

Development of PC-based nuclear instruments for gamma-ray spectroscopy using scintillation detectors

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Software-based nuclear instrument modules (SNIMs) were developed that retain complete control and functionality of their hardware equivalents. Using SNIMs, a PC-based nuclear instrument laboratory (NIMLAB) was developed in C. The library of the modules developed includes amplifiers, counters/timers, single- and multichannel analyzers, and digital oscilloscopes. The main advantages of SNIMs over conventional nuclear instruments are their portability and their ability to assist in the design of experiments. For the latter, a complete set of standard laboratory gamma-ray sources and NaI (Tl) detector with a preamplifier were also simulated using the integral response function and stochastic sampling technique. The SNIMs can also be used as a tool in teaching and training. © 1997 American Institute of Physics. [S0894-1866(97)01905-6]

INTRODUCTION

Scintillation and solid-state radiation detectors are widely used for both quantitative and qualitative analysis of nuclear radiations. Generally, standard nuclear instrumentation modules (NIMs) are employed for pulse processing and detailed analysis is performed using a multichannel analyzer (MCA). The NIMs and the MCA give satisfactory performance in a normal laboratory environment. Since they are not very portable, however, one faces problems when field or *in situ* radiation measurements have to be carried out.

In order to overcome the portability problems, personal computer (PC)-based data acquisition and analysis systems are currently being developed. Many well-known manufacturers of NIMs/MCAs have already started marketing MCA plug-in cards that allow the standard PC to be used as a MCA as well after their installation. These cards also come with the necessary software. Recently, Annand *et al.*¹ developed the ACQU system for data acquisition and analysis in medium energy electro- and photonuclear experiments. The ACQU system makes use of computer automated measurement and control (CAMAC) technology. It allows the user to control and automate both the data acquisition and the analysis parts of the experiment. But the ACQU is not a portable system. It is worth noting that similar efforts have also been made in related radiation measurement areas. For example, Liu *et al.*² have also developed a low-cost yet very sophisticated CAMAC-PC data acquisition and control system for high-resolution spectroscopy in the extreme-ultraviolet region.

The design of experiment (DOE) is another important issue. A good DOE enables one to get the most detailed picture of the response behavior of the system. But DOE

can be time-consuming and costly. In order to assist in DOE, computer simulations “models” are used that are vastly cheaper than the actual experiment.³ Both deterministic and stochastic models are used for DOE.

Numerical simulations, and Monte Carlo simulations in particular, have widely been used in computer modeling of nuclear instruments. Recently, De´combaz and Laedermann⁴ developed a Monte Carlo-based model of a large well type NaI (Tl) detector to estimate the counting efficiency of the system. They find that the accuracy of such simulations is in the range of about one-tenth of a percent, which is similar to that obtained by other methods.

In this article the development of software-based nuclear instruments (SNIMs) is presented. These SNIMs retain the complete control of their hardware equivalents. SNIMs can be easily installed on the current generation of portable laptop PCs. Here, a complete software simulation of major nuclear instruments is given. Based on these SNIMs, the software package NIMLAB was developed. The complete range of commonly used nuclear instruments is included in this package. The NIMLAB includes software simulations of NaI (Tl) detectors, preamplifiers, amplifiers, counter/timers, single- and multichannel analyzers, and oscilloscopes. At this stage, the NIMLAB can be used for real-time data acquisition as well as for off-line design of the experiment. The details of this software package are presented in this work along with some of the results.

I. THEORETICAL DETAILS

The standard electronic setup used for NaI (Tl) gamma-ray counting and spectroscopic analysis is shown in Fig. 1. The photons emitted by the source interact with the NaI (Tl) crystal, producing scintillations that are detected by the photomultiplier tube (PMT), and an electrical pulse is produced. The preamplifier collects this signal and produces a tail pulse with a height proportional to the total collected

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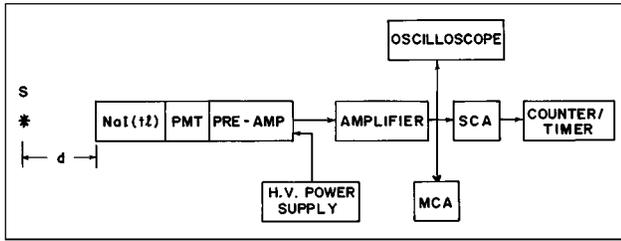


Figure 1. Typical gamma-ray spectroscopy detection setup for the NaI (TI) detector.

charge. The spectroscopic amplifier amplifies the tail pulse and shapes it into linear unipolar or bipolar forms. During this process, the pulse height remains essentially proportional to the energy deposited by the photon in the detector.

The voltage pulse produced by the PMT has the following form:⁵

$$V(t) = \frac{1}{\lambda - \theta} \left(\frac{\lambda Q}{C} \right) (e^{-\theta t} - e^{-\lambda t}), \quad (1)$$

where λ is the scintillation decay constant and θ is the inverse RC time constant of the charge-collecting circuit. The spectroscopy amplifier shapes this pulse and shapes it using its adjustable shaping time θ_c as well as amplifies it by gain A . The resulting amplified shaped linear pulse can be mathematically represented by

$$V(t) = \frac{A}{\lambda - \theta} \left(\frac{\lambda Q}{C} \right) (e^{-(\theta + \theta_c)t} - e^{-\lambda t}). \quad (2)$$

The gain of the spectroscopy amplifier can be varied from 0 to 5 K with the help of coarse and fine gain controls.

The next unit in the pulse processing system is the single-channel analyzer. This unit produces a standard logic pulse for each linear pulse when its amplitude is between the lower and the upper levels of the discriminators. Mathematically, the logic pulse is produced when

$$LL \leq V_{\max} \leq LL + \Delta V, \quad (3)$$

where LL is the lower level of the discriminator, ΔV is the "window" width of the single-channel analyzer, and V_{\max} is the amplitude of the shaped linear pulse.

The logic pulses are sent to the counter/timer unit, which simply increments the current value of the counter upon the arrival of the logic pulse. This unit has an adjustable timer so that counting of the signals can be carried out for specified intervals of time.

The multichannel analyzer is used for detailed pulse-height analysis. Each linear pulse is sorted into the appropriate channel according to its height and this pulse-height spectrum is displayed by the MCA. The spectrum continuously gets updated. The analog linear pulses are digitized by the analog-to-digital converter (ADC) unit inside the MCA.

The oscilloscope shown in Fig. 2 is used to see the pulse shapes at various stages. The necessary power is supplied by the EHT unit.

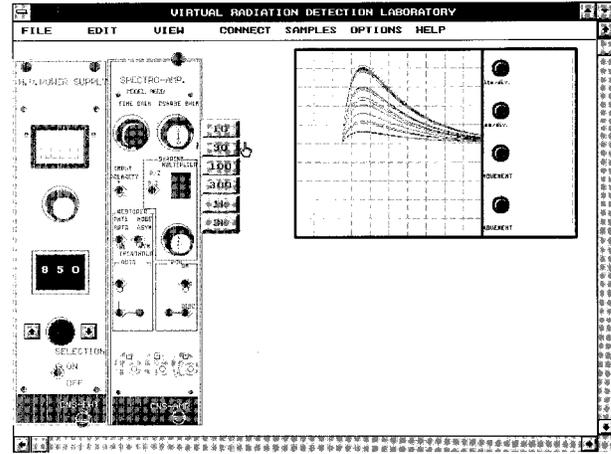
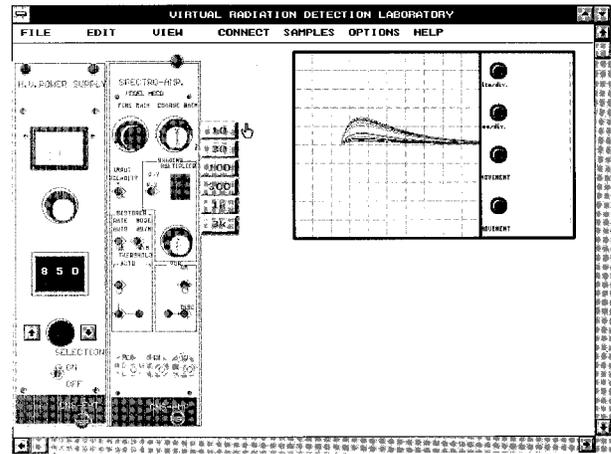


Figure 2. The effect of the coarse gain amplifier on pulse shapes.

II. SOFTWARE SIMULATION

All of the above-mentioned NIMs were simulated in this work. For this purpose, a complete graphical user interface with mouse controls, pull-down menu bars, user prompts, and dialogue boxes was developed. A visual display of the front panel of each unit is provided with active controls including push buttons, coarse and fine gain knobs, and status display windows. An effort was made to design the SNIMs so that they provide the look and the feel of their hardware counterparts. This visualization is expected to make them easier to adapt to, since the user can clearly identify the functions of each simulated instrument. The software is based on the event-driven technique.

The simulation was carried out using C because of its inherent simplicity and portability. Standard bios calls were used throughout the software in order to retain the functionality of these modules over the complete range of IBM PCs and those compatible with them.

An interface with an ADC/digital-to-analog (DAC) card was developed for data acquisition from the actual detector. The digital signal is converted into the internal "tail" pulse representation and then processed by the various SNIMs. The first unit in this line is the simulated spectroscopy amplifier, which provides the necessary pulse

shaping and gain. The simulated front panel of this unit contains the coarse and fine gain knobs along with the necessary shaping time controls. The single-channel analyzer is the second unit in the line. It has two controls: the lower level and the window width. The user can adjust these controls during the simulation. For the pulses obeying Eq. (2), a corresponding logic pulse is produced. The next unit is the counter/timer, which has timer start/stop/reset push buttons. The counting time can also be adjusted by simulated front panel controls. When active, it displays the current value of the recorded counts dynamically.

In order to view the pulse shapes at various stages, a simulated oscilloscope was also developed. It has a full set of standard controls. Both the time base and the vertical gain knobs are available. The multibuffering technique was used to make the display of the simulated oscilloscope look as realistic as possible.

In order to view the pulse-height spectrum, a multi-channel analyzer was developed. It has 2000 channels and provides full control over the spectrum collection and display. The collection time can be specified. The vertical scale can be selected as linear or logarithmic. The collection time and the total recorded counts can also be obtained.

The other motivation for this work was the design of the experiment. Optimization of the counting time and proper adjustment of various parameters can be simplified considerably by utilizing computer simulations. For this purpose, the software package includes a large set of simulated standard laboratory gamma sources. These are essentially point sources and for each one of these sources the Monte Carlo-based stochastic sampling method is employed for the deposited energy. In order to avoid long computational times and to keep the simulations realistic, actual integral spectra of these sources were used as the basis of the sampling. The random samples from these sources provide the necessary values of the deposited energy inside the detector, which is later converted into the "tail" pulses using specified values of the system's parameters and the above-discussed mathematical models. The user can control the source-to-detector distance that results in the variation in the photon incidence rate according to $4\pi/\Omega$ where

$$\Omega = 2\pi \left(1 - \frac{d}{\sqrt{d^2 + a^2}} \right), \quad (4)$$

where a is the diameter of the detector and d is the distance between the source and detector. As the value of d increases, the count rate decreases.

In order to facilitate in the design of experiment, a simulated power supply is included in the software package. The variation of the count rate with the applied voltage was modeled by the following equation:

$$C(V) = \begin{cases} C_m(1 - e^{-\alpha(V-V_0)}), & \text{when } V \geq V_0, \\ 0, & \text{otherwise,} \end{cases} \quad (5)$$

where $C(V)$ is the count rate at V applied voltage, C_m is the maximum count rate of the simulated detector and V_0 is the threshold voltage up to which no counts are recorded. The parameter α is determined empirically for the detector.

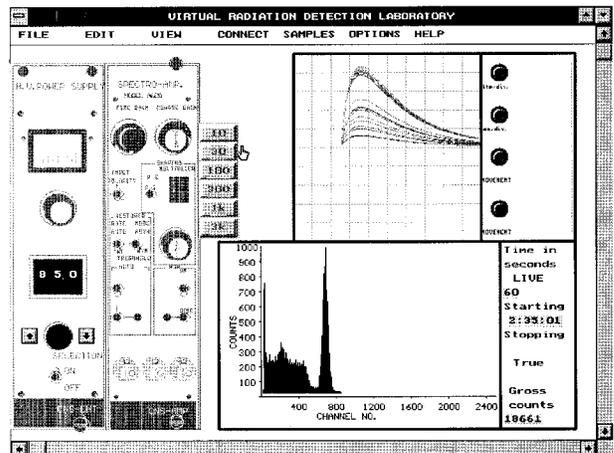
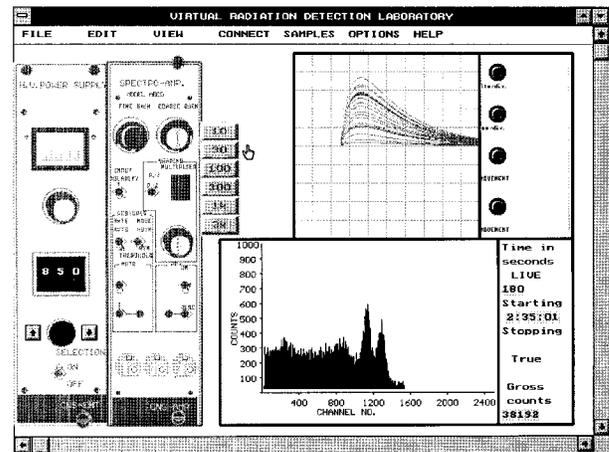


Figure 3. The differential pulse-height spectra recorded by the MCA for ^{60}Co (top) and ^{137}Cs (bottom) sources.

III. RESULTS

This software package was employed to carry out various types of gamma-ray spectra collections. Figure 2 shows the study of pulse height with variation in the amplifier gain. Here, the simulated oscilloscope shows shaped linear pulses in a quite realistic manner. The source used in this case was ^{137}Cs and for this source one expects a bright strip of pulses corresponding to the photo events at the top of the rest of the pulses; it is clearly visible in both parts of Fig. 2.

Figure 3 shows the pulse-height spectra for the ^{60}Co (top) and ^{137}Cs (bottom) sources. The former emits two gamma-rays photons in each disintegration whereas the latter is a monoenergetic gamma-ray source. One can see the characteristic spectra of each of these sources quite clearly in Fig. 3. The photo-peak regions and the Compton continuum are present. Here, it is seen that the MCA shows the pulse-height spectra dynamically.

The effect of amplifier gain was also studied by changing the coarse gain values through the virtual knobs of the amplifier. The results are shown in Fig. 4 for coarse

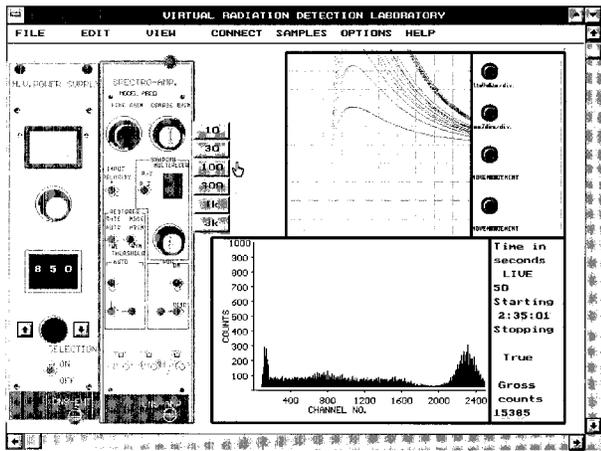
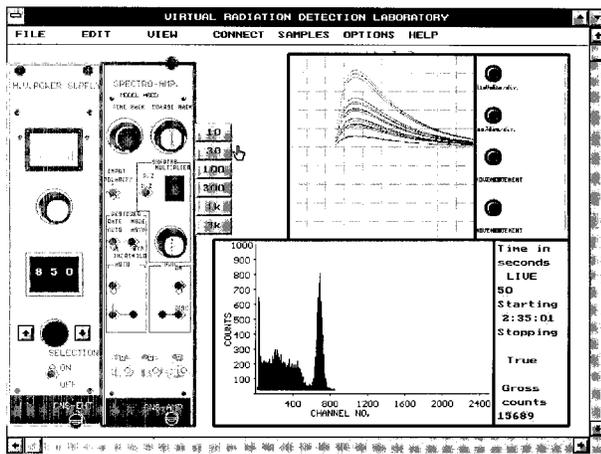


Figure 4. Variation of the amplifier gain A and its effect on the spectrum: top shows $A=30$ and bottom shows $A=100$.

gain values of 30 and 100, respectively. The increase in the gain results in an increase in the pulse height and the corresponding change in the spectrum that is displayed on the MCA.

The major portion of this software package was developed as a M.S. thesis project⁶ and it was used in the introductory radiation detection laboratory course. It has proven quite useful for various experiments including inverse-square-law verification and differential and integral pulse-height spectra studies for isotope identification and quantification using the relative counting technique.

IV. CONCLUSIONS

The software-based nuclear instrumentation modules developed in this work present an attractive alternative to their currently available hardware counterparts. They can be used to overcome portability problems as well as for proper design of the experiment. They are also very good teaching and training tools, since they have the look and feel of an actual nuclear instrumentation module. The student can learn the operation of various modules by simply installing the software on a PC and using the specific module.

The SNIM-based software package NIMLAB includes simulations of NaI (Tl) detectors, preamplifiers, amplifiers, a single-channel analyzer, a counter and timer, a multichannel analyzer, a power supply, and an oscilloscope. The effect of changes in the source types, source strength, source-to-detector distance, amplifier gain, and in the upper and lower levels of discriminators can be studied with the help of this software.

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