INL/CON-05-00284
PREPRINT

Comparison Between Digital and Analog Pulse Shape Discrimination Techniques for Neutron and Gamma Ray Separation

2005 IEEE Nuclear Science Symposium and Medical Imaging

Rahmat Aryaeinejad
John K. Hartwell
David F. Spencer

October 2005

Comparison Between Digital and Analog Pulse Shape Discrimination Techniques For Neutron and Gamma Ray Separation

Rahmat Aryaeinejad, John K. Hartwell, and David F. Spencer

Abstract-- Recent advancements in digital signal processing (DSP) using fast processors and a computer allows one to envision using it in pulse shape discrimination. In this study, we have investigated the feasibility of using a DSP to distinguish between neutrons and gamma rays by the shape of their pulses in a liquid scintillator detector (BC501). For neutron/gamma discrimination, the advantage of using a DSP over the analog method is that in an analog system, two separate charge-sensitive ADCs are required. One ADC is used to integrate the beginning of the pulse rise time while the second ADC is for integrating the tail part. In DSP techniques the incoming pulses coming directly from the detector are immediately digitized and can be decomposed into individual pulses waveforms. This eliminates the need for separate ADCs as one can easily get the integration of two parts of the pulse from the digital waveforms. This work describes the performance of these DSP techniques and compares the results with the analog method.

Index terms- Digital signal processing, gamma ray/neutron pulse shape discrimination.

I. INTRODUCTION

In a digital signal processing (DSP) technique [1-5], the detector preamplifier outputs are directly digitized without any analog signal shaping and then, according to specific application, processed to deduce desired results. This technique captures the detailed shape of the preamplifier signals using the fast analog-to-digital converters (ADCs), decomposes the inputs into their individual signals, and processes captured waveforms in real time using field-programmable gate arrays (FPGA) and fast digital signal processors to perform all necessary data processing functions digitally. The digital real time processing is now possible because computer CPUs are not only becoming faster and faster, they also have larger and faster memories. In addition, front-end ADCs and FPGAs are currently available at speeds up to 500 MHz and up to 16-bit resolution. A combination of these factors makes possible the digitizing of pulse trains at speeds approaching one digitization every 1-2 nanoseconds. This opens the door to direct digital signal processing for radiation spectroscopy. Most importantly, the captured waveforms stored on an event-by-event basis can be used for pulse shape discrimination (PSD) of different types of radiation (e.g. alphas, protons, gamma rays, and neutrons).

The major difference between analog and digital signal processing is that with the digital method after signal conditioning, the preamplifier pulse is digitized immediately and all operations are carried out in digital filters. With the analog signal processing method, the filtering must be completed in relatively slower analog circuits. The DSP system offers significant advantages over the analog system in the areas of cost, accuracy, and efficiency by eliminating a need for extra electronic modules.

DSP techniques have been used for pulse shape discrimination to simultaneously measure multiple radiation types such as beta, gamma, and alpha using a single CSI detector [6] or a phoswich detector [7] in which several different scintillators are coupled to a common photomultiplier tube. These techniques were also compared with the analog methods [8,9]. However, this technique has not been fully studied using a liquid scintillator detector (e.g. BC501) to distinguish neutrons from gamma rays by the shape of their pulses produced in the detector.

In our past work, we used two analog methods of the pulse shape discrimination (PSD) of charge integration and zero crossing and performed the comparisons between the two. The results of these studies were presented at the IEEE Nuclear Science Symposium in 2001 and published in the Transactions on Nuclear Science journal [10]. They showed that the zero crossing method gives much better PSD for 100 keV electron equivalent (keVee) and lower, whereas the charge integration method leads to better separation above 100 keVee.

In this study, we investigated the feasibility of using the digital signal processing to separate neutron from the gamma ray events in a liquid scintillator.

II. EXPERIMENTAL PROCEDURE

Fig. 1 shows the experimental setup with a detector to source distance of 4 inches. The liquid scintillator used in this work was made of the organic scintillator BC501 manufactured by Saint-Gobain, Inc. This is the same detector that we used for the analog signal processing measurements. This detector is 2" in diameter and 2" long coupled to the Phillips XP2020 photomultiplier.

Prepared for the U.S. Department of Energy through the Idaho National Laboratory LDRD program under DOE Idaho Operations Office, the Contract No. DE-AC07-99ID13727.

R. Aryaeinejad is with the Idaho National Lab., Idaho Falls, ID 83415-2114 USA (telephone: 208-526-1670, e-mail: rahmat.aryaeinejad@inl.gov).

J.K. Hartwell is with the Idaho National Lab., Idaho Falls, ID 83415-2114 USA (telephone: 208-526-9366, e-mail: john.hartwell@inl.gov).

D.F. Spencer is with the Idaho National Lab., Idaho Falls, ID 83415-3779 USA (telephone: 208-526-1489, e-mail: David.Spencer@inl.gov).

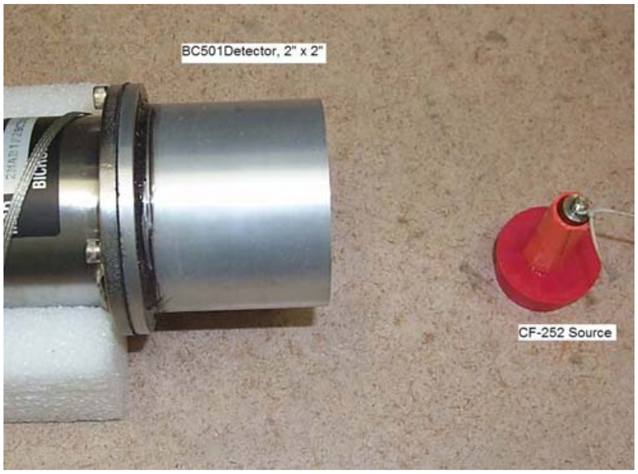

Fig. 1. Experimental setup showing the 2"x2" liquid scintillator detector and Cf-252 source.

The pulse shape discrimination techniques are based on the fact that neutrons and gamma rays give different pulse shapes when interacting with the neutron sensitive organic scintillators. The neutron interaction results in a slower timing signal than the gamma-ray interaction. This means that a gamma-ray pulse rises and decays faster from and to the baseline, respectively, than a neutron pulse generated by the recoiled protons. The major difference between these two signals occurs in the tail. A neutron creates a large ionization density by producing a recoil proton resulting in a long tail. A gamma ray, on the other hand, produces scattered electrons with a very small ionization density, and as a result, decays much faster. In analog signal processing two separate charge-sensitive ADCs are needed: one ADC to integrate the beginning of the pulse rise time; and the second ADC for integrating the tail part. Using a DSP eliminates the need for separate ADCs as one can easily get the integration of two parts of the pulse from the digital waveforms.

We used the CAMAC digital signal processing module model DGF-4C made by the XIA Corporation [11]. It is a 4-channel module with waveform digitization capable of on-line pulse shape analysis (PSA). It can store waveforms of up to 100 µs long and process 50,000 counts per second per channel into 32K spectra. Unfortunately, its digitization rate is only 40MHz, which means the minimum sampling time is limited to 25 ns. This is not the ideal rate that one would like to use for fast output pulses of the organic liquid scintillator. However, it was the only commercially available DSP module at the time of our investigation. The digitization rate is important for two reasons: 1) the rise of the pulses is slightly different for the gamma rays and neutrons on a 0-10 ns time scale. With a faster ADC (>100MHz), one can easily see this difference and then use it to help distinguish between two events. On the other hand, one can only look at the long component part of the signal and get even a better separation. 2) In this case, the difference in the long component could be examined more accurately if a faster ADC were to be used. Basically, one would be able to optimize the point where the "tail" begins to distinguish between gamma and neutron events.

III. MEASUREMENTS AND SUMMARY OF THE RESULTS

Table I summarizes the list of parameters used in our measurements. Because the anode signal of the liquid scintillator detector has a fast rise time, we used 0.05 µs for the trigger filter and 0.8 µs for the energy filter, respectively. For pulse shape analysis, a total trace length of 1.0 µs and a delay time of 0.1 µ were used. The latter was necessary for defining the background before the start of the pulse and comparing it with the background in the last 0.1 µs of the end of the trace.

Table I. Filtering and PSA parameters used in this study.

Filter Parameters			Pulse Shape Analysis	
	Trigger Filter	Energy Filter	Trace Length (µs)	1.0
RiseTime (µs)	0.05	0.8	Delay (µs)	0.1
Flat Top (µs)	0.0	1.2	PSA Start (µs)	0
			PSA End (µs)	1

The DGF-4C data acquisition system can be operated in two modes - multi-channel analyzer (MCA) mode and list mode. In the MCA mode, the system acts like a typical singles spectrum in which data are collected for a defined period of time and stored in the internal memory. The spectrum can then be saved into a file. In the list mode, however, all the waveforms, energies, and time stamps are collected on an event-by-event basis. In this mode the data can be stored in various formats. In our measurements we used a "0x100" list mode to store full event data plus waveforms into a binary file for later off-line data analysis. Fig. 2 shows the energy spectra

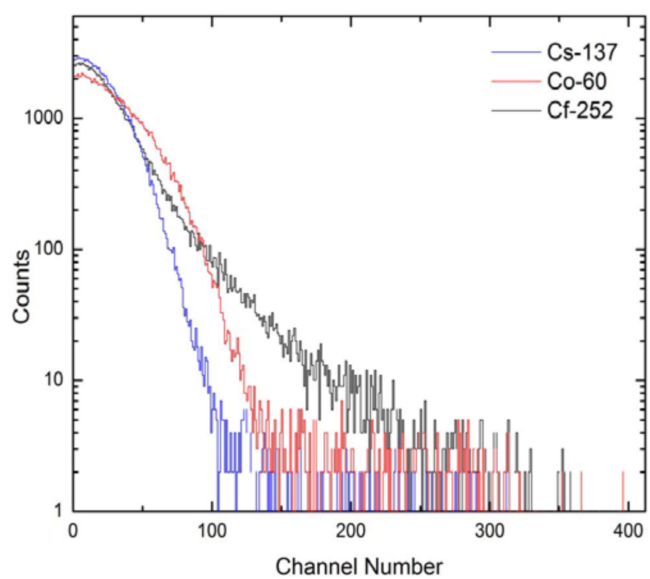

Fig. 2. Spectra taken with Cs-137, Co-60 and Cf-252.

taken with the Cs-137, Co-60, and Cf-252 sources. As we mentioned in our previous work [10], due to the low Z-value of the liquid scintillator, photopeak efficiency is low and an energy calibration using photopeaks is not viable. Consequently, the Compton edge energies of 447 keV for the 662 keV Cs-137 emission and 1041 keV for the average energy of Co-60 1173 and 1333 keV emissions were used to perform the energy calibration [12]. This calibration was used to correlate equivalent electron energy (keVee) corresponding to each threshold setting.

A data-sorting program was developed to read the binary event-by-event data file for generating waveforms and sorting the data according to specific configuration parameters defined by the user in the configuration file. This file establishes the default values for the particle identification range, the total normalization range, the background range, and waveform start and end indexes to be displayed. In addition, the energy threshold value can be set in the configuration file. This value will be used to ignore any data that falls below this threshold in the sorting process. The user can modify any or all of these values via an options pop-up dialog shown in Fig. 3. The user has the option to either define a region to determine the average background, or supply a fixed background value in the "Fixed Background Value" edit box. After the program is started and the configuration file parameters are loaded, the screen displays a list of current file and associated waveform values. The program determines overall file length, buffer length (in bytes), the number of words in an event, the number of events in a buffer, and the total number of events for the binary input file. After the threshold-qualified data is stored into internal arrays, it is sorted in ascending order and then compacted. The compacting reduces the input arrays to a list of values and the count of the number of occurrences of the associated values. The output file is then written to disk with header information indicating the range of the optional selections followed by the compacted output values. The configuration parameters determine how the pulse shape analysis will be processed.

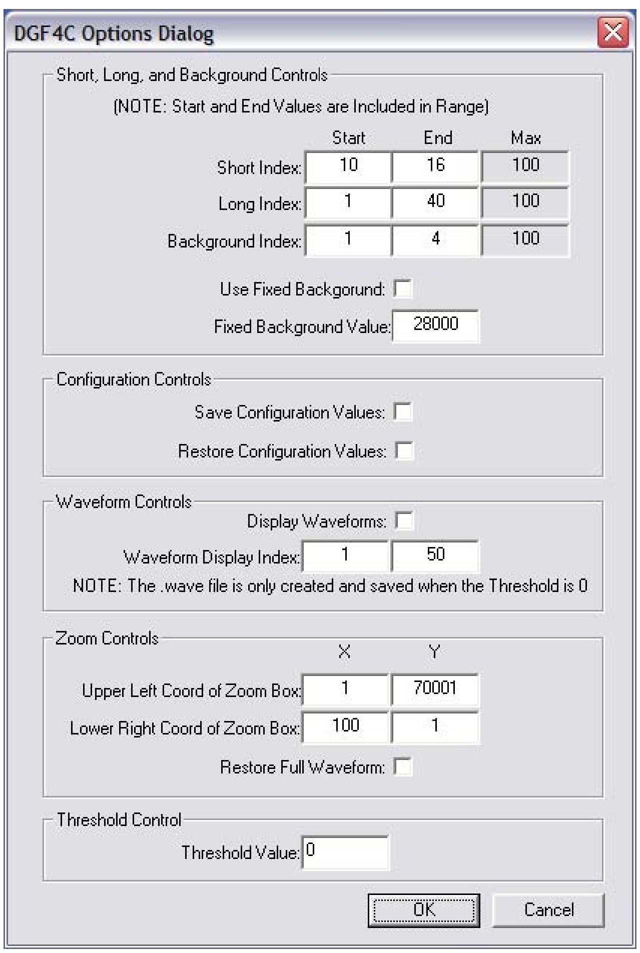

Fig. 3. An example of configuration parameters set in the options pop-up dialog box.

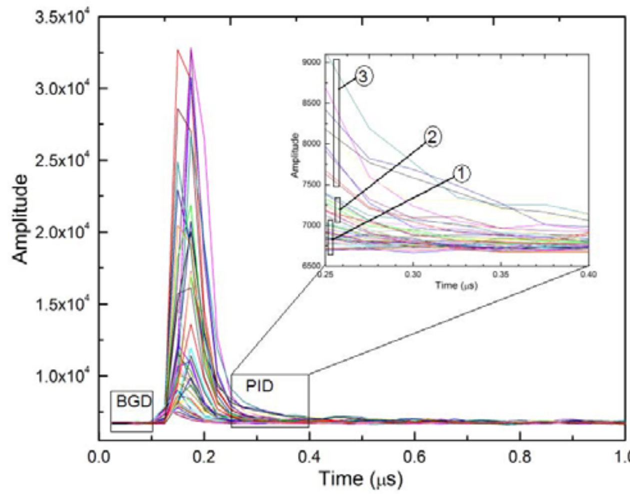

Fig. 4. This plot shows the first 50 waveform traces, which were extracted from the data file.

IV. PSD Analysis Results and Comparison with Analog Method

Fig. 4 shows typical waveform traces obtained in our measurements using a Cf-252 source. The total waveform trace length was set to 1.0 µs as shown in table I. The delay region of 0.0-0.1 µs at the beginning of the trace was used to deduce the average background to be subtracted from each data point. In this work we only looked at the long tail component of the traces to distinguish between gamma rays and neutrons. This is because the ADC digitization of the DGF-4C is only 40 MHz and therefore is not fast enough to distinguish between fast rise time components of the traces. The pulse shape analysis can be achieved by properly selecting a region of the tail called the particle identification (PID) window as shown in Fig. 4. The insert in this figure shows the expanded plot of this region. There are three distinct groups of traces labeled 1, 2, and 3. Groups 1 and 3 represent pure gamma ray and pure neutron events, respectively. In group 2 the gamma ray and neutron events are mixed. This is the area that determines how well the low-energy neutrons are separated from the gamma rays, which consequently depends on the energy threshold. It is very important to optimize where the PID window starts and ends in order to achieve the largest separation between the traces. In our case, we found that the best discrimination between gamma rays and neutrons was achieved when this PID window is from 0.25 µs to 0.4 µs. We also found the position of the start is substantially more important than the end. In addition, selecting the background at the beginning or the trace led to a slightly better discrimination than the end of the trace.

For PSD analysis, each waveform was integrated in the PID region and then divided by the integral of the whole trace. This ratio is called the particle identification index and is between 0 and 1. It was then plotted versus the number of events or counts. Fig. 5 shows the results of the PSD analysis obtained for the Cs-137, Co-60, and Cf-252 sources. The blue and red plots are for the Cs-137 and Co-60 sources, respectively, that emit only gamma rays, the black plot is for Cf-252, which emits both neutrons and gamma rays. Clearly, for Cf-252, the neutron peak is separated and distinguishable from the gamma-ray peak.

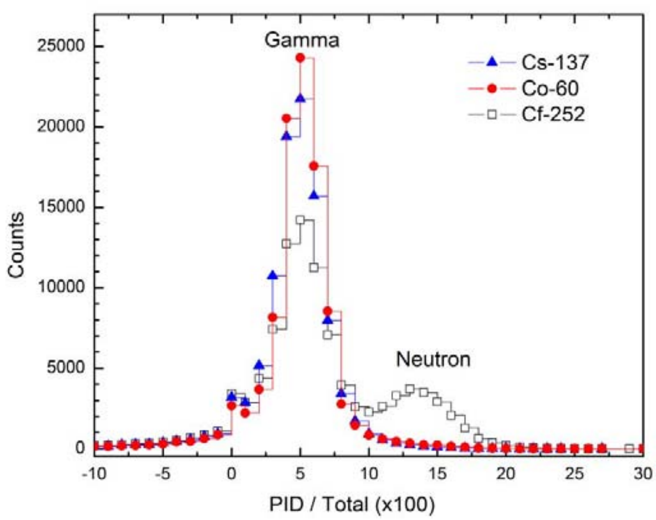

Fig. 5. Digital pulse shape discrimination using Cs-137, Co-60, and Cf-252 sources. No energy thresholds were applied to these spectra.

Fig. 6 shows the results of the spectra produced with energy threshold cuts of 50, 100, 300, and 600 keVee from the top. To quantify the separation of the peaks corresponding to the neutrons and gamma rays, a figure of merit (FOM) was used:

$$FOM = \frac{peak\_separation}{FWHM_{\gamma} + FWHM_{n}}$$

The peak_separation is the number of channels between the gamma ray peak and neutron peak centroids and the FWHM γ and FWHM $_n$ are the full width at half maximum (channels) of the gamma and neutron peaks, respectively. FOM values increase from the top to the bottom spectra as expected. The FOM is shown for each energy threshold. At 50 keVee, the peaks are not completely separated which doesn't allow the discrimination between all the neutrons and gamma rays. However one can easily separate neutrons from gamma rays with energies above 100 keVee.

A comparison with the analog pulse shape discrimination of the zero crossing technique was done using previous measurements performed at the same threshold settings between 50 to 600 keVee [10]. The same detector and Cf-252 source were used. The detector signal was sent to a γ/n discrimination module (Canberra 2160A), which contains an RC-shaping amplifier. This signal was also sent through to a CFD (Tennelec TC454),

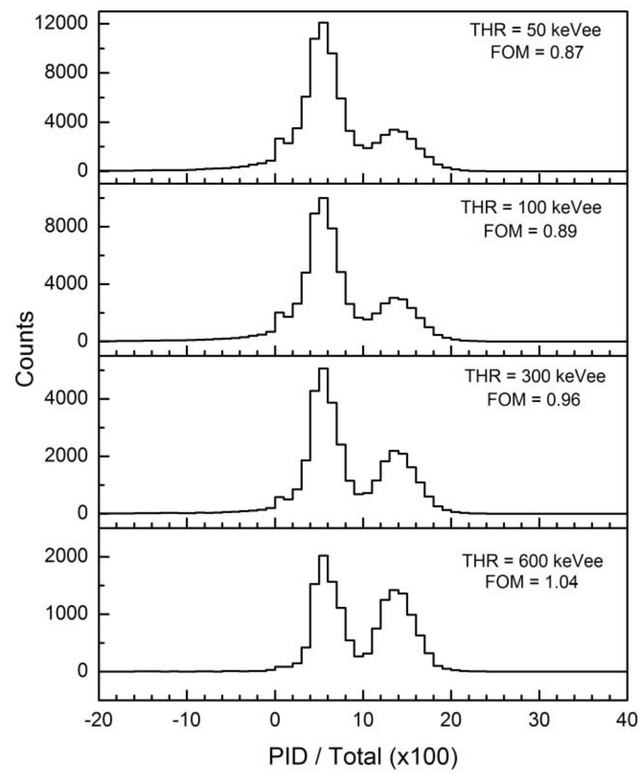

Figure 6. Digital pulse shape analysis showing gamma ray and neutron separation at various electron energy thresholds.

which produced the start trigger for the time-to-amplitude converter, TAC (Canberra 2143). The γ/n discrimination module sent a pulse corresponding to the

Table II. Comparison between digital and analog zero crossing methods versus threshold energy.

Threshold (keVee)	Digital Method (FOM)	Analog Zero Crossing method (FOM)
50	0.850	1.19
100	0.89	1.30
300	0.96	1.45
600	1.04	1.65

zero crossing point of the signal. This signal was then delayed before it was sent to stop the TAC. Finally the TAC signal was sent to an MCA (Canberra Series 20) and the time spectra were recorded. Plots of the MCA spectra are shown in Fig. 7. Table II summarizes the comparison between the two methods of PSD at different electron energy thresholds. A figure of merit was used to compare the results of the two methods. Here, the FOM values for both digital and analog methods increases as a function of energy threshold setting. At first glance one can clearly

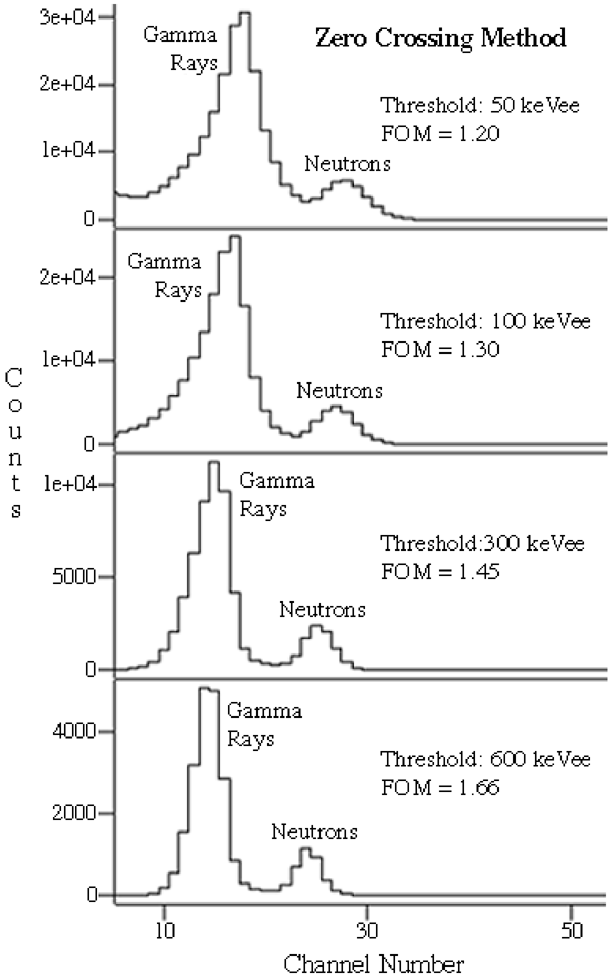

Fig. 7. MCA spectra of the zero crossing method at various electron energy thresholds.

see that the zero crossing method is better for all threshold values from 50 keVee to 600 keVee by a factor of 1.4 to 1.6, respectively. This is mainly because in digital processing the DGF-4C module we used was slow (40 MHz), which limited the sampling rate to 25 ns only. We believe using faster FPGA chips that are commercially available today, like ACTEL 350 MHz or XILINX 450 MHz devices, will substantially improve the separation between gamma-ray and neutron peaks. A 500 MHz chip, for example, gives us a 2 ns resolution as compared to 25 ns sampling rate. With this resolution we can get much better separation, even better than the analog PSD technique, between gamma rays and neutrons.

V. Conclusions

In this work, we have investigated the feasibility of using the digital signal processing technique to distinguish neutrons from gamma rays by the shape of their pulses in a liquid scintillator detector (BC501). The results based on FOM values for energy thresholds of 50 to 600 keVee show that a good γ/n discrimination can be achieved using this technique. Comparison with the analog zero crossing method shows that the zero crossing technique gives higher FOM values and therefore a better separation. This is because of the digital processing rate limitation of 40 MHz. Using a faster DSP chip, like a XILINX 450 MHz device with a 2 ns sample rate, will result in much better discrimination.

VI. Acknowledgment

The authors would like to thank the X-Ray Instrumentation Associates, especially Dr. Hui Tan. His help and advice was instrumental in carrying out this work.

References

[1] G. Knoll, "Radiation Detection and Measurement", John Wiley and Sons, New York, (2000).

[2] R.G. Lyons, "Understanding Digital Signal Processing", Addison-Wesley, Reading MA (1997).

[3] W. Skulski and M. Momayezi, B. Hubbard-Nelson, P. Grudberg, J. Harris, W. Warburton", "Towards Digital Gamma-ray and Particle Spectroscopy", X-ray Instrumentation Associates (XIA) web site http://www.xia.com/DGF4C_Download.html.

[4] L. Szentmiklósi, T. Belgya, Zs. Révay, and G. L. Molnár, "Digital Signal Processing in Prompt-Gamma Activation Analysis", Journal of Radioanalytical and Nuclear Chemistry, Vol. 264, No. 1, pp. 229-234, (2005).

[5] W. Warburton, M. Momayezi, B. Hubbard-Nelson, and W. Skulski, " Digital Pulse Processing: New Possibilities in Nuclear Spectroscopy", X-ray Instrumentation Associates (XIA) web site http://www.xia.com/DGF-4C_Download.html.

[6] W. Skulski and M. Momayezi, "Particle Identification in CsI(Tl) Using Digital Pulse Shape Analysis", X-ray Instrumentation Associates (XIA) on their web site http://www.xia.com/DGF-4C_Download.html.

[7] W. H. Miller and M. Diaz de Leon, "Utilization of phoswich detectors for simultaneous, multiple radiation detection", Journal of Radioanalytical and Nuclear Chemistry, Vol. 264, No. 1, pp. 163-167, (2005).

[8] Moszynski, M.; Wolski, D.; Ludziejewski, T.; Arnell, S.E.; Skeppstedt, and Ö.; Klamra, W., " Particle identification by digital charge comparison method applied to CsI(Tl) crystal coupled to photodiode", Nuclear Instruments and Methods, A336, pp. 587-590 (1993).

[9] Gál, J.; Kalinka, G.; Nyakó, B.M.; Perez, G.E.; Máté, Z.; Hegyesi, G.; et. al., " Particle discriminator for the identification of light charged particles with CsI(Tl) scintillator + PIN photodiode detector", Nuclear Instruments and Methods, A366, pp. 120-128, (1995).

[10] R. Aryaeinejad, Edward Reber, and Dave Spencer "Development of A Handheld Device for Simultaneous Monitoring of Fast Neutrons and Gamma Rays," IEEE Transactions on Nuclear Science Vol. 49, No.4, pp. 1909-1913, August 2002.

[11] B. Hubbard-Nelson, M. Momayezi, and W. Warburton, " A module for energy and pulse shape data acquisition", Nuclear Instruments and Methods, A422, pp. 411-416, (1999).

[12] R. Cherubini, G. Moschini, R. Nino, R. Policroniades, A. Varela, "Gamma Calibration of Organic Scintillators," *Nucl. Instr. Meth*, vol. A281, pp. 349-352, 1989.