INSTRUMENTATION FOR

GAMMA-RAY SPECTROSCOPY

by Terence J. Kennett

Ge(Li) detectors and analog-to-digital converters are teaming up with computer hardware and software to collect, store and analyze gamma-ray spectra. Running an experiment for a few days now gives more spectral information than one used to get in a few months.

During the past decade and a half gamma-ray spectroscopy has increased by orders of magnitude in its ability to reveal information. At present the high resolution of lithium-activated germanium detectors justifies 4000-channel analysis, and computer programs speed interpretation. The result is a system that does in days what used to take months even with fairly sophisticated computers. Today's methods are a considerable advance over methods that started with the introduction of thallium-activated sodium-iodide crystals and 256-channel analyzers, just as those, in their turn, were a great advance over devices that preceded them.

Detector development

In 1950, development of the NaI (Tl) detector by John McIntyre and Robert Hofstadter[1] opened the field of gamma-ray studies to an unprecedented degree. This efficient counter, with its reasonably good resolution, permitted the study of many decay processes previously considered impractical. However, the prevalent electronic systems for the acquisition of nuclear information were exceedingly restrictive and prevented exploitation of the full potential of this detector. The technology of ferrite-core memories and the suggestion by Dennis Wilkinson[2] of a practical converter were combined by R. W. Schumann and J. P. McMahon[3] to produce a 256-channel pulse-height analyzer in 1956. For about five years a certain balance between detectors and acquisition systems was maintained. By 1962 the nature of experiments was requiring much larger acquisition systems for multiparameter correlations, and analyzers of 20 000 channels were manufactured. Most of these systems were perfectly adequate for measurements conducted with NaI (Tl).

In 1964, A. J. Tavendale[4] succeeded in fabricating a practical Ge (Li) detector. Although volume and hence efficiency were small, resolution was better than that achieved with most magnetic spectrometers so that, on this basis, it was in effect a very efficient spectrometer. As manufacturing techniques have developed, the volume of Ge (Li) counters has risen[5] to about 50 cm^3 and resolution values have improved until recently Harry Mann[6] obtained 0.8 keV and 4.9 keV full width at half maximum for 100-keV and 10 200-keV gamma rays respectively. His measurements suggest that, provided electronic noise and germanium quality can be improved, this resolution may improve by a factor of two.

This impressive jump in detector technology has placed severe demands on existing data-acquisition systems. Linearity and resolution inherent in the Ge (Li) detector can only be fully exploited if the entire range of gamma-energies of interest in a particular experiment is sampled concurrently. This in effect demands an analog-to-digital converter (ADC) having 4000 channels and a stability of one channel

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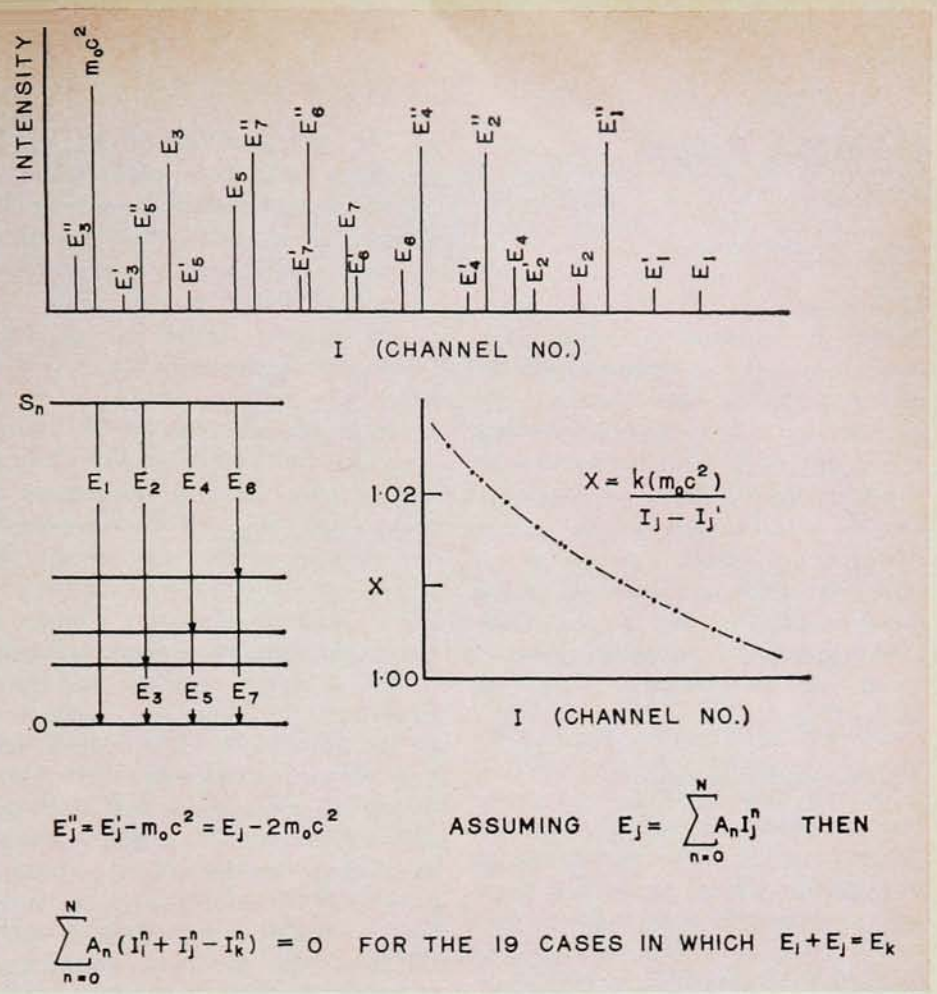


ENERGY DETERMINATION of neutron-capture gamma rays using a Ge(Li) counter. From the hypothetical line spectrum and decay scheme shown, one can determine the nonlinearity of the system; by employing constrants, energies can be obtained relative to m_0c^2.—FIG. 1

for the entire system. Thus for the most ordinary types of gamma-ray spectroscopy one can expect to see the 4000-channel analyzer filling the role previously held by the 256-channel analyzer.

Investigation of time correlations requires a multiparameter system. For gamma-ray studies one can anticipate Ge(Li)-NaI(Tl) and Ge(Li)-Ge(Li) spectrometers. The use of a 10 000- or 20 000-word random-access memory is adequate for a NaI(Tl)-NaI(Tl) spectrometer, but improved resolution associated with Ge(Li) as one of the parameters makes such storage capacity marginal. The reduced efficiency of spectometers using Ge(Li) increases the need for acquiring as much information as possible. However the requirement for data fields of 200 000 or more channels conflicts seriously with this objective. One is forced to consider a real-time experiment involving 10 000- to 20 000-word memories or to resort to delayed-time analysis featuring virtually unlimited memory size.

Although delayed-time analysis has been employed for many years[1], sophistication of commercially available equipment coupled with appearance of fast large-memory computers has made this technique come of age. To illustrate some of the points raised above, a brief discussion of experimental results is useful. Since the field of gamma-ray spectroscopy is rather broad, the examples presented will be taken from neutron-capture gamma-ray studies.

Detector output

Determination of precise gamma-ray energies has been limited to low energies, where crystal and conversion spectrometers are useful. For energies greater than 3 MeV precision has been orders of magnitude poorer. The Ge(Li) counter, with an inherent precision of $\sigma/N^{1/2}$ (where σ is about 2 keV and N the number of counts in a peak) could yield extremely accurate energies except that only relative measurements can be made. Precision pulsers are often used to overcome this problem, but nonlinearities associated with both detector and pulse shape are not included in such calibrations. Therefore a procedure more intimately connected with the experimental conditions should be sought. The technique we have used (at McMaster University) is to take advantage of the response of the Ge(Li) counter to high-energy gamma rays.

For gamma-ray energies greater than 2 m_0c^2 the response function of a Ge(Li) detector that has a volume of a few cubic centimeters includes three Gaussian distributions. These arise from detection of: (1) the e^-, e^+ pair (corresponding to an energy E_i), (2) the e^-, e^+ pair plus one of the annihilation photons captured in the crystal (energy E_i') and (3) either the e^-, e^+ pair plus both annihilation photons or a photoelectric event (energy E_i''). Thus for each gamma ray we obtain three peaks, separated by an accurately known energy (511.06 ± 0.006 keV). In addition, for thermal-neutron capture many cascades or decay modes exist that have a common initial and final state. Figure 1 illustrates a hypothetical example of this situation and schematically shows the spectrum one might expect.

The line spectrum in figure 1 shows the three peaks E_i, E_i', E_i'' associated with each gamma ray. Also indicated is the annihilation peak at m_0c^2, which arises in such experiments from pair production within the source and surrounding material. From the data itself it is possible to deduce the transfer function relating energy E and channel number I and to determine all the gamma-ray energies relative to m_0c^2. The transfer function is actually revealed in semiderivative form by examination of the quantities $m_0c^2 = E_i - E_i' \propto \Delta I_i$ and $E_i' - E_i'' \propto \Delta I_i'$ as a function of I. This permits one to form a model function relating E and I that is consistent with the data, although not unique.

To obtain best estimates for descriptive parameters one invokes a series of constraints involving closure of energy loops (that is, $E_1 + E_2 = E_0$, $E_1 + E_2' = E_0'$, etc.) in a generalized regression analysis.

Position of the annihilation peak is then used to place the energy scale on an absolute basis. In such an analy-

sis, locations of all peaks are determined by standard nonlinear least-squares techniques. Examination of certain favorable cases indicates this method can lead to accuracies a few tenths of a keV without the use of secondary standards. It requires concurrent accumulation of the entire spectrum on a mesh sufficient to ensure good analytical retention of the Gaussian distributions; for the energies encountered in these measurements a 4000-channel basis is necessary.

Two-parameter analysis

Multiparameter analysis is most readily illustrated for two parameters. If we represent these parameters by x and y, where one or both dimensions have Ge(Li) spectrometers, then the correlation surface being sought is described by

$$P(x,y) = \sum_{ij} a_{ij} X_i(x) Y_j(y) \qquad (1)$$

where $X_i(x)$ is the response of the ith gamma ray in the x counter as a function of x, $Y_j(y)$ is the response of the jth gamma ray in the Y counter as a function of y and a_{ij} is the correlation coefficient relating the gamma rays i and j. The quantities a_{ij} are the only physically meaningful parameters being sought. Since the analog counter signals are digitized into I_x and I_y channels, the array into which the surface $P(x,y)$ is to be stored is characterized by dimensions $I_x \times I_y \times$ count capacity. As we noted, such a large array is impractical at present since it implies a random-access memory of the same dimensions if real-time analysis is to be conducted.

The need to record the entire surface is immediately apparent if one wishes to apply standard regression techniques to obtain the coefficients a_{ij} of equation 1. If one does not demand an up-to-date record of $P(x,y)$ during the experiment, but only, say, the distribution $L(x) = \Sigma_y P(x,y)$ for monitoring, then by writing correlated pairs (x,y) in serial fashion on magnetic tape and monitoring $L(x)$ on a real-time basis, the entire surface can be recorded. This delayed-time data must be sorted at a future time if $P(x,y)$ is to be examined. The use of a buffer storage device in conjunction with the recording system derandomizes the input information and also reduces average dead time for writing.

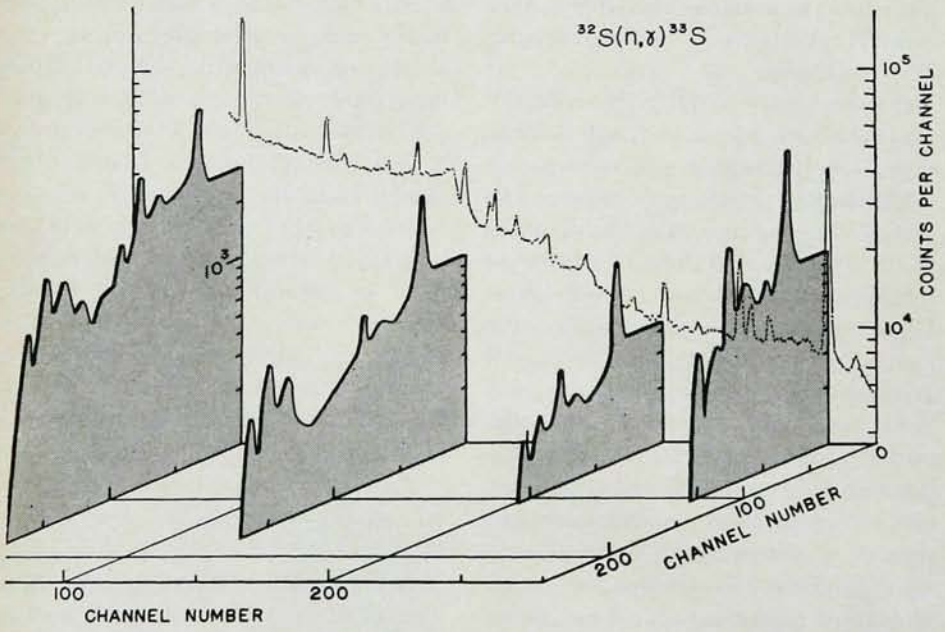
With a 556-bit/inch format, a recording rate of about 4000 counts/sec can be achieved with a capacity of approximately 3×10^6 18-bit words for a 2400-foot roll of magnetic tape. Sorting of the serial information must ultimately be accomplished with a random-access memory. Since the number of passes necessary for a tape in such a sorting procedure is equal to the recorded mesh size divided by the memory size, the memory should be as large as possible. The most economical approach is to use a large-memory computer in which word length is divided down as far as possible. For example, a 36-bit word can generally be used as four 9-bit words since the frequency of a given coördinate per tape is usually less than 512 events. In effect this procedure increases the computer memory by a factor of four.

Time correlations

A typical example of this multiparameter technique is our investigation of time correlations of the reaction $^{32}S(n, \gamma)^{33}S$. We used a Ge(Li)-NaI(Tl) spectrometer, and a mesh size of 1024×256 channels was necessary to retain resolution. The Ge(Li) counter had an active volume of 6 cm^3 and the NaI(Tl) was 7.6×7.6 cm. A total of 1.2×10^7 coincidence events were stored on magnetic tape and ultimately sorted with an IBM 7040 computer. During sorting, digital restrictions that can most easily be selected on the basis of the monitored projections $L(x)$ and $L(y)$ can be readily applied.

For this experiment about 200 000 channels were sorted; figure 2 illustrates a small portion of the surface $P(x,y)$ to show the nature of the results. The more significant decay-mode features can be revealed in about 200 hours of counting for neutron-capture gamma rays and about eight hours for beta decay. If some form of restriction gating were used in a real-time configuration with, say, 4000 words of memory, these types of experiments would require about three months and about four days, respectively, with the existing spectrometer.

In anticipating needs for the next decade one is very dependent on tech-



TWO-PARAMETER MEASUREMENT of the γ-γ time correlation from the reaction $^{32}S(n, \gamma)^{33}S$. Measurement was done with a Ge(Li)-NaI(Tl) spectrometer and recorded on a 1024×256 mesh. Delayed-time data were sorted on an IBM 7040 computer. The total Ge(Li) coincidence spectrum $L(x)$ is projected onto one plane and a few spectra from the surface $P(x,y)$ are illustrated. —FIG. 2

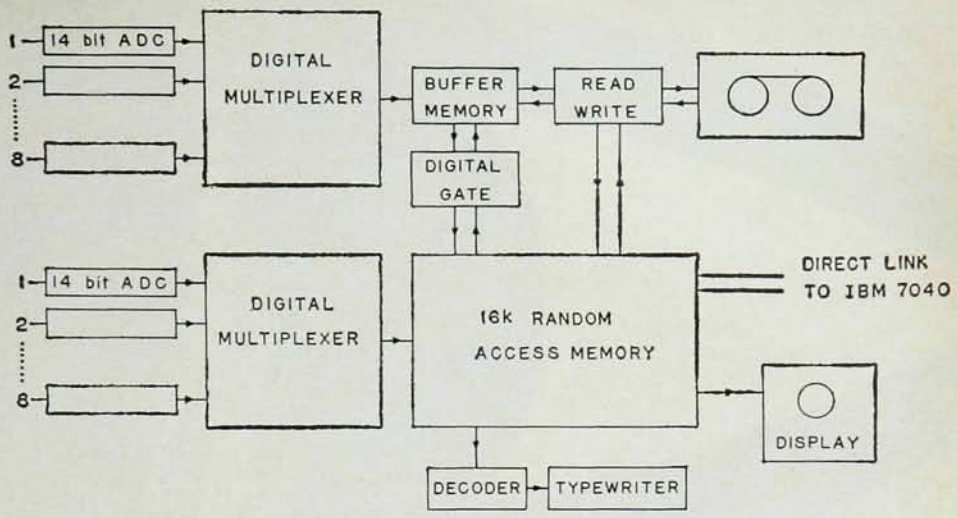
nology. It seems that the Ge(Li) detector will, with the associated preamplifier, continue to show improved resolution. But acquisition systems will determine the direction in which spectroscopy will move. Although mathematical techniques for reducing large data fields have already been developed, the best way to accumulate experimental data has been the subject of many discussions and remains undecided.[8,9]

A new acquisition system

About two years ago at McMaster University we made a detailed evaluation of the type of acquisition system best suited to the pulse-spectrometry research centered about our reactor. The principal criteria we imposed were that (1) the system must be able to fulfill requirements of all realistically conceived experiments, (2) operation and setup should be convenient, (3) cost should be reasonable and (4) provision for real- and delayed-time analysis should be made with the ability to operate in each mode independently. Fast stabilized converters having 1:8000 resolution appeared necessary to accommodate anticipated needs during the next few years. We concluded that a 16 000-word random-access memory with an 18-bit word length would provide desired flexibility.

The value of stored- and fixed-program systems was considered in the context of the requirements and our past experimental experience. Separating data acquisition from subsequent data reduction in a large general purpose computer, we found, leads to better quality experimental data and scheduling ease and, in addition, it appears to have pedagogical merit. We concluded that the fixed-program instrument satisfied most of the points that have been delineated.

The acquisition system we chose was designed and constructed by an industrial manufacturer (Nuclear Data, Inc.) and it is scheduled to go into operation this summer. A schematic representation of the system is shown in figure 3. Delayed-time and real-time modes can be operated independently and up to eight analog-to-digital converters can be digitally multiplexed into both systems. The converters can, of course, be used in multiple-parameter or multiple-experiment configurations. Time sharing is necessary within the two modes but is not required between them. Sorting of delayed-time data can be achieved through the large random-access memory by digital gates.



ACQUISITION SYSTEM being built for McMaster University. —FIG. 3

A stored program, permitting the looping of an automatic sequential sorting routine, transforms the delayed-time mode into pseudo real-time analysis. To illustrate the form of operation, let us assume a 256 × 256 data field is being buffered and recorded onto tape in the usual serial fashion. When the tape is filled with about three million correlated addresses, there is an interruption of the delayed-time mode and the system switches to the search operation.

The recorded information can be completely sorted by making four passes of the tape with the 16 000-word random-access memory. The four blocks of accumulated data are written at the beginning of the tape, and the system returns to the delayed-time mode. When the tape is again filled with correlated addresses it is sorted, and the new information is added to that previously accumulated. By using this looping procedure all serial data, except those recorded on tape since the last search, are readily available in accumulated form. For experiments involving several tapes, this mode of operation allows one to examine virtually all data obtained in gathered form and to avoid the usual limitations of delayed-time analysis.

The display system offers several new features of particular importance to experimentalists. Analog and digital intensification simplifies the setting of digital windows and digital coördinate readout of significant information. Access to the 7040 computer is accomplished with direct links and magnetic tape.

The discussion of our acquisition system has implied the application to reactor-oriented experiments. The same system is applicable to accelerator experiments, however. Because certain logical decisions are frequently necessary, a small computer can be interfaced with the main system. Such a system costs about one third to one half as much as a general-purpose computer capable of comparable flexibility. □

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