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Development of a zero-cost multichannel analyser based on digital signal processing for γ-ray spectroscopy using the PC sound card

A JANA[1], S K SINGH[1], A GUPTA[1], S DAS[2], K BASU[2], S SAMANTA[2], R RAUT[2], S S GHUGRE[2,*] and A K SINHA[3]

[1]School of Nuclear Studies and Applications, Jadavpur University, Sector III, LB-8, Bidhan Nagar, Kolkata 700 098, India
[2]UGC-DAE Consortium for Scientific Research, Kolkata Centre, Sector III, LB-8, Bidhan Nagar, Kolkata 700 098, India
[3]UGC-DAE Consortium for Scientific Research, University Campus, Khandwa Road, Indore 452 017, India
*Corresponding author. E-mail: ssg.iuc@gmail.com

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Abstract. A zero-cost multichannel analyser (MCA) system based on the digital signal (pulse) processing (DSP) convenient for γ-ray spectroscopy with conventional detectors such as scintillators and high-purity germanium (HPGe) has been implemented. The in-built high-performance analog-to-digital converter (ADC) in the sound card, an integral component of the present day personal computers, was used to digitise the signals from the radiation detectors. These pulses were then shaped using the established digital signal processing recursive algorithms. The filtered data were then displayed as histograms which then could be subjected to the traditional analysis to obtain peak parameters and the associated quantities were deduced. The developed system combines the performance of the sound card hardware with the flexibility allowed by the DSP to achieve a versatile MCA.

Keywords. Sound card; digital signal processing; pulse height analysis.

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1. Introduction

The spectroscopic measurement of the decay phenomena in unstable or excited nuclei allows us to have an insight into the fascinating world of nucleons, and is of relevance in areas of pure as well as multidisciplinary sciences. The signals from the detector are processed (shaped and amplified) to extract the amplitude of the electrical signal. The signal is proportional to the energy loss of the incident radiation in the active volume of the detector, using conventional analog electronic modules, and then digitised using the analog-to-digital convertor (ADC) for further storage and processing. Recent advancements in the domain of digital signal processing (DSP) have allowed us the flexibility to digitise the pre-amplifier signal and then subject it to numerical processing, using programmable digital filters, which provide a flexible and superior alternative to the conventional chain of analog electronics. Such a basic system plays a central role in introducing the students (both at the undergraduate and post-graduate levels) to the basics of experimental nuclear physics. However, these systems are usually very expensive, and very few students are privileged to have them operational in their respective laboratories. This motivated us to develop a zero-cost pulse processing and recording system by retaining only the radiation detector from the conventional set-up. The set-up as detailed in the subsequent sections, utilises the routinely available, 16-bit, 192-kHz sampling ADC, available in the sound card in a personal computer, to digitise the detector signal, which is then subjected to the digital pulse (signal) processing recursive algorithms which effectively (both in terms of cost as well as maintenance) replace the analog signal processing units. Prior to demonstrating the feasibility of the present methodology on live detector data, the recursive algorithms were extensively benchmarked using simulated pulse shapes to verify the system's performance. This allows the students the flexibility to have an insight into the associated pulse processing methodology (techniques). Results of the measurements using a pulse generator and a γ-ray detector are presented.

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At the onset, we assert that the present system by no means intends to dispense the whole range of state-of-the-art counting systems (either discrete or integrated) available in the domain of nuclear instrumentation. However, this implementation does attempt to circumvent the overheads of commercial systems and provide a basic acquisition hardware for teaching laboratories that may be plagued by limited resources.

2. Multichannel analyser system

Conventionally, the output of a radiation detector obtained from the pre-amplifier is shaped to improve the signal-to-noise ratio (SNR) and amplified to make it suitable for processing by the peak sensing ADC, and subsequently stored by the multichannel analyses (MCA). The pre-amplifier pulse is characterised by a sharp rise time $\tau_r \sim$ nanoseconds, and long decay time $\tau_d \sim$ microseconds, with a SNR of ∼1. This signal is then processed by a CR–RC^n $n \sim 4$ analog filter, for optimum SNR, and then is digitised using the peak-detect ADC, and recorded in the MCA.

Thus, the digitisation of the analog signals which links the analog and digital domains, is the most important process in modern day radiation counting set-ups. The conventional multichannel ADCs are extremely costly, which prevents their use in routine laboratory experiments. However, for a lower speed MCA, the complex commercially available ADC can be bypassed using ingeniously available in-built ADCs in the present day computer sound cards. The sound cards are usually equipped with low sampling speeds (48–192 kHz), with moderately high resolution, typically 16-bit ADCs. Assuming a 48 kHz sampling speed for the sound card, Nyquist rate (the minimum sampling rate desired to avoid aliasing of the input signal) limits the count rate of the decaying radionuclide to ∼24 kcps, which is considerably lower than the strength of the calibration sources routinely used in the laboratory set-ups. Hence, it is possible to design a system wherein we achieve successfully, the implementation of the computer sound card as a potent replacement for the ADCs utilised in conventional radiation counting set-ups. This has indeed been successfully demonstrated by Sugihara *et al* [1] and Ibrahim *et al* [2]. However, both these approaches demand the use of an intermediate pulse shaping interface amplifier to achieve the CR–(RC)^n shaping along with some options for pole zero cancellation as well as baseline restoration for the analog signal. The output of the amplifier is then connected to the line-in input of the sound card, through a RCA jackpin connector, while ensuring that the signal is limited to $\sim \pm 1$V, the dynamic range of the sound card. Conventional sound capture programs were utilised to capture and record the sound in the WAV format. The subsequent analysis programs were also developed by the authors, as discussed in the respective references.

As the preamplifier signals from the radiation detector have a typical amplitude of <1 V, they can be directly used as an input to the sound card, so as to digitise the signals and record them using the open source sound recorder software such as Audacity® [3] in the WAV format. The digitised signals can then be processed and subjected to the conventional digital pulse processing techniques following the use of recursive algorithms, implemented using both open source (such as ROOT [4]) as well proprietary software such as MATLAB® [5] packages. The major advantage of this approach is that it has eliminated the intermediate circuitry for pulse shaping and amplification. It therefore, can provide us with a nearly zero-cost pulse processing and data acquisition system, with features adequate for a routine laboratory experiment, besides providing flexibility to the user to enhance the degree of sophistication in the underlying pulse processing methodology. This paper reports the development of a DSP-based MCA system which utilises the in-built ADC of the sound card to digitise (record) the signals from a radiation detector.

3. Digital pulse processing with simulated detector pulse

The present endeavour to establish a DSP-based MCA requires us to develop the recursive algorithms (wherein the input–output relation involves a finite sum of products), as detailed subsequently. It is imperative that these algorithms be tested and benchmarked offline using simulations prior to them being applied on live detector data. With this motivation, we have simulated the pre-amplifier pulse from a scintillator and a semiconductor detector. The empirical functional form for the pre-amplifier pulse is detailed in refs [6–8]. The pulse shape from liquid scintillators can be described using the six-parameter exponential model:

$$v(t) = A\left[e^{-[(t-t_0)/\theta_1]} - e^{-[(t-t_0)/\lambda_s]} + B e^{-[(t-t_0)/\lambda_l]}\right], \quad (1)$$

where A and B are respectively the amplitudes of the short and long components at $t = 0$ and λ_s and λ_l are the decay time constants for the short and long component respectively. The parameter t_0 is necessary to describe the time reference for the start of the signal, and θ_1 is the decay constant of the pre-amplifier. However, Guo *et al* [7] have demonstrated that for inorganic scintillators such as NaI(Tl) and LSO, the above equation may

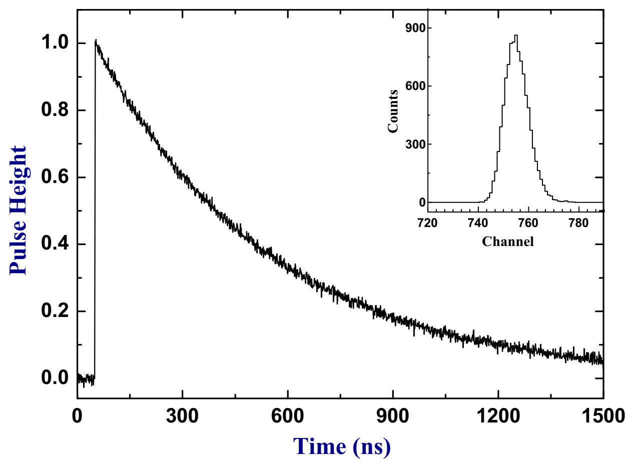

Figure 1. Simulated scintillator pulse for NaI(Tl), with SNR = 40 and the inset shows the corresponding energy histogram without the shaping of the pre-amplifier signal.

be truncated to a two-component exponential model, to symbolically represent the pre-amplifier pulses from a scintillation detector, which has been used in the present simulations:

$$v(t) = A[e^{-[(t-t_0)/\theta_1]} - e^{-[(t-t_0)/\lambda_s]}]. \quad (2)$$

The parameters of relevance for NaI(Tl) scintillator are $A = 1$, $t_0(\text{ns}) = 50$, $\theta_1(\text{ns}) = 499$, $\lambda_s(\mu s) = 49.005$. However, superimposed on the signal is an inherent 'white noise' (having a flat spectral density). Thus, the output from the pre-amplifier is a superposition of the actual signal and a white noise (generated with SNR of 40), purely for a demonstrative purpose, is presented in figure 1.

Now, if this signal was to be unconditionally amplified, and the histogram generated, then we would observe a substantial degradation in the relevant parameters, which quantify (detail) the peak, such as the full width at half maximum (FWHM), as depicted in the inset of the figure, owing to the simultaneous amplification of both the noise as well as the signal.

Consequently, it is imperative that we selectively amplify the signal while suppressing the noise using a circuit which has a frequency-dependent response such as the conventional RC–CR network. A RC–CR^n network is used in the analog domain, to obtain an enhanced SNR, which in turn also shapes the pulse to near Gaussian-shaped pulses. Such conventional filters are not optimised for high count rate applications. Radeka [9] has presented a trapezoidal filter which adequately addresses the two conflicting requirements in pulse processing, pertaining to optimum filtering for charge collection and for electronic noise, which are of relevance to high count rate applications, especially using large semiconductor detectors. Jordanov and Knoll [6] and Jordanov *et al* [10] have demonstrated the advantages of employing the 'trapezoidal filter' for high-resolution radiation spectroscopy in both the analog and digital domains of pulse processing. The details of this technique along with the associated electronics and the recursive equations are beyond the scope of the present manuscript and are elucidated in refs [6,10,11].

The trapezoidal filter transforms the characteristic exponential decay signal generated by the charge-sensitive pre-amplifier into a trapezoidal pulse, with identical rise and fall time. The flat top, whose duration is greater than the collection time, is immune to the rise time variations of the input pulse, as detailed by Jordanov *et al* [10]. Hence, the flat-top provides us the flexibility for noise suppression, and correction of ballistic defects by suitable adjustments of the parameters in the mathematical expression for the recursive algorithm [10,11] is detailed below:

$$d^{k,l}(n) = v(n) - v(n-k) - v(n-l) + v(n-k-l),$$

$$p(n) = p(n-1) + d^{k,l}(n), \quad (n \geq 0),$$

$$r(n) = p(n) + Md^{k,l}(n),$$

$$s(n) = s(n-1) + r(n), \quad (n \geq 0), \quad (3)$$

where k and l represent the rise time of the trapezoidal pulse and the sum of the rise time and the flat top. The parameter M is related to the decay time constant of the exponential pulse and the sampling time of the digitiser. It has been observed that if the flat top duration is chosen as half of the corresponding rise time, it results in an optimal energy resolution.

The result after subjecting the pre-amplifier pulse (depicted in figure 2) to a trapezoidal filtering (with a rise time of $\sim$500 ns, 200 ns as the flat top, and $M = 500$) is presented in figure 2a and the histogram formed subsequent to the shaping is presented in figure 2b. As seen from the figure, the effect of shaping the signal has minimised the contributions from noise as is evident from the substantially improved FWHM $\sim$ 1 channels. Thus, as per our expectations, due to the minimised noise contribution, the energy information is now spread over fewer channels, thus providing us with a yardstick for the merits of the implemented algorithm.

Having successfully implemented the algorithms for processing the simulated pulses from a scintillator, the same was extended to the pulses from a semiconductor detector, high-purity germanium (HPGe) for example. As detailed in ref. [6], the following expression was used to describe the pre-amplifier pulse from a HPGe detector:

$$v(t) = \frac{l}{\tau - \theta}(e^{-t/\tau} - e^{-t/\theta}), \quad (4)$$

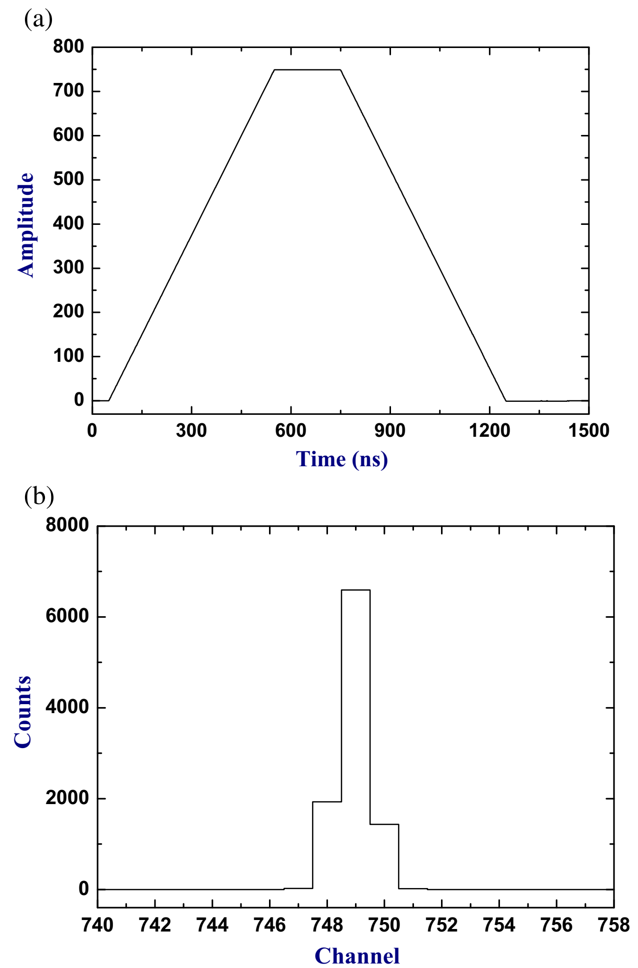

Figure 2. (**a**) Trapezoidal filtering of the pre-amplifier pulse and (**b**) the corresponding energy histogram after the shaping of the pre-amplifier signal.

where l represents the length of the convolution function, τ corresponds to the decay constant and θ accounts for the finite rise time of the pulse (∼tens of nanoseconds). The time duration of the flat top pulse is long enough to encompass the rise time variations in realistic set-ups [6]. However, care has to be taken to ensure that this length is not unreasonably long so as to introduce pile-up effects [6,12,13]. The trapezoidal filter had the rise time set as 2000 ns, with a flat top of 500 ns and $M = 2000$. The obtained results were very similar to those presented in figure 2 after the trapezoidal filtering, wherein the corresponding parameters were adjusted accordingly.

Having established the methodology for processing the pre-amplifier pulse from radiation detectors in the digital domain, we extended our methodology to the pulses from an actual radiation detector acquired with conventional radioactive sources.

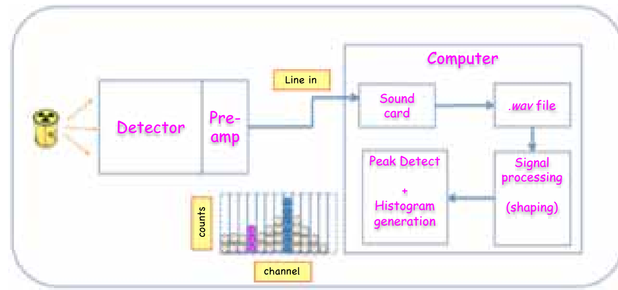

Figure 3. Schematic block diagram of the experimental set-up.

4. Tests using radioactive sources

The hardware comprises just the radiation detector and the PC with a sound card. The schematic block diagram of the set-up is presented in figure 3. The tests were conducted to investigate the linearity and the overall system performance such as the obtained energy resolution, the total recorded counts using a pulser as well as a radioactive source.

An essential or desirable characteristic of a data acquisition system is its linear response of the digitised output with respect the amplitude of the input pulse. The linearity of the present system was first examined, wherein the input to the sound card was derived from a pulse generator (from M/s BNC, Model DB-2) for various amplitudes and the corresponding digitised channel output was noted. For the pulser, the trapezoidal filter has a rise time of 150 μs, with a flat top duration of 80 μs and $M = 40$.

The correlation between the peak centroids and the input pulser amplitudes is illustrated in figure 4, and as is evident from the figure we have a fairly reasonable linear response of the system. Following this, tests were extended to live detector data acquired using conventional radioactive sources.

One major difference between the pulser data and the actual data is the presence of electronic noise. Due to this noise, an averaging operation is desirable, on the acquired digitised pulses before subsequent processing. Option for performing such averaging, based on the moving window filter [14] algorithm, has been incorporated. This methodology has the advantage of efficiently reducing the random noise while retaining the sharp step responses. In addition to the moving window averaging, we can also subject the recorded data to a pile-up inspection. When it comes to actual measurements with real detectors, using radioactive sources, there is a finite probability that two consecutive pulses are sufficiently close in time, with respect to one another, such that the second pulse rides on the long tail of the

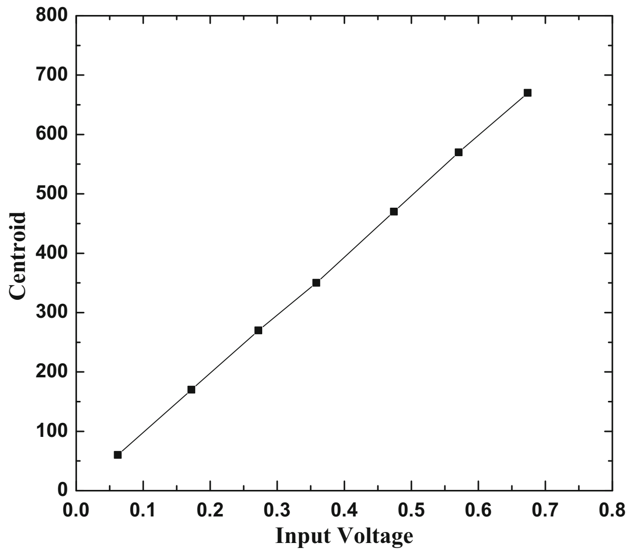

Figure 4. The observed correlation between the recorded peak centroid and the amplitude of the input voltage from a pulse generator recorded using the developed system.

first pulse. This affects the energy resolution as it usually adds wings to the full energy peak. This effect, referred to as ‘pile-up’, is minimum when the detector operates at moderate count rates (typically, 4−5 kHz). Nevertheless, it is desirable that the pulse processing software/hardware is equipped to inspect the pulses and reject the pulses which are piled up on one another. In the present software-based pulse processing routines, in conjunction with the peak detection algorithm, a check for pile-up was also implemented. Once the peak had been detected, the data were inspected for a fixed time period (successive to the detected peak), corresponding to the time required by the signal to reach a near-zero value. During this interval, if another peak (pile-up occurrence) was detected, then both the events were rejected. Only the non-overlapping peaks were accepted and subjected to the trapezoidal shaping and subsequently the γ-ray energy spectrum in the conventional histogram format are generated and displayed.

For one of the measurements, the system was used in conjunction with a tapered BaF_2 scintillator detector, from M/s Harshaw, coupled with XP220Q PMT. The signal from the anode was directly connected to the sound card, and was recorded using the Audacity® [3] software. The trapezoidal filter had its rise time = 50 μs, flat top = 25 μs and $M = 5$. The acquired data using the ^{137}Cs source are illustrated in figure 5.

The measured energy resolution at $E_\gamma = 662$ keV was ∼74 keV. When the data were acquired using a commercial MCA, the measured energy resolution was ∼ 61 keV. Further, the observed photopeak counts were

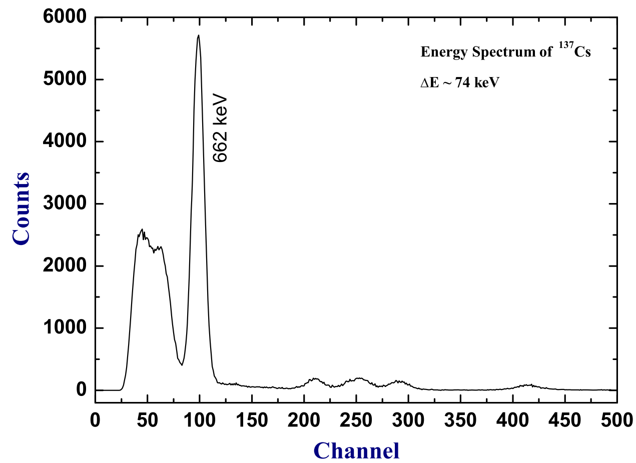

Figure 5. ^{137}Cs spectrum measured with the developed system.

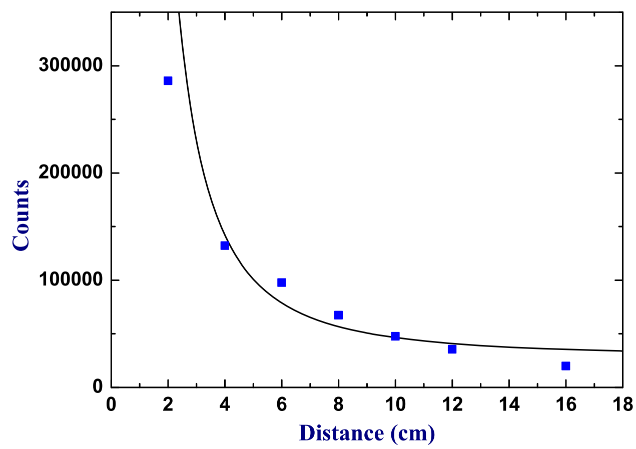

Figure 6. The observed counts for $E_\gamma = 662$ keV as a function of the distance of the source from the detector face. The solid line presents the fit to $y \propto 1/r^2$.

about 1,00507 and 77,000 respectively for the commercial MCA and the sound card based MCA. The difference may be attributed to the inherently slower bandwidth of the in-built ADC in the sound card. To further test the performance of the system, measurements to verify the dependence of the detection efficiency as a function of the distance r from the source were carried out. The results are presented in figure 6, wherein the data exhibit the expected compliance to the inverse square law.

To perform a quantitative measurement, attempts were made to deduce both the linear (μ_l) as well as the mass attenuation (μ/ρ) coefficients using the Lambert’s law:

$$\frac{I(x)}{I_0} = \exp(-\mu_l t).$$

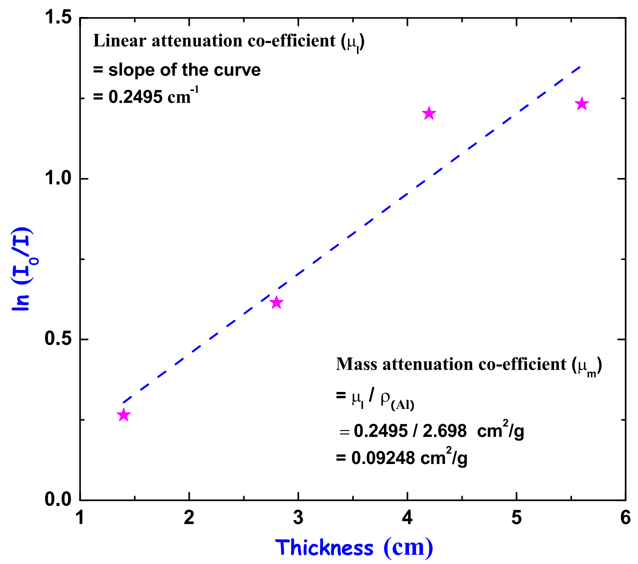

Figure 7. Plot of the observed attenuation for $E_\gamma = 662$ keV as a function of the absorber thickness.

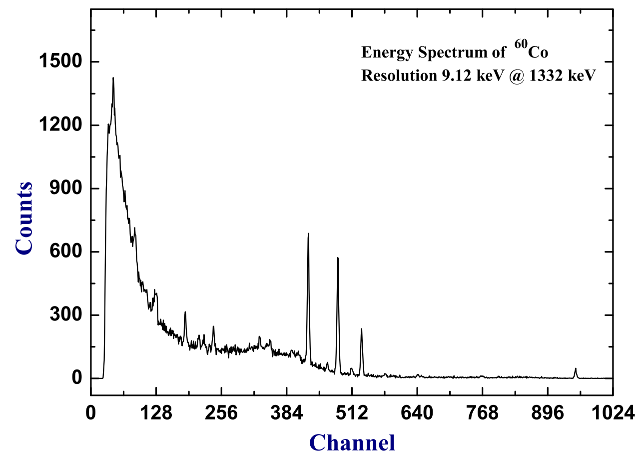

Figure 8. ^{60}Co spectrum acquired with the present system using HPGe detector.

A direct measurement with the ^{137}Cs source placed at a distance of ∼6 cm from the detector face without any absorbers provides us with I_0, the unattenuated intensity from the source, following which, four blocks of Al (each ∼1.4 cm in thickness) were sequentially placed between the source and the detector, and the respective counts provide the attenuated intensity $I(x)$, as a function of the absorber (Al) thickness. A plot of $\ln(I_0/I)$ as a function of the absorber thickness (t) is presented in figure 7.

The deduced value of μ/ρ for Al at 662 keV is 9.2×10^{-2} cm^2/g, which is in qualitative agreement with the reported value of 7.4×10^{-2} cm^2/g [15]. This exercise demonstrates the feasibility of the present developments to pursue laboratory level quantitative measurements, as well.

We have also used this system in conjunction with a HPGe detector, using both ^{137}Cs and ^{60}Co sources. As mentioned earlier, we have directly connected the signal from the pre-amplifier to the sound card, without taking recourse to any intermediate circuit. The pre-amplifier signal was captured by the sound card using the Audacity® [3] software. For the trapezoidal filter, we had set the rise time as 100 μs, with the corresponding flat top as 50 μs and M as 50. The acquired data for ^{60}Co source are illustrated in figure 8.

As seen from the figure, two distinct peaks from ^{60}Co are visible in the spectrum. Further, we are able to identify the presence of a peak at ∼1460 keV, which is attributed to a background γ-ray peak originating from the decay of ^{40}K, present in the paint used on the walls. The observed centroids indicate the linear response of the system. The obtained energy resolution was found to be ∼9 keV, while the commercial MCA reported a value of ∼3 keV at 1332 keV. As the present system is conceptualised primarily as a teaching tool, attempts would be made to further improve the energy resolution which are beyond the scope of the present work. It would also be worthwhile to explore the effect of using different sound cards especially with focus to reduce the captured noise.

The digitiser of the sound card has a sampling frequency of 192 kHz, that amounts to a 5.2 μs time gap between two sample points of the detector output. This is way too large for fast scintillator detectors, or even semiconductor (HPGe) detector. For the former, a sampling gap of 5.2 μs actually amounts to one point over the whole of the pulse width. For the latter, it implies once again maximum one point on the rising edge, of tens of nanoseconds and few points on the slow decay over tens of μs. Obviously, such sparse sampling would lead to a loss in the full energy peak area as well as the total counts in the recorded spectrum. The loss in the full energy peak area has been quantified as 25% for the spectrum, the BaF_2 acquired spectrum and 87% for the data acquired using a HPGe detector, measured with respect to the corresponding spectra acquired with a commercial MCA. The decreased loss for BaF_2 can be attributed to its inherent inferior energy resolution that overrides the (energy) width consequent to the different sampled point, with respect to the actual peak in the detector pulse. Further, the loss is dependent on the count rate (of the incident radiation) and it is recommended that the system be used for lowest rates ∼100–200 cps, typically characterising the laboratory sources.

We have observed that parameters such as the rise time and the flat top for the trapezoidal filtering, obviously, are greater than expected from a realistic and research-oriented digital data acquisition system. We understand that these render the system to a pulse processing time scale that is much slower than even an analog system. However, these are required to achieve a reasonable energy resolution from a tentatively represented pulse digitised with as sparse a sampling as offered by the sound card. The system, we assert, is not intended for application in a high count rate scenario and befits a low cost training application for nuclear physics laboratory in teaching institutes.

Such shortfalls not withstanding, we adhere to our assertion that this system, with minimum overheads, gives output spectrum that may still be used for laboratory training.

We have successfully demonstrated an effective zero-cost MCA device with reasonable features and flexibility for use. The present methodology can be successfully applied on pulses which have long decay time ($\tau_{\text{decay}} \sim \mu$s) routinely encountered in radiation detectors used in nuclear spectroscopy. The performance of the developed system is sufficient for laboratory experiments which require modest resolution.

5. Conclusion

A MCA which utilises the in-built sound card of the PC as the digitiser, to adequately digitise the pre-amplifier pulses from a radiation detector has been developed. The digitised data are processed by recursive algorithms for digital synthesis with provisions for implementing detector-dependent parameters. This methodology has been successfully applied to process the pulses from the scintillator as well as the semiconductor detector. The system has been tested at around 500 cps, which should satisfy the requirements for typical undergraduate experiments. This system presents an attractive tool for laboratory teaching in nuclear physics experiments [16].

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