r} - \overline{\left(\frac{s}{r}\right)}\right)^2 r^2}}{\overline{s^2}} \qquad (1)$$

where 'r' is the reference pulse waveform, 's' is the measured pulse waveform and the '$\overline{\ldots}$' indicates mean values.

Also the shape factor m can not be used efficiently for very small pulses because with mathematical passages m assumes the form:

$$m=\frac{1+\frac{\overline{n^2}}{\varepsilon^2}A^2}{1+\frac{\overline{y^2}}{\varepsilon^2}A^2} \qquad (2)$$

where 'A' is the amplitude of the pulse, 'e' is the noise in the pulse waveform, 'y' is the good reference pulse waveform and 'n' is an eventual distortion of the reference pulse due to the mean process ($r = y + n$). This expression shows that the shape factor doesn't depend from the amplitude of the pulses only for sufficiently high pulses. For little pulses it is very complicated to use.

Also traditional estimators such as Chi–square have the same problem. These estimators are useful in order to reject bad pulses like spikes, but they are very useless for discriminating against pile up.

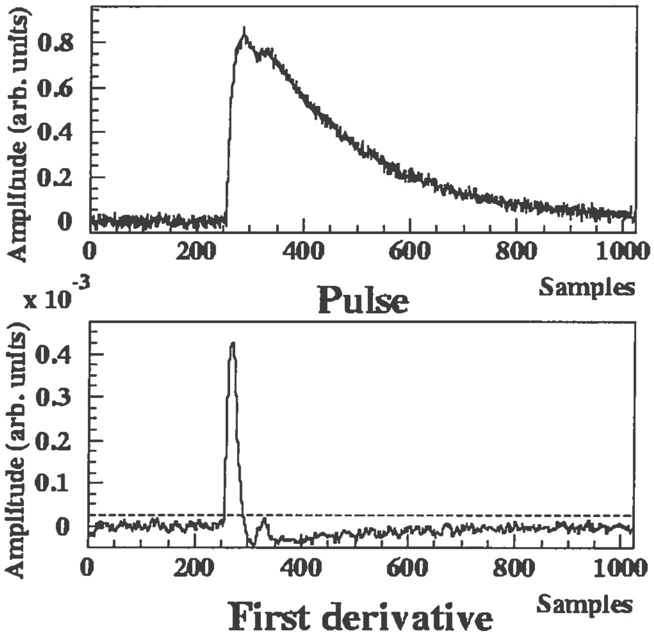

FIG. 1 – Pileup which can't be individuated by a simple derivative method: the negative derivative of the first pulse compensates the rise of the second one that remain under the trigger level (dotted line).

4 – CONVOLUTIVE METHOD

We suggest a completely different method which uses the reference pulse that we have at our disposal. In order to extract the real pulses with respect to the noise spikes we convolve the registered waveform with the rise interval of the reference pulse. This eliminates time information shorter than the rise time, but it is unimportant in this case because the pileup shorter then the rise time is in any case indistinguishable. This method, that is a simple matched filter, is very efficient in eliminating noise spikes. Because of the form of the pulses depends from the bolometer, in the case of a low–pass digital filter the parameters of the filter (shape, cut frequency and so on) must be changed every time. In the convolutive method the parameters change automatically when the form of the reference pulse change; then this method avoid a continuous study of the characteristics of the pulses and the consequent update of the digital filter parameters.

In order to eliminate the problem seen in fig. 1 we replaced the derivative method with a differential detector that identifies step in the signal greater then the noise fluctuations. Our algorithm is then independent of the shape of the pre–pulse region.

When we have identified how many pulses are present in a registered waveform and where they are located, we analyse the waveform. If only one pulse or zero pulse are detected we simply analyse the waveform with the matched filter, we discard the multiple pileup (generally very rare cases) and we try to separate the two original pulses in a simple pileup. In order to do this we estimate the amplitude of the first pulse convolving the acquired waveform with the reference pulse windowed with a rectangular window smaller then the distance between the two pulses, then we subtract the reference pulse normalised to this amplitude and we obtain the original second pulse. Interactively when we have the second pulse we use the same process in order subtract this pulse to the original waveform and we have the original first pulse. At this point we can analyse both the two pulses separately with the matched filter. Of course we save the information about the pileup in order to check the coherence of the results.

5 – EXPERIMENTAL RESULTS

In order to evaluate the relative efficiency of the derivative and the convolutive methods a series of tests has been made with real and simulated pulses. In particular a series of simple pileup waveforms are generated as follows: from a sample of low rate monochromatic X–ray registered waveforms a pulse with the noise of about the 5% of the pulse height was extracted; then by software a second pulse was attenuated by a factor varying from 1 to 1/10 and delayed with respect to the trigger ranging from –50 to 50 samples (a sample correspond to 0.1 msec) and then it was added to the first pulse; the intrinsic limit in the pileup discrimination due to the rise time of the pulses is 20 samples. Both derivative and convolutive methods are used for analysing generated waveforms and the result is reported in figure 2: the dark region contains the pileup cases discriminated by the traditional pileup detection and by the convolutive method, in the grey region pileup is detected only by our method and the derivative level crossing detection fails, the white central zone indicates that the pileup is not discriminated by both methods; the two dotted lines indicate the zone where the pileup is undetectable because the time interval between the two pulses is less than the rise time of the pulses.

In figure 3 we have also reported an example of pileup discrimination by our method, while in figure 4 we show a typical pileup and the reconstruction of the two original pulses made with our recursive algorithm. The efficiency of this algorithm is also shown in figure 5: a continuous simulated beta spectrum was analysed. The ratio between the spectrum obtained considering only signals containing pileup and the spectrum obtained considering only signals without pileup is reported. The ratio is constant, that indicates the agreement of the reconstructed pulses with the clean pulses.

These results convinced us to utilise this method in real experimental cases and in particular in the measurement of the activity of a Beryllium–7 source and in the measure of the end point of the Rhenium–187 β–decay with cryogenic detectors.

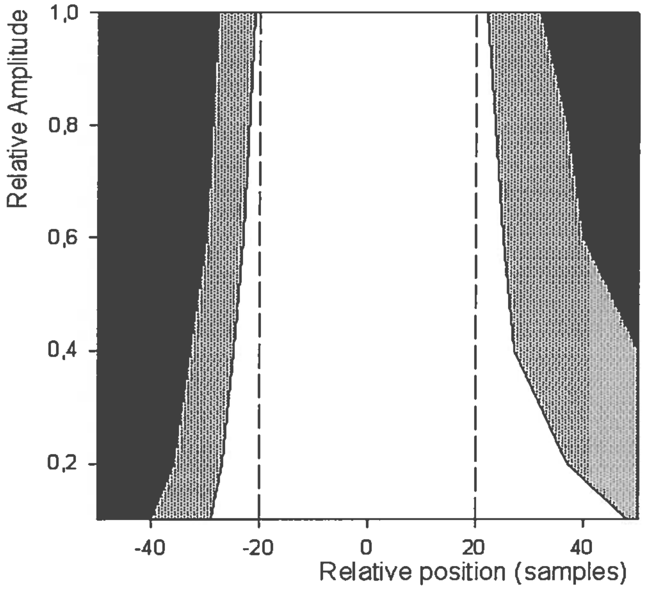

FIG. 2 – Individuating pileup efficiency of the derivative (black region) and the convolutive (grey region) method.

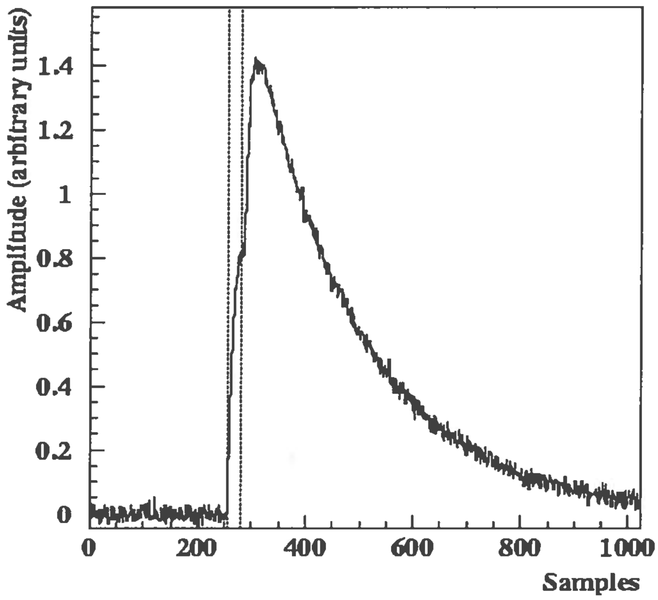

FIG. 3 – A typical pileup discriminated by the convolutive method: the distance between the two pulses is 25 samples, the rise time of the pulses is 20 samples.

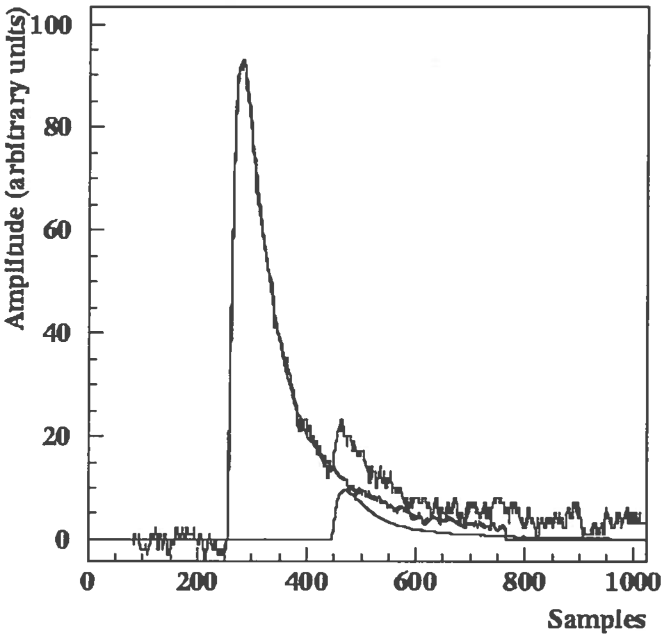

FIG. 4 – A typical pileup decomposed in the two original pulses by the convolutive algorithm.

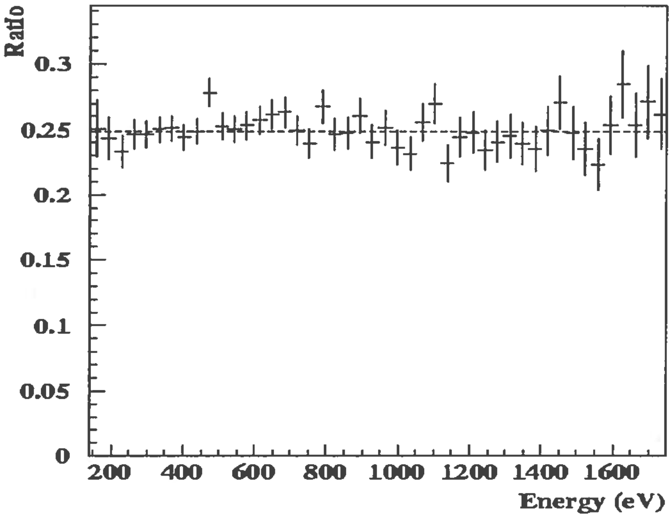

FIG. 5 – Analysis of a simulated beta spectrum: ratio between the spectrum obtained considering only signals containing pileup and the spectrum obtained considering only signals without pileup.

In figure 6 the spectrum of the Beryllium–7 obtained with a cryogenic detector is shown(5). Beryllium–7 decays by electron capture in Lithium–7: in the 90% of the cases the decay is to the ground state with an energy release of about 112 eV (53 eV in Auger electron or X–rays and 59 eV in recoil). In the remaining 10% of the cases the decay is to an excited state with the emission of a 478 keV γ–ray. The continuous line indicates the spectrum obtained by our analysis method, while the dotted line indicates the spectrum obtained by the traditional analysis method. The activity of the source was very high with respect to the detector response time (1.4 Bequerel) thus using the traditional method it is practically impossible to have a good spectrum: a lot of good pulses are rejected and a few pileup pulses are undetected. The spectrum obtained with the convolutive method is very good and the measured activity agrees with the measurement of the 478 keV γ–rays made with a conventional germanium γ–rays detector.

The most important physical result of our analysis method is shown in figure 7, that is, the measurement of the end point energy of the Rhenium–187 β–spectrum(6). Using a low activity source (dotted line in the figure) we found that the end point energy is $E=(2470\pm25)eV$. In order to measure the anti–neutrino mass, with this activity the measure time will be a few years; using a higher activity source the measure time will be lower but the pileup will be non–negligible.

Figure 7 shows a measurement with a high activity source analysed with the derivative and the convolutive method: in the first case the end point is about 2600 eV due to the poor rejection of the pileup, while in the second case the end point is E=(2478±6)eV, a value that well agrees with the previous one measured with the low activity source.

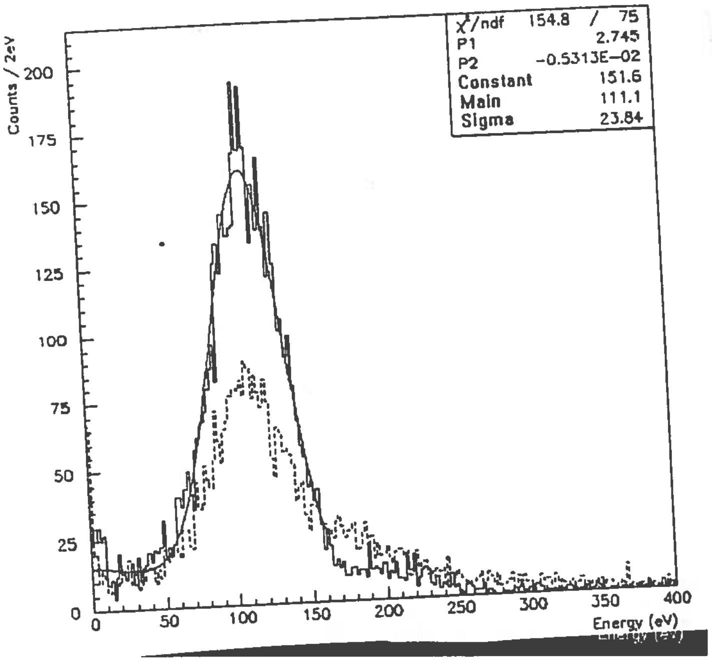

FIG. 6 – Beryllium–7 spectrum with a μ–calorimeter analysed with the traditional method (dotted line) and with the convolutive method (continuos line); data are referred to the convolutive method: P1 and P2 are the parameters of the exponential fit (noise and background).

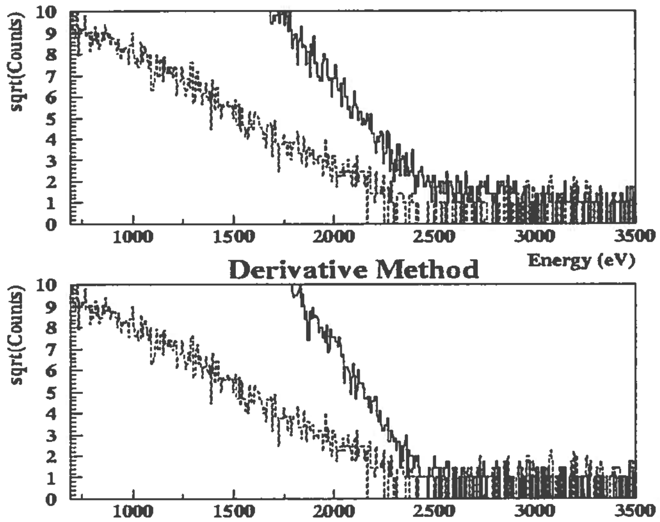

FIG. 7 – ^{187}Re spectrum with a μ–calorimeter analysed with the derivative and the convolutive method; dotted line indicate the same spectrum with a lower activity source (negligible pileup).

6 – CONCLUSIONS

A new convolutive method for individuating pileup in the analysis with a digital signal processor was described. The method was tested with off–line analysis of experimental data and it was demonstrated the improvement with respect to the traditional methods. In particular this method allow the use of a higher activity source in measurements that require high statistics. This means that the measuring time can sensibly decrease.

Limiting factors of our method are the necessity of knowing the form of the pulses and the dependence of the amplitude of the reconstructed pulses from the distance between the pulses. The use of an adaptative filter(7) instead of the matched filter in the algorithm can reduce this effect.

This method will be used in the measure of the antineutrino mass by the study of the ^{187}Re β–decay.

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