COMPARISON OF A DIGITAL AND AN ANALOGICAL GAMMA SPECTROMETER AT LOW COUNT RATES

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Un spectrometru digital pentru radiație gamma este comparat cu unul convențional analogic la rate mici de numărare folosind un detector cu germaniu hiper pur de eficacitate mică (25%) şi unul de eficacitate medie (60%). Folosind optimzarea parametrilor de achiziție, au fost efectuate experimente pentru a compara performanțele din punct de vedere al rezoluției energetice şi al ratei de transfer obținute.

Aceste specrometre sunt folosite în laboratorul LaMAR pentru măsurători de mediu ale activității radiaților gamma.

A comparison of a digital gamma-ray spectrometer to a conventional analogical one is performed at low count rates using a low (25%) and a medium (60%) efficiency HPGe detector. Acquisition parameter optimization was done in order to compare performance in energy resolution and throughput.

These spectrometers are currently employed in LaMAR laboratory for environmental measurements of the gamma-ray activity.

Keywords: digital, gamma-ray, spectroscopy, HPGe.

1. Introduction

Resolution, throughput and stability of gamma ray spectrometers have improved considerably with the development of faster and more complex electronics. Development of application specific digital systems, has led to enhancements both in energy resolution and throughput for gamma-ray spectroscopy [1, 2]. In the present paper a desktop digital spectrometer is weighed against an analogical counterpart to compare the devices' performance in resolution and throughput.

Recent progress in digital electronics led to the development of small and cost effective digital spectrometry solutions. These digital spectrometers offer acquisition customization through advanced shaping features, allowing the user to optimize performance beyond the limitations of equivalent analogical solutions [2]. To determine the importance of acquisition parameter optimization regarding energy resolution and throughput of the systems, in the present work, experiments were conducted using sets of purpose optimized parameters.

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Also one of the goals of the present study was determining the influence of detector efficiency in the comparison of the two spectrometers. Two high purity germanium detectors were used for data acquisition one with low efficiency (25%) and one with medium efficiency (60%).

2. Digital gamma-ray spectrometers

Digital gamma-ray spectrometers have come a long way since their introduction about two decades ago. They are functionally different from their analogical counterparts both in structure and in operation [2, 3]. While analogical systems usually consist of discrete single-packaged, single-purpose instruments (i.e. amplifier, high voltage supply, multi channel analyzers, and delays) the operation principles and advanced customization features of a digital system allow the production of single package, multi-purpose devices. This, correlated with the evolution of faster and more complex digital circuits over the last decade, led to the development of solutions which offer better performance in comparison to their analogical counterparts. The difference in structure between the two types of devices comes as a result of the different operation principles [2].

In an analogical spectrometer, an amplifier (AMP in Fig.1) shapes the analogical pulses (current or voltage) received from the detector's preamplifier. After shaping, the analogical signal is conveyed to a multi-channel analyzer (MCA in Fig.1) which digitizes the shaped pulse through an ADC and processes the results to build and store a spectrum over the available channels in the memory [3,4] as shown schematically in the left panel of Fig.1.

In contrast to this processing structure, a digital system first samples and quantizes the analogical signal, received from the detector's preamplifier, through an ADC. The performance of this ADC is a key feature in obtaining good resolution and throughput using this system. Both resolution and throughput improve with faster (larger sampling rates) and more precise (higher bit resolution) ADC designs as a result of better digitization of the input signal [2, 4, 5].

The results of the experiments conducted in order to compare the resolution of the spectra obtained using a digital acquisition system to the one obtained using an analogical system are presented in this paper. The signal processed by the ADC, which is comprised of a string of numerical values, is then filtered through a complex programmable digital circuit. This circuit is a FPGA (Field Programmable Gate Array) and its role in the signal processing chain is to offer flexibility, through programming, for the optimization of certain operating parameters [5]. During the experiments reported in this work, both the analogical and the digital system were optimized in turn to achieve maximum energy resolution during the first set of experiments and then to achieve maximum throughput during the second one. Beside the essential features of an analogical amplifier, like amplifier gain adjustments, baseline restoration or pole zero compensation, the FPGA and microcontroller (µC in Fig.1) provide advanced shaping features using customizable filters as presented in the next section. Using the processed numerical data from the digital filtering stage the microcontroller increments bins located in a memory (Mem in Fig.1) buffer accumulating spectra.

The different operation of a digital spectroscopy system, compared to the analogical one, results in a completely different architecture. The main two architectural differences between these spectroscopy systems are the point where digitization occurs in the signal chain and the way the signal is filtered, as schematically shown in Fig. 1.

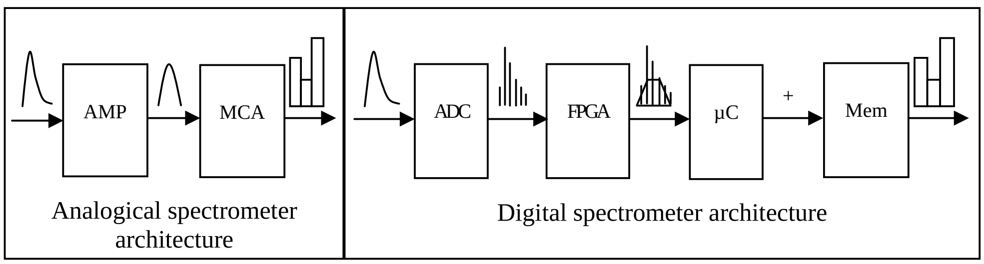

Fig. 1. Architecture comparison for gamma-ray spectrometers. See text for explanations.

A digital system begins signal processing by digitizing the analogical signal received from the detector's preamplifier, using an ADC. The signal is first fed into a signal conditioning unit. The task of this circuitry is to adapt the incoming signal to the input voltage range of the ADC, by using a programmable gain stage and offset control. Very high frequency components are usually removed by an anti-aliasing filter prior to feeding the signal into the ADC [4, 5].

After the signal has been digitized, stream from the ADCs is sent to a real time processing unit (FPGA), at the full ADC sampling rate. This real time processing capability is made possible using a pipelined architecture [5]. Pipelining is a technique used in digital processing where the microprocessor executes instructions concurrently or the memory can transfer multiple data segments simultaneously. This unit performs digital filtering for the incoming stream of data. The key difference from analogical signal filtering is in the type of filter used. Digital circuits are more suited for the implementation of finite impulse response filters, and in the case of gamma-ray spectroscopy, a trapezoidal filter [6].

2.1 Trapezoidal digital filtering operation

Digital filtering works with signals that have been digitized, consisting of a string of discrete values, separated in time by a constant interval. The goal of a digital filter in gamma-ray spectroscopy is to obtain the peak value of a pulse, considering its direct proportionality to the energy of the event that caused it. Given a certain pulse, the obvious approach to determine the peak value would be to take some sort of average over the points before the step and subtract it from the value of the average over the points after the step. Of course, in order to eliminate the influence of the rapid signal change in the step, a **gap (G)** must be inserted between the two **lengths (L)** of the signal that are being averaged, as shown in Fig. 2.

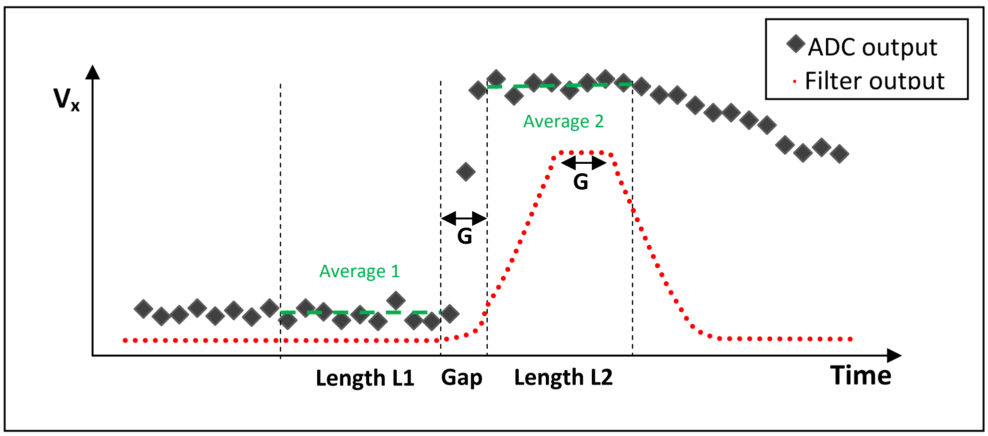

Fig. 2. Digital signal filtering operation. See text for discussion.

Each sample is multiplied with a weighting factor used in the averaging calculation. In theory, the very best filtering is accomplished by using cusp-like weights and time variant filter length selection [6, 7]. There are serious costs associated with this approach however, both in terms of computational power required to evaluate the sums in real time and in the complexity of the electronics required to generate (usually from stored weighing coefficients) normalized sets of weighs on a pulse by pulse basis. Given this, to obtain optimal results for high speed operation, a fixed length filter with all weighing coefficients values equal to unity must be implemented. Thus, the equation (Eqn.1) used to implement the digital filtering algorithm computes the value of V_x afresh for each new signal value k.

$$LV_{x,k} = -\sum_{i=k-2L-G+1}^{k-L-G} V_i + \sum_{i=k-L+1}^{k} V_i \qquad (1)$$

The factor L multiplying $V_{x,k}$, arises because the sum of the weights here is not normalized. This is the digital equivalent of triangular (or trapezoidal if G =0) filtering which is the analogical industry's standard for high rate processing. One can show theoretically [6, 7] that if the noise in the signal is white (i.e. Gaussian distributed) above and below the step, which is typically the case for the short shaping times used for high signal rate processing, then the average in Eqn. 1 actually gives the best estimate of V_x in the least squares sense. The filter output is clearly trapezoidal in shape and has a risetime equal to L, a flattop equal to G, and a symmetrical falltime equal to L. The basewidth, which is a first-order measure of the filter's noise reduction properties, is thus $2L+G$, as shown in figure 2.

The peak detection and sampling in digital spectroscopy systems is achieved by using two trapezoidal filters: a **fast filter** and a **slow filter**. The fast filter, also known as the "trigger filter", is used to detect the arrival of gamma-ray pulses constantly comparing filter output to a set threshold while the slow filter, known as the energy filter, is used for the measurement of V_x, with reduced noise at longer rise times. The value V_x captured will only be a valid measure of the associated gamma-ray's energy provided that the filtered pulse is sufficiently well separated in time from its preceding and succeeding neighbor pulses so that their peak amplitudes are not distorted by pileup phenomena [4]. Pileup occurs when the rising edge of one pulse lies under the peak (specifically the sampling point) of its neighbor. Thus, the two pulses must be separated by at least an interval of $L+G$. Due to the fact that the present study is aimed for low count rates (about 1000cps), pileup was a marginal problem.

As described above, a digital spectroscopy system operates using several timing parameters (L and G for each of the two filters), a signal threshold for the fast filter, and there are also several other parameters for the digital amplifier [5]. The purpose of these parameters is to offer a large degree of flexibility in data acquisition. These parameters were adjusted for the digital system during the experiments in order to optimize either resolution or system throughput. Similar optimizations were also conducted on the analogical acquisition system. See the following section for discussion.

Both the energy filter and the trigger filter are conditioned by their length, or risetime, L (the main parameter used to optimize energy resolution) and by their gap, or flattop, G. For the energy filter, longer risetimes result in better resolution to the cost of reduced output, and the flat top in general needs to be wide enough to accommodate the longest typical signal rise time from the detector. The computing architecture doesn't allow usage of very short flat tops along with very long rise times because of fast memory requirements. The settings of the trigger filter have only minor effects on the resolution of the system. However, changing the triggering parameters might have some effect on certain undesirable peak shapes. A longer trigger rise time allows the threshold to be lowered more, since the noise is averaged over longer periods. A long trigger filter flat top will help to trigger on slow rising pulses and thus result in a sharper cutoff at the threshold. Regarding high count rates, whether pulses suffer pileup in the energy filter channel depends critically on the rise time of the filter being used. The amount of pileup which occurs at a given average signal rate will increase with longer rise times. In the present work, these issues were carefully considered in setting up the digital spectrometer's parameters.

3. Experiments setup and data collection

In the present study, a digital spectrometer was compared to an analogical nuclear acquisition system in order to evaluate the systems' performance at a fixed, low count rate of about 1000 cps. In order to compare performance over a wide energy range, four radioactive sources were used: ^{241}Am, ^{152}Eu, ^{133}Ba and ^{60}Co. These four nuclear spectrometry gamma radiation sources were stacked as a single one allowing peak analysis of an energy spectrum ranging from 59.5KeV to 1408KeV. The energies of the gamma-rays considered for analysis in this paper were 59.5KeV, 121.8KeV, 356KeV, 778KeV, 1173.2KeV, 1332.5KeV and 1408.1KeV, corresponding to the fore mentioned radiation sources.

To analyze the effect of the detector's performance on overall system performance, experiments were carried out using two germanium detectors with different relative efficiencies: one with medium-high efficiency (60%) and the other with a lower efficiency (25%). The two detectors were both from the same GEM series of ORTEC detectors and had the same encapsulation and connections [8]. Both detectors were cooled using the X-COOLER II mechanical cooling system to avoid mechanical noise level differences. The mechanical vibrations of the cooler can add some electrical noise to the output signal of the detector. This is caused by mechanical vibrations transmitted to the Ge crystal causing slight variations in capacity through small displacements, which result in current pulses through the high sensitivity internal preamplifier FET's grill [8]. These are amplified through the circuit and result in electrical noise. In order to reduce the mechanical vibrations' effects on the output signal, both detectors and the cooler were placed on vibration absorbing polyurethane supports.

Both detectors were biased using a high voltage supply, the ORTEC 659 5-kV Detector Bias Supply [9]. The detectors were shielded by using Pb bricks to reduce background radiation detection.

The experimental setup was designed in order to measure simultaneously and compare the two data acquisition systems' performances. The two outputs of the detectors were connected one at a time, for each experiment, to the two spectrometers as shown in Fig. 3.

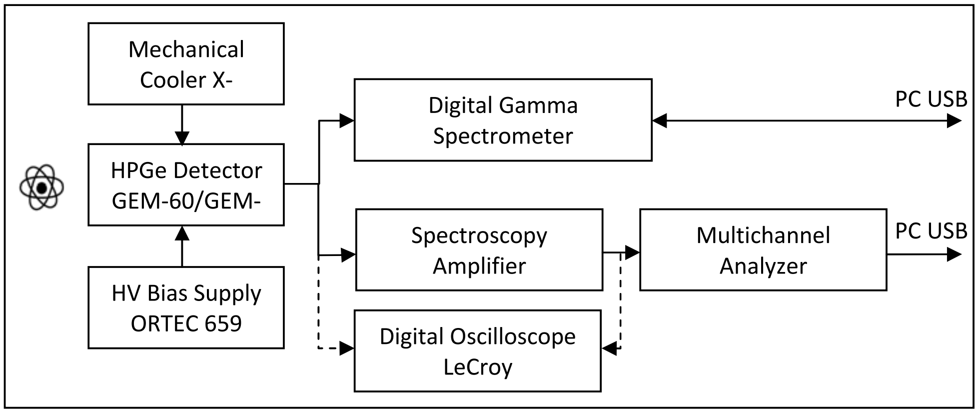

Fig. 3. Layout of the experimental setup employed in the present study. The oscilloscope was used only for setup and monitoring. See text for discussion.

Two sets of experiments were conducted for each of the germanium detectors, and as a result four experiments took place. The goal for the first set of measurements was to maximize the throughput of each of the systems through the optimization of acquisition parameters and to study its effect on the energy resolution of the recorded spectra. The second set of measurements was aimed at optimizing resolution by choosing an appropriate set of acquisition parameters. All experiments were conducted over long periods of acquisition time (approx. 20 hours per measurement), in order to collect statistically relevant data at a low count rates. All acquisition devices were powered using the same UPS to prevent both ground loops and detector damage in case of a cooling system malfunction or power supply outage. The temperature of the measurement room was monitored and controlled to ensure that measurements were not affected by temperature changes.

Prior to data collection and acquisition parameter optimization, both systems were set up for the input signal. On the analogical system, baseline restoration, gain setting and pole zero (PZ) adjustments were done for the shaping amplifier using the gamma-ray source, each of the two detectors and an oscilloscope to monitor the input and the output signals of the amplifier [3, 4]. The input parameters of the digital acquisition system were set similarly monitoring the signal using the integrated software oscilloscope [5]. The “Preamp Gain” and DC offset parameters were set for each of the two detectors to bring the input signal into the ADC's 1V voltage range and set the dynamic range of the channel. The “Decay Time” parameter is preamplifier’s decay time (a constant given by the RC network) and it is used to correct the energy of a pulse sitting on the falling slope of a previous pulse. This parameter was auto-set by a programmed routine in the digital spectrometer and also measured using the oscilloscope to verify if the given estimate is correct. It is important to keep count rates reasonably low if auto setting this parameter because pulse pileup can affect measurements [5]. However, because the count rate for these experiments was set around 1000cps a precise and consistent value was found by the software routine.

In order to optimize acquisition parameters for the analogical system to achieve maximum throughput during one experiment and to optimize energy resolution during the other, a digital oscilloscope was used to view the signal entering the shaping amplifier and its output signal. Throughout all experiments Gaussian shaping was selected for the analogical amplifier. The gain was set to bring the output signal into the 10V voltage range of the NIM multichannel analyzer's ADC [10]. In order to obtain the best resolution of the spectra using the analogical acquisition system, the amplifier's shaping time was set to 6μs. For throughput optimization a 3μs shaping time was used. During each experiment, the digital oscilloscope was disconnected from the acquisition chain in order to eliminate possible interference with the results.

On the digital system, the optimization of acquisition parameters was done through the software command interface of the device [5], installed on the computer, which can program the internal FPGA of the Polaris DGF directly through USB. The acquisition parameters used for the digital system optimizing throughput or resolution for each of the detectors used, are given in Table 1.

Table 1

Parameters of the digital spectrometer optimizing throughput or resolution for each of the detectors used in the present study. See text for discussion.

Parameter/Detector used	25GEM Throughput	25GEM Resolution	60GEM Throughput	60GEM Resolution
Preamp Gain(mV/MeV)	103.49	102.8	40.86	40.76
Decay Time (μs)	53.74	53.74	59.24	59.24
Energy Filter Range	3	5	4	5
Energy Filter Rise Time (μs)	4	12.8	6	20
Energy Filter Flat Top (μs)	1.6	9.6	3.2	2.4
Trigger Filter Threshold (keV)	9.56	10.5	26.1	40
Trigger Filter Rise Time (μs)	0.375	0.475	0.675	0.475
Trigger Filter Flat Top (μs)	0.4	0.3	0.1	0.3

The digital spectrometer's software also allows to build energy spectra and to conduct measurements offline (after data collection). The spectra produced by the analogical acquisition system, stored in the internal memory of the multichannel analyzer, were collected on the same computer using the MAESTRO-32 software solution provided by ORTEC [11]. For accurate data comparison the spectra collected through the Polaris software (*.mca format) were exported in the same format as the ones obtained through the analogical system (*.chn). This was done in order to facilitate use of the same data processing software, namely the ORTEC MAESTRO-32. This software package was used for calibration and all data analysis.

4. Data analysis and results

Following data collection and the spectra format conversion, data analysis began with the comparison of the acquisition statistics. The analogical and the digital device both present a real acquisition time, which is the actual runtime of the experiment in seconds, and a live time, which is the time the devices analyze data and build spectra. The difference between these two times, normalized to real time, is a coefficient called dead time and it is used to compare throughput between devices and experiments [5]. In all experiments dead time for the 25% efficiency detector was higher than for the one obtained while using 60% detector, regardless of device or parameter optimization. This is caused by the relationship between physical volume of detection and dead time [3, 4]. Using throughput optimization dead time was, as expected, much lower (1-2%) than the dead time obtained using the resolution optimization (4-5%) even at low count rates. The results show that the dead time for the digital acquisition system was always higher than the one for the analogical system, especially for the throughput optimized experiments. This means that the analogical system obtained better throughput in all experiments, with both detectors. This could be a consequence of the low count rate acquisitions, where the analogical device performs better than its digital counterpart.

Regarding energy resolution, the two systems were compared by evaluating FWHM of the total absorption peaks of the gamma-rays presented in Table 1. After measuring and computing FWHM for each of the total absorption peaks of interest the data was plotted using MATLAB software. The results are shown in figure 4.

As expected, in all experiments, for both devices, FWHM increases with the energy of the peak considered, because it is proportional to the gamma-ray's total absorption peak’s energy.

The results show that all spectra obtained using the 25GEM detector, have better resolution compared to the ones obtained using the 60GEM detector. However at high energies, like the ones of the ^{60}Co 1332.5keV peak and the ^{152}Eu 1408.1keV peak, the resolution optimized analogical device acquiring pulses from the 60GEM detector showed similar results to the digital throughput optimized device acquiring pulses from the 25GEM detector.

The best resolution was obtained using the 25GEM detector while acquiring data through the analogical resolution optimized system. This was expected because analogical acquisition systems of this type offer generally better results at low count rates than digital desktop gamma spectroscopy systems.

Furthermore, the throughput optimization of the analogical device offered similar resolution performance to the resolution optimized digital system acquiring data through the 25GEM detector. It can be concluded that for the 25% efficiency detector the analogical acquisition system offers better energy resolution than its digital counterpart.

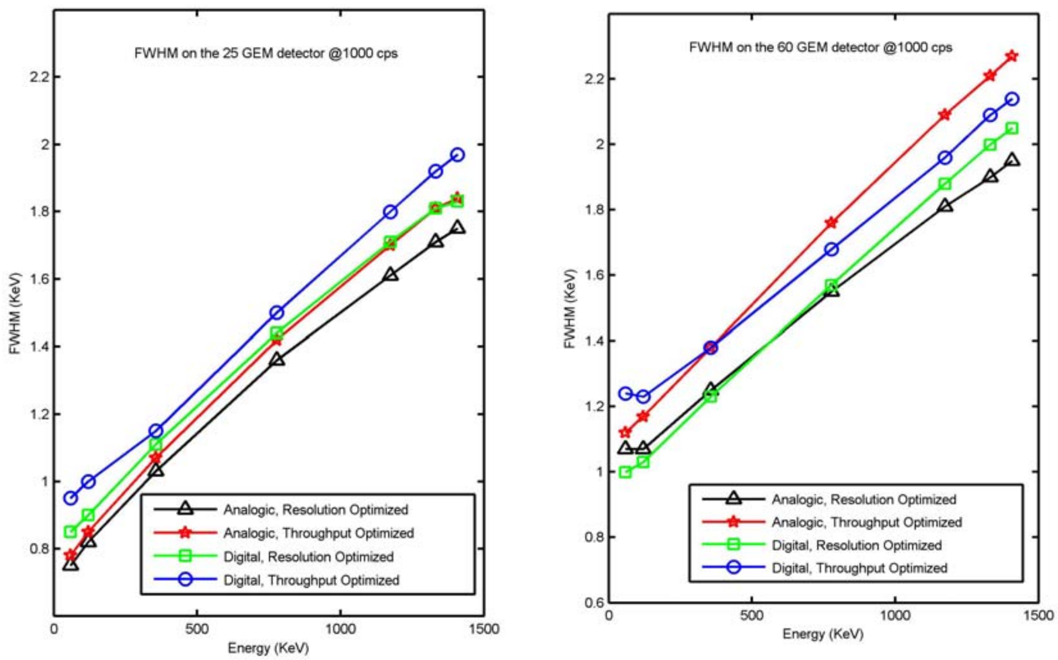

Fig. 4. FWHM on 60GEM and 25GEM detectors, resolution and throughput optimized, comparison between analogical and digital spectrometers at a low count rate

The experiments involving the 60GEM detector show different results concerning the energy resolution. The data shows that for the resolution optimization experiment, the digital acquisition system offers slightly better resolution at lower energies compared to its analogical counterpart. However, at higher energies, the analogical system gains a slight advantage compared to the digital system with lower FWHM. This is an empirical result and can be a subject for further study. Using the throughput optimization, the results are opposite, as the analogical system offers better resolution at lower energies while at medium to high energies the digital acquisition system obtained much better results. Also, the difference in energy resolution between the two parameter settings for this detector is significant, compared to the other one. From these results it can be concluded that optimization of parameters for the purpose of the experiment is much more important with the use of a higher efficiency detector and that the digital spectroscopy system offers better performance regarding energy resolution while acquiring data using a higher efficiency detector. In particular this is relevant for measuring environmental samples with large efficiency detectors.

5. Conclusions

Extensive measurements have been performed in order to compare analogical and digital gamma-ray spectrometers at low count rates as those encountered in environmental measurements. While both acquisition systems showed significantly better throughput through acquisition parameter optimization even at a low count rate, the analogical spectrometry system offered better results in comparison to its digital counterpart regarding both energy and throughput.

As expected, in acquisitions performed using the lower efficiency detector, both systems achieved better energy resolution compared to the higher efficiency detector, regardless of optimizations. However, results show that acquisition parameter optimization is very important while acquiring data using a higher efficiency detector.

The results of the experiments showed that a purpose optimized desktop digital spectrometer, in this case the Polaris DGF, can obtain roughly similar performance to a NIM analogical spectrometry acquisition chain and a slight increase in energy resolution using the higher efficiency detector.

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