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A SPECTROMETER FOR THE INVESTIGATION
OF GAMMA RADIATION PRODUCED
BY NEUTRON-INDUCED REACTIONS

by
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MASTER

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ABSTRACT

A spectrometer for measurement of cross sections for gamma-ray production by neutron-induced reactions has been constructed for use at the Argonne National Laboratory Tandem Dynamitron Accelerator Facility. Gamma radiation is detected by a shielded Ge(Li) detector in the angular range 30 - 135°. Neutron fluence is monitored with either a fission detector or a plastic scintillation detector. Raw data are recorded with an on-line digital computer and these data are subsequently reduced to cross sections by off-line processing. The characteristics of this facility and general features of the data processing are described herein.

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1. INTRODUCTION

Neutron irradiation of atoms produces gamma radiation by means of various nuclear processes such as capture, fission and $(n, X\gamma)$ reactions. Most of the gamma radiation results from prompt electro-magnetic de-excitation of the reaction products; however, delayed gamma production occurs if the reaction products are left in isomeric states or decay first from ground states via weak processes or alpha particle emission. Analysis of these gamma-ray spectra is a powerful method for investigation of nuclear structure. The $(n, n'\gamma)$ reaction is a particularly useful tool for spectroscopic studies of the low-lying excited states of isotopes which can be obtained in sufficient quantities (~ 1 mole) to fabricate a scattering sample [1].

Production of prompt gamma radiation via neutron inelastic scattering and subsequent absorption is an important factor in the transformation of neutron kinetic energy to heat in nuclear reactors. The importance of this process to the development of nuclear energy sources has prompted considerable research effort [2]. In spite of this activity, it is apparent that the available gamma-ray data falls short of satisfying the needs for applications [3,4,5].

A spectrometer has been constructed for use in the investigation of neutron-induced gamma-ray production. The objective is to measure cross-section excitation functions and gamma-ray angular distributions for a large number of isotopes of importance to nuclear-energy applications. The properties of discrete gamma-ray transitions from threshold to several MeV of excitation are sought. No single instrument or technique is universally applicable for all categories of measurements. Therefore, it was decided to concentrate on gamma-rays with energies in the range 0.1 - 5 MeV, and neutron bombarding

energies below 5 MeV. While these limitations exclude consideration of some important areas, they do permit investigation of a very significant domain [6].

The spectrometer makes use of a Ge(Li) detector for gamma-ray measurements. Ge(Li) detectors provide the high resolution necessary to investigate complex spectra, and lately they have become available with substantial efficiencies. The timing characteristics of these detectors are not outstanding, but experience has shown that timing performance which is adequate for the intended application can be obtained without excessive difficulty. Inaccurate measurement of neutron fluence is a common source of systematic error in neutron cross section measurements. A fission detector is used with the present spectrometer for reasons which will be discussed in Section 2.4. A scintillation detector with a plastic scintillator is employed as a secondary monitor for relative neutron measurements. The importance of appropriate shielding for the gamma-ray detector should be emphasized. The spectrometer has been under development for several years and most improvements in data quality during this period can be attributed to shielding modifications. The application of pulsed-beam neutron time-of-flight techniques in several areas of neutron spectroscopy have been described by various authors (e.g. ref. 7,8,9 and 10). The Argonne National Laboratory Tandem Dynamitron Accelerator has pulsed-beam capability and use has been made of this feature in design of the spectrometer in order to reject background and distinguish prompt from delayed gamma radiation. The spectrometer also utilizes a small digital computer for data acquisition. The data quantity and rate are manageable for a small computer and one can thereby incorporate a degree of complexity and flexibility in data acquisition which is not feasible with hard-wired recorders [11]. Ease of setup and long-term stability are required for an instrument designed for programmatic cross

section studies. During one measurement period, this spectrometer was utilized continuously for six weeks with approximately 120 hours of continuous operation per week.

The objectives of this paper are to describe the spectrometer and its operating characteristics, discuss its capabilities, present representative examples of spectral data acquired with this instrument, and outline the data acquisition and processing procedures.

2. APPARATUS AND DATA ACQUISITION

2.1 General

Figs. 1-6 describe the hardware components of this spectrometer. Scattering samples are supported by an adjustable stem (Figs. 2,3 and 5) on a beam line of the ANL Tandem Dynamitron Accelerator Facility (commonly referred to as the Fast-Neutron Generator or FNG [12]). The sample is irradiated with neutrons emitted in the vicinity of zero degrees; the ${}^7\text{Li}(p,n){}^7\text{Be}$ and ${}^2\text{H}(d,n){}^3\text{He}$ reactions are the neutron sources most often employed. Gamma radiation from neutron induced reactions is measured at various scattering angles by a Ge(Li) detector which is enclosed in a massive shield which pivots about the sample (Figs. 1,2,3 and 5). Neutron fluence is usually measured with a fission detector placed on the beam line between the neutron source and the sample (Figs. 1,2,3 and 4). The low mass of the fission detector insures that the perturbation of the neutron beam incident upon the sample is relatively small (Fig. 4). Alternatively, the fission chamber can be moved out of the way (Fig. 5) and the neutron fluence can be monitored by a shielded scintillation detector situated ~ 5 meters from the neutron source (Fig. 2). A long counter is also used for radiation safety purposes and for monitoring target yields (Fig. 2). Signals from the detectors are processed with electronic apparatus which will be described in Section 2.5. Details of on-line data processing by the digital computer will be treated in Section 2.6.

2.2 Neutron Source

Characteristics of the FNG are described elsewhere [12]. This accelerator currently provides direct-current or pulsed beams of protons or deuterons with energies in the range 1.5 - 8.0 MeV. With klystron bunching, the FNG can deliver, on target, an average pulsed-beam current of ~ 5 μ A with a burst repetition rate of 2 MHz and pulse widths of ~ 1 nanosec. Other pulsing modes are available, but that mentioned above is satisfactory for the present application. Natural lithium metal is evaporated on tantalum cups to form the targets for neutron production via the ${}^7\text{Li}(p,n){}^7\text{Be}$ reaction (Figs. 3,4 and 5). Target oscillation and air-jet cooling increases target life time. Properties of the Li+p neutron source are well known [13,14,15]. A gas target assembly is used for measurements incorporating the ${}^2\text{H}(d,n){}^3\text{He}$ neutron source reaction. This assembly is not shown in this paper; however, properties of this source are described elsewhere [14,16]. Timing signals are derived by passing the beam bursts through a pickoff tube placed near the target (Fig. 2). This method has the advantage of providing a zero time which is relatively independent of beam energy [9]. The beam "spot" on target is defined by vertical and horizontal slits and is normally ~ 0.5 cm square. The neutron source extends along a line ~ 2 cm long when a gas target is used. At higher energies, background and secondary-source neutrons are emitted from both lithium and deuterium targets. Various techniques are employed for dealing with this problem; these are discussed in other reports [15,16,17].

2.3 Gamma-Ray Detector and Shield

A 52-cm³ true-coaxial Ge(Li) detector in a right-angle dipstick cryostat is used as the gamma-ray detector. The nominal full-energy peak efficiency for this detector is 10.5% relative to a 7.6 cm x 7.6 cm cylindrical NaI (Tl) scintillation detector (measured with 1.332-MeV gamma-rays from a ${}^{60}\text{Co}$

source placed at a distance of 25 cm). A scintillation detector could be used in the spectrometer; however, the advantage of high resolution for the Ge(Li) detector outweighs the disadvantage of decreased efficiency.

The gamma-ray detector is shielded from the neutron source so that it sees primarily those gamma-rays from the irradiated sample. This shielding should be effective over a considerable angular range if angular distribution measurements are to be made [1]. The shield tank currently used for the Ge(Li) detector (Figs. 1,2,3,5 and 6) is constructed from 0.63-cm thick steel sheets. The shield is modular so that shield components can be added or removed in order to vary the distance from the detector to the sample. The shield is mounted on a steel platform which smoothly traverses a circular path by means of an air-flotation pad (Fig. 1). The Ge(Li) detector views the scattering sample through a square collimator which provides optimal shielding for a given solid angle. Shielding of the throat of the collimator is provided by an adjustable shadow bar constructed of lead (Fig. 1,2,3,5 and 6). However, other shielding materials (e.g. tungsten) could also be employed.

Fig. 6 is a schematic diagram of the internal structure of the shield. Lead near the front absorbs gamma radiation from the neutron source. Various neutron shield materials were evaluated on the basis of three parameters. The first parameter is hydrogen density, n_H , which determines the effectiveness of the shielding in slowing fast neutrons. Lithium is a desirable component of a neutron shield for a gamma-ray detector because the ${}^6\text{Li}$ atoms in natural lithium remove moderated neutrons by the non-radiative ${}^6\text{Li}(n, {}^3\text{H}){}^4\text{He}$ reaction. The ${}^1\text{H}(n, \gamma){}^2\text{H}$ reaction captures moderated neutrons but produces 2.2-MeV gamma rays which contribute to detector background. Therefore,

two additional parameters to consider for shielding comparison are ${}^6\text{Li}$ concentration, n_{Li-6} , and the ratio, R , of non-radiative $(\sigma_{Li-6}(n, \alpha) + \sigma_{Li-6}(n, p))$ to radiative $\sigma_{Li-6}(n, \gamma)$ absorption (low-energy neutrons). R was computed for thermal neutrons using published cross sections [1b]. Values of n_{Li-6} , R_{Li-6} , and R for several shield materials appear in Table 1. Lithium hydroxide monohydrate powder was selected for the bulk shield material (Fig. 6). This compound is inexpensive, easily handled and noncorrosive. A removable collimator was fabricated from a mixture of 50% lithium carbonate and 50% paraffin. This material has a larger value of R than the bulk shield material and is easy to mold. The front and side of the Ge(Li) detector are surrounded by an inner layer of lead and an outer layer of lithium carbonate powder (Fig. 6). Lithium carbonate is not a good neutron moderator, but was chosen for its large value of R (Table 1). The lead provides an effective final barrier against gamma rays produced by neutrons absorbed through radiative processes in the shield. The inner shielding components could be removed and replaced by an anti-Compton mantle [1] if required; however, it has not proved necessary to do so since the current research program is concerned with neutron reaction processes at energies of a few MeV and below. The shield, as shown in Fig. 1, places the Ge(Li) detector ~ 130 cm from the sample. The center of the sample is normally ~ 12 cm from the neutron source. Angular distribution measurements over the range $30^\circ - 135^\circ$ are possible with this apparatus. The forward angle limitation is determined by the necessity of shielding the detector from direct target radiation, while the back angle limitation is geometric in nature (Fig. 1 and 2).

2.4 Neutron Fluence Monitors

Experience in this laboratory has shown that a fission detector which contains a calibrated deposit of

uranium, enriched in either ^{235}U or ^{238}U , is a convenient and reliable neutron fluence monitor for a variety of cross section measurements. Uranium fission cross sections are important in fission reactor technology and considerable effort has been expended toward improving the accuracy to which they are known. The ^{235}U fission cross section appears to be known to better than 5% for $E_n = 0.1-5$ MeV. The $^{238}\text{U} : ^{235}\text{U}$ fission cross section ratio is probably known to better than 2% for $E_n = 1.5-5$ MeV although ^{238}U is not desirable for use as a neutron monitor below 2 MeV. Both these cross sections vary smoothly and gradually with neutron energy (no resonance structure) in the region of interest.

Fission detector technology has been reviewed by Lamphere [19]. The detector used for the present spectrometer is shown in Figs. 3,4 and 5. This detector is a parallel-plate ionization chamber which utilizes pure methane at 1 atm. The grounded electrode contains a thin, uniformly thick deposit of uranium, 2.54 cm in diameter. A bias is applied to the second electrode which is isolated from the grounded electrode by three 0.63-cm long teflon insulators. Pulses are transferred from the biased electrode and shaped by a preamplifier. All fission events except those which emit fragments near 90° produce signals in the detector. Corrections for loss of fission fragments in the deposit and for fissions masked by alpha-particle emission are small (< 4%), measurable and relatively insensitive to neutron energy for the deposits used in this spectrometer ($\sim 0.2-1$ mg/cm² of uranium). The chamber electrodes and walls are 0.025-cm thick and the net change in fissions resulting from "In" and "Out" scattering is only $\sim 1-2\%$. Therefore, the efficiency of the fission detector is essentially proportional to the macroscopic fission cross section for the uranium deposit.

The proportionality constant is governed by the mass of the uranium deposit and geometric factors. A set of calibrated uranium deposits is available in this laboratory and these have been used in the present work. These deposits were calibrated using mass spectrographic and spectrochemical techniques in conjunction with measurements of specific alpha activity. The procedure has been described by Meadows [20]. The uranium masses for these deposits are known to $\sim 1\%$ and the isotopic fractions are known to a finer precision. Table 2 gives the results of the mass spectrographic analyses for these uranium deposits. The deposits are placed $\sim 5\text{-}6$ cm away from the neutron source during cross section measurements. It is possible to obtain adequate time resolution with the fission detector and time-of-flight discrimination is employed to reject scattered-neutron background. The scattered-neutron background varies slowly with primary neutron energy and is $< 2\%$ for a ^{235}U -enriched deposit.

Gamma production excitation functions are measured vs. neutron energy with the fission detector in position and the Ge(Li) detector located at 55° (Figs. 1 and 3). This angle corresponds to a node in the P_2 term for the Legendre polynomial representation of the angular distribution functions. Angular distributions can be measured at selected energies without regard to absolute neutron fluence. For these measurements, the fission detector is removed from the beam line (Fig. 5) and a scintillation detector is used as an auxiliary neutron monitor. This is desirable because the fission chamber interferes with back-angle measurements. The scintillation detector consists of a 2.54-cm dia x 0.63 cm thick plastic scintillator (Pilot-B) optically coupled to an RCA 6810A photomultiplier tube. The detector is mounted in a paraffin shield ~ 5 meters from the target and views the

neutron source, but not the sample, through a collimator. Since the timing resolution of this detector is superior to both the Ge(Li) detector and the fission chamber, it is used to monitor the pulsed beam during measurements.

A long counter is used as a third neutron detector, primarily for radiation safety and target yield monitoring purposes. This detector is also valuable for calibrating the FNG beam energy via neutron-producing reaction thresholds. The long counter is mobile and for threshold measurements it is placed at zero degrees.

2.5 Electronic Components

The electronic circuitry employed for this spectrometer has been assembled with the objectives of simplicity and reliability. Block diagrams of the circuitry are shown in Figs. 7-10.

The circuitry used for derivation of zero-time signals from the beam burst is shown schematically in Fig. 7. A preamplifier amplifies the fast bipolar signal derived from the time-pickoff tube. Delay cables of various lengths are used for adjustment of time-of-flight spectra. A discriminator senses the zero-crossing time for the bipolar signal and generates a standard fast logic signal which drives the "Stop" inputs for three time-to-amplitude converters.

The electronic components used to derive signals from the Ge(Li) detector and the fission detector are shown in Fig. 8. Both time and pulse-height (gamma-ray energy) information are derived from the Ge(Li) detector; only a timing signal is derived from the fission detector. A bias level on the fission detector discriminator rejects noise and alpha-particle pulses. All signals above the alpha cutoff are produced by fission fragments.

Time-of-flight information from the Ge(Li) detector and fission detector is routed through a passive "Or"

network. A linear amplifier, single-channel analyzer and special purpose module designated "monitor logic unit" are used to satisfy the logic conditions required for on-line data processing with the digital computer. The single-channel analyzer is used to set a wide window which encompasses all significant portions of the fission detector time-of-flight spectrum. The analyzer drives the monitor logic unit which serves two logical functions: (i) It generates a signal with an adjustable amplitude which is used as a "dummy" energy pulse simulating the nonexistent fission detector energy channel. The "dummy" energy signal is routed to the second input of the energy "Or" network. The output from this unit drives an amplifier which processes the true energy signal from the Ge(Li) detector and the "dummy" energy signal from the fission detector on an equal basis. (ii) An identifier signal (or "Tag") is generated, with variable delay, which ultimately enables the digital computer to differentiate Ge(Li) detector and fission detector pulses and thereby process them according to procedures dictated by the computer software. Each input pulse to the monitor logic unit produces one "dummy" energy pulse and one "Tag" pulse. The delay amplifier is required to insure that the fission detector time-of-flight and "dummy" energy signals are presented to the computer data terminal in the appropriate chronological order.

The circuitry employed with the scintillation detector is shown schematically in Fig. 9. Both timing and pulse-height information are derived from this detector. The time-of-flight signals from the TAC are amplified and sent to a linear gate which opens only when the corresponding pulses in the energy channel (slow) exceed a selected level established by a single-channel analyzer. This scheme provides the desired rejection of photomultiplier noise and

a relatively stable response (efficiency) for the monitor. Beyond the linear gate, the electronic circuitry is identical to that employed with the fission detector. In fact, it is possible to interchange the fission detector and scintillation detector monitors by interchanging one cable.

A Systems Engineering Laboratories Model 840MP digital computer is used for data acquisition. This computer has a 24-bit word length, 24K core capacity and a 1.75 μ sec cycle time. The computer has the usual compliment of hard-wired instructions and 14 levels of priority interrupt. The immediate peripheral compliment consists of a standard ASR-33 teletype keyboard, a fast paper tape I/O unit, disk storage and a CRT display in addition to the data-terminal interface [21].

The two analog-to-digital converters in the data terminal transform time-of-flight and energy information from the analog circuitry into binary numbers which are stored in two ADC scalers until they are read and processed by the computer according to the resident software. During this processing time, the analog circuitry is blocked so that there is a data-acquisition deadtime. This deadtime does not affect the accuracy of the relative measurements because the Ge(Li) detector and neutron monitor channels experience identical deadtime from this source. Once processing has been completed, the analog circuitry is opened to await subsequent signals from the detectors. The contents of the data terminal scalers are used in formulation of a 24-bit word which is read into the accumulator of the computer in the first step of on-line data processing. The word structure is as follows: Bits 1 and 11 are unused. Time-of-flight information enters bits 2-10 while energy information enters bits 12-23. Bit 0 has a special role.

It is left in the "on" or "one" mode unless it is set to the "off" or "zero" mode by a signal from the interface. This signal is generated whenever there is a coincidence between the data terminal slow-coincidence output and the "Tag" signal from the neutron monitor circuitry. Logically, this corresponds to a condition where there has been a pair of energy and time signals processed by the data terminal analog circuitry and recorded in the ADC scalers, and a "Tag" signal was present, simultaneously, indicating that the event originated in the neutron monitor. Therefore, the status of bit 0 tells the computer whether the event originated in the Ge(Li) detector (bit 0 set "on") or in the neutron monitor (bit 0 set "off").

In addition to the ADC scalers, there exist six auxiliary, addressable scalers in the data terminal. These scalers can be cleared, started, halted and read by the computer. They are routinely used for acquisition of supplemental data such as current integrator readings, long counter events and 60 Hz clock times.

2.6 On-Line Data Processing

A version of the SEL 840: P on-line operating system COSACS is used as the software for acquisition of data from the spectrometer [21]. Many pertinent features of the software are discussed in detail in Ref. 21 so only those aspects unique to the present application will be mentioned here.

The computer is not programmed to record an energy/time matrix because this would be too costly of storage space; therefore, sums are computed and the results are stored as one dimensional arrays (spectra). Two Ge(Li) detector energy spectra, a Ge(Li) detector time-of-flight spectrum and a neutron monitor time-of-flight spectrum

are accumulated by the computer. These spectra are generated by manipulation of the 24-bit word formulated in the computer accumulator as described in Section 2.5.

Normally, the time-of-flight spectrum for the Ge(Li) detector consists of a flat background of time-uncorrelated events and two resolved peaks. This time spectrum includes events with various energies recorded by the detector (summed over energy). One peak is attributed to prompt gamma rays from neutron-induced reactions in the sample and prompt gamma rays from the neutron source which are Compton-scattered by the sample or collimator walls into the Ge(Li) detector. The second peak in the spectrum corresponds to a later time and is produced by the interaction of neutrons (mainly those scattered by the sample) with the Ge(Li) detector. The computer software permits the experimenter to select two regions of interest in the Ge(Li) detector time spectrum (of equal channel width) and then record the two energy spectra from the detector corresponding to these selected time-of-flight intervals. The channel boundaries for these time intervals are stored in the memory as parameters. The usual choice for these intervals is the prompt gamma-ray time peak and an adjacent region of time-uncorrelated background. The difference between these two recorded energy spectra (background subtraction) is the spectrum of prompt gamma rays. The experimenter can choose to record Ge(Li) detector energy spectra with 512, 1024, 2048 or 4096 channels. The Ge(Li) detector time-of-flight spectrum is always confined to 512 channels.

The phenomenon of time walk is well known in time-of-flight spectroscopy [10]. The measured time for an event recorded by a detector varies with the amplitude of the pulse (energy) because the discriminator is triggered at different times by pulses with different amplitudes. The

effect is quite noticeable for Ge(Li) detectors since the signal risetimes are relatively slow for these detectors. The effect of time walk is a broadening and tailing of time-of-flight peaks when a wide dynamic range of pulse amplitudes is accepted. Leading-edge timing, as used for the present spectrometer, is susceptible to time walk for obvious reasons. Various techniques have been applied in the design of discriminators to minimize this effect. In the present facility, the digital computer corrects the Ge(Li) detector time information for walk effects prior to storage of the data. This real-time correction is made utilizing a 32-element correction array stored in the computer. The energy spectrum is subdivided into 32 equal-channel intervals and the time shift applied to the incoming data depends upon the amplitude of the corresponding energy signal. The time-shift parameters can be measured with aid of a specialized subroutine of the operating system. All these adjustments and storage functions represent only operations on the 24-bit word formulated in the accumulator of the computer. There is no feedback to the analog circuitry used to generate the signals.

As indicated in Section 2.5, the computer interprets a data word as corresponding to the neutron monitor whenever the monitor logic unit generates a "Tag" pulse which ultimately sets bit 0 to "off". Up to this point, the only apparent function for the "dummy" energy signal from the monitor logic unit has been to satisfy a coincidence requirement in the data terminal. However, this signal plays an important role in minimizing random coincidence effects which could lead to improper interpretation of the stored data. The method is as follows: The "dummy" energy signal produces a sharp line in the spectrum. The amplitude of the pulse is selected so that the peak falls in a region of the Ge(Li) spectrum which is of no interest

to the experiment and which preferably has few Ge(Li) counts (usually the upper-channel end of the spectrum). A digital "window" is set on this peak and the operating system of the computer will not store any data as a neutron monitor event unless the "dummy" energy signal falls within the window. A 512-channel time-of-flight spectrum is recorded corresponding to signals which satisfy all criteria necessary for interpretation as neutron monitor events.

The data acquired by the computer can be recorded on either paper tape or the disk. The output includes selected parameters of the operating system, two Ge(Li) energy spectra, the Ge(Li) time-of-flight spectrum and the neutron time-of-flight monitor spectrum.

3. SPECTROMETER PERFORMANCE AND REPRESENTATIVE EXPERIMENTAL RESULTS

3.1 Ge(Li) Detector Calibration

The Ge(Li) detector used in this spectrometer is calibrated for energy vs. channel and for relative efficiency using common techniques [22-27]. All calibrations are based on full-energy peak measurements.

Non-linearity in the energy vs. channel calibration is treated by fitting a simple polynomial to the calibration data. The energy calibrations are sufficiently reliable to permit routine measurement of gamma-ray energies to within ~ 0.5 keV. Gain stabilization circuitry is not employed; however, the position of the 0.847-MeV gamma ray line from the $^{56}\text{Fe}(n,n'\gamma)^{56}\text{Fe}$ reaction was observed to drift by no more than ~ 2 keV in a three week period.

Fig. 11 shows the relative efficiency vs. gamma-ray

energy for $E_\gamma = 0.1-3.6$ MeV. The smooth curve is a least-squares fit of the formula

$$\ln \epsilon = \sum_{k=1}^n a_k (\ln E_\gamma)^{k-1} \quad (1)$$

to calibration data. The relative efficiency calibrations appear to be accurate to $\sim 3\%$ over this range.

The absolute efficiency of the Ge(Li) detector is determined by placing calibrated point sources from the U.S. National Bureau of Standards in a special holder at the sample position. Measurements of the absolute gamma-ray efficiency made using a ^{60}Co source and a ^{22}Na source agree to within $\sim 2\%$. The efficiency calibrations are observed to be stable to within this accuracy for periods of several weeks.

An energy resolution of ~ 2.5 keV FWHM for the 1.332-MeV ^{60}Co line has been observed for the Ge(Li) detector. The resolution achieved is adequate, for example, to completely resolve the 0.996- and 1.005-MeV gamma rays produced in the decay of ^{154}Eu [26]. However, the gamma-ray lines are broadened by the Doppler effect in neutron-induced reaction measurements. Therefore, the ultimate energy resolution capabilities of the detector are generally not exploited.

3.2 Electronics Performance

Two requirements of the electronics apparatus are stability and fidelity. Fidelity, in this sense, means the ability to record events without rejection of information through improper signal processing. The fission detector is very reliable. Measurements indicate a fidelity of better than 99.99% in the processing of signals by the discriminator. The stability of the discrimination level is such that less than 0.01% variation in absolute efficiency can be expected over a period of several days.

There have been no instances noted when the discrimination level shifts into the alpha peak. In the event that this should happen, the alpha events would contribute to the time uncorrelated background in the time-of-flight spectrum and would be rejected by off-line data processing. The Ge(Li) detector appears to be equally reliable.

Studies have been made to determine deadtime during typical measurements, to examine the fidelity of several elements of the analog and digital circuitry and to determine limits on the effects of random coincidences which could result in failure to distinguish Ge(Li) detector from neutron monitor events. The results of these studies show that the deadtime is typically 1-2% when the fission detector is used as the monitor and 5-10% when the scintillation detector is used as the monitor. The difference is attributed to count rates. The count rate for the Ge(Li) detector is typically $\sim 100-200$ per sec. The fission detector count rate is $\sim 2-5$ per sec while that for scintillation detector is $\sim 20-50$ per sec. These are count rates for pulses accepted by the data terminal for storage in the computer. The deadtime may seem large to individuals accustomed to data acquisition with a multi-channel analyzer; however, it must be remembered the computer is required to perform numerous operations on each data word prior to storage. Loss of data as a result of improper pulse processing (exclusive of deadtime) is less than 0.1% for typical measurement conditions. Improper storage as a result of random coincidence effects is a negligible factor for practical purposes. Stability tests on the "dummy" energy signal associated with the neutron monitor channel indicate that drifting over a period exceeding a week was less than 0.05%.

The scintillation detector is used as a secondary monitor for angular distribution measurements. The stability of this detector is dependent primarily on stabil-

ity of the photomultiplier high voltage power supply. Experience has shown that the efficiency normally drifts by no more than a few percent over a 24-hour period which is far longer than required to complete most angular distribution measurements.

The time resolutions observed for the time-of-flight spectra recorded for the detectors depend on several factors including the pulsed beam resolution. Improved time resolution of the pulsed-beam is generally accompanied by a loss of average beam current. Clearly, a tradeoff is desirable and no attempt is made to optimize time resolution unless it is required for a given set of measurements. Typical operating conditions will yield ~ 2 -3 nanosec FWHM for the target gamma-ray peak recorded by the scintillation detector, ~ 9 nanosec FWHM for the fission detector and ~ 19 nanosec FWHM for the Ge(Li) detector (0.1-2 MeV dynamic range in gamma-ray energy). In spite of the walk correction, low-energy gamma rays produce considerable deterioration of Ge(Li) detector time resolution.

3.3 Miscellaneous Characteristics

The gamma-ray detection efficiency of the spectrometer varies by $< 2\%$ over the range $30^\circ - 135^\circ$ as a result of geometric effects.

The presence of the fission detector perturbs the measurement of gamma rays from neutron inelastic scattering in a minor way. Calculations indicate that "Out" scattering of incident neutrons by the detector exceeds "In" scattering so that the fluence incident upon the sample is reduced by ~ 1 -2% by the presence of the fission detector. Attempts to measure this effect have been inconclusive since the difference is generally masked by statistical uncertainty of the gamma-ray yield. More significant is the fact that weak lines are observed in

the gamma-ray spectra measured at 55° which can be attributed to $(n,n'\gamma)$ reactions with components of the fission detector. This can be troublesome for measurements with sample materials which are also found in the detector (e.g. Al, Fe, Cu or Zn). In these circumstances, the scintillation detector can be calibrated relative to the fission detector and used as a "stand-in" monitor.

Backscattering of neutrons from the sample to the fission detector appears to be a small effect. Computations for a large Fe sample (~ 350 grams) yield a value of $< 3\%$. The results of measurements made to investigate this effect were inconclusive since the differences were masked by statistical uncertainty.

The effects of air scattering and scattering by apparatus in the vicinity of the neutron source (e.g. target assembly or shadow bar) appear to be small and in any event largely cancel for relative measurements utilizing the fission detector as a fluence monitor. These effects are not considered in analysis of the experimental data.

3.4 Representative Experimental Results

Fig. 12 is representative of the experimental data obtained with this spectrometer. This measurement was performed with an iron sample and 2-MeV neutrons. The spectra were accumulated in ~ 30 min. Spectrum 1 is the Ge(Li) detector energy spectrum which corresponds to the prompt gamma-ray time peak while Spectrum 2 corresponds to time-uncorrelated background. Spectrum 3 is the difference. Spectrum 4 is the Ge(Li) time-of-flight spectrum (with prompt gamma-ray, neutron and background regions labelled). Spectrum 5 is the fission detector time-of-flight spectrum (the scintillation detector was not used in this measurement).

Fig. 13 is a composition of various spectra recorded using a vanadium sample. This figure shows the effects of

time walk on the structure of the Ge(Li) detector time-of-flight spectrum. Furthermore, it is seen that the energy spectrum corresponding to the neutron time peak is dominated by lines characteristic of neutron inelastic scattering within the Ge(Li) detector itself. These lines are broadened because of ionization by recoiling germanium nuclei within the detector. The 0.69-MeV transition in ^{72}Ge occurs with a half life of 0.422 μsec and is therefore observed in the background (23,29).

4. OFF-LINE DATA PROCESSING

The raw spectral data are transcribed from paper tape or disk to magnetic tape in binary-coded decimal format to facilitate subsequent processing. The spectra are then plotted and the numerical values are listed so that the data can be inspected for discrepancies. The peaks in the spectra are identified and the number of counts present in selected peaks are determined with the aid of a digital computer. The counts for Ge(Li) energy or time-of-flight peaks are computed by summing the channel counts between selected limits after background subtraction. Smooth backgrounds are fitted with ordinary polynomial expansions utilizing least-squares techniques; unresolved peaks are analyzed by fitting Gaussian peak shapes to the data.

The time-of-flight peak counts for the fission detector are corrected for the experimental effects listed in Table 3. The Ge(Li) detector full-energy peak counts are corrected for the experimental effects listed in Table 4. Neutron cross sections needed to determine these corrections are obtained from the literature [2] or from data files at the National Neutron Cross Section Center [30]. Photon cross sections are obtained from an evaluation by Storm and Israel [31].

Differential gamma-ray production cross sections are computed from the corrected detector counts, the masses of the samples and uranium deposits and the appropriate fission cross sections. Currently, fission cross sections from the ENDF/B-IV file are used for this purpose [30]. The computation procedures also yield average neutron energies and neutron energy resolutions for the measured cross sections. Most computations are performed with a digital computer.

Discussion of specific data processing procedures is omitted from this paper since they depend upon such factors as sample geometry, neutron source reaction and properties of the sample material. The spectrometer can be utilized for measurements involving a variety of experimental configurations. A few general statements can be made about the relative importance of various sources of experimental error. Gamma-ray absorption by the sample is generally the principal source of systematic error for most measurements. Neutron absorption and multiple scattering effects are second on the list. Absorption and scattering directly affect the normalization of measured differential cross sections and are responsible for a characteristic asymmetry (enhanced back-angle yield and suppressed forward angle yield) observed in uncorrected angular distributions. Statistical uncertainties in the Ge(Li) detector or neutron monitor peak counts are generally not major sources of uncertainty. Exceptions are weak gamma-ray transitions or gamma-ray full energy peaks superimposed on large Compton distributions. Corrections for neutron source properties are relatively minor and tend to cancel. Geometric effects can be easily calculated. Corrections for other factors listed in Tables 3 and 4 are either minor or can be calculated with sufficient accuracy.

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Table 1
 Values of n_H , n_{Li-6} and R for
 Several Neutron Shield Materials

Material	n_H (atoms/cm ²)	n_{Li-6} (atoms/cm ³)	R ^a
Pure Water (H ₂ O)	0.67×10^{23}	0	0
Pure Paraffin (CH ₂)	0.81×10^{23}	0	0
Lithium Hydroxide Monohydrate Powder (Li OH · H ₂ O)	0.43×10^{23}	0.10×10^{22}	5.26
Water Saturated with Li OH	0.57×10^{23}	0.35×10^{21}	1.32
Lithium Carbonate (Li ₂ CO ₃)	0	0.12×10^{22}	Infinite
50% Paraffin + 50% Li ₂ CO ₃	0.11×10^{23}	0.82×10^{21}	15.8
Solid Lithium Acetate (Li C ₂ H ₃ O ₂)	0.53×10^{23}	0.57×10^{21}	2.27

^a R = $(n_{Li-6} \sigma_{Li-6} / n_H \sigma_H)$. Computation of R based on the following thermal neutron cross sections obtained from Ref. 18:

$${}^1_0\text{H}(n_{th}, \gamma){}^2_0\text{H} \quad : \quad \sigma_H = 0.332 \text{ barn}$$

$${}^6_3\text{Li}(n_{th}, {}^3_2\text{He}){}^4_2\text{He} \quad : \quad \sigma_{Li-6} = 70.7 \text{ barns}$$

Table 2
Isotopic Content of
Uranium Deposits^a

Isotope	²³⁵ U enriched deposit	²³⁸ U enriched deposit
²³⁴ U	0.656%	Negligible
²³⁵ U	93.25%	0.42%
²³⁶ U	0.332%	Negligible
²³⁸ U	5.56%	99.58%

^aRef. 20.

Table 3

Corrections to Fission Detector
Data Made in Off-Line Processing

1. Fission fragments absorbed by the uranium deposit or rejected by the discriminator (1-3%).
2. "In" and "Out" scattering of source neutrons by components of the fission detector (net correction 1-2%).
3. Backscattering of neutrons from the sample (< 3%).
4. Geometric effects (1-2%).
5. Characteristics of the neutron source (depends upon source reaction).
6. Isotopic content of the uranium deposit (see Table 2).

Table 4

Corrections to Ge(Li) Detector
Data Made in Off-Line Processing

1. Detection efficiency. (see Fig. 11).
2. Neutron absorption and multiple scattering in the sample (depends upon sample).
3. Gamma-ray absorption and coherent scattering in the sample (depends upon sample).
4. Geometric effects (1-2%).
5. Characteristics of the neutron source (depends upon source reaction).
6. Perturbation of the incident neutrons by the fission detector (1-2%).
7. Chemical and isotopic composition of the sample (depends upon sample).

FIGURE CAPTIONS

- Fig. 1. Photograph of gamma-ray spectrometer showing beam line, fission detector neutron monitor, Ge(Li) detector shield and air-flotation pad track.
- Fig. 2. Schematic diagram of principal components of the gamma-ray spectrometer.
- Fig. 3. Photograph showing the target cup, fission detector neutron monitor, scattering sample and sample support stem, shadow bar and shield collimator.
- Fig. 4. Schematic diagram of the target cup, fission detector neutron monitor and a scattering sample.
- Fig. 5. Photograph showing the fission detector removed as required for angular distribution measurements which employ the scintillation detector as the neutron monitor.
- Fig. 6. Schematic diagram of the Ge(Li) detector shield showing structural components.
- Fig. 7. Block diagram of electronics used for derivation of timing signals from the pulsed beam.
- Fig. 8. Block diagram of electronics used for generation and routing of signals from the Ge(Li) detector and the fission detector.
- Fig. 9. Block diagram of electronics required when the scintillation detector is used as a neutron monitor instead of the fission detector.
- Fig.10. Block diagram of the analog circuitry and computer interface. Ge(Li) and neutron monitor signals are processed identically by the analog circuitry but are distinguished in the computer by means of the monitor identifier tag.
- Fig.11. Measured relative full-energy-peak efficiency curve for the Ge(Li) gamma ray detector used in the spectrometer.
- Fig.12. Representative spectra recorded in the computer during a measurement: (1) energy spectrum corresponding to segment labelled "G" in spectrum 4, (2) energy spectrum corresponding to segment labelled "B" in spectrum 4, (3) difference

of spectrum 1 and spectrum 2, (4) Ge(Li) time-of-flight spectrum, and (5) fission detector time-of-flight spectrum.

Fig.13. Correlation of Ge(Li) detector energy and time spectra. Spectra labelled 1 to 16 are time spectra corresponding to indicated portions of the energy spectrum. Notice the walk effect. Spectra labelled "N+B", "G+B" and "B" correspond to indicated portions of the Ge(Li) detector time spectrum.

Fig. 1



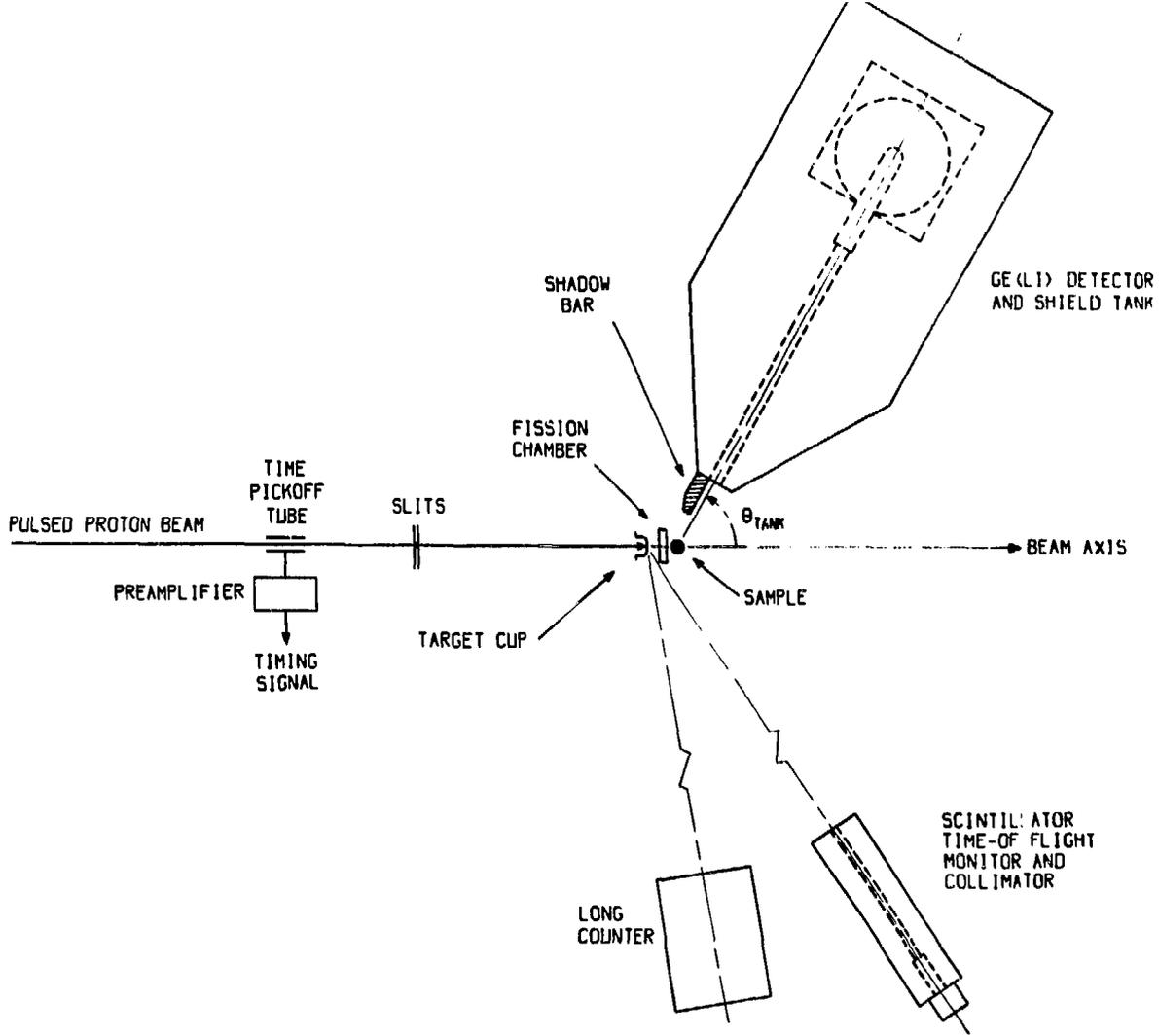


FIG. 2

Fig. 3

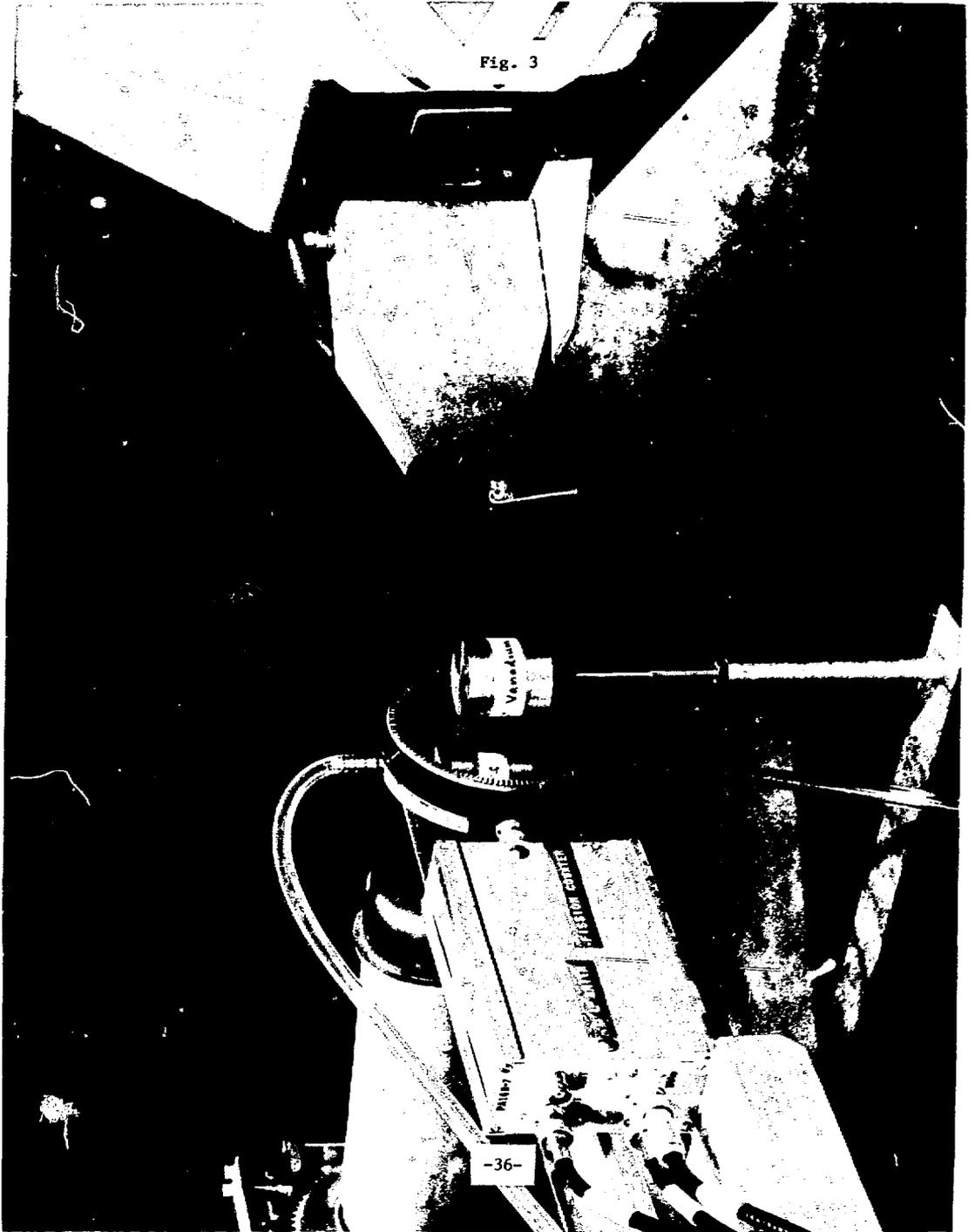


Fig. 4

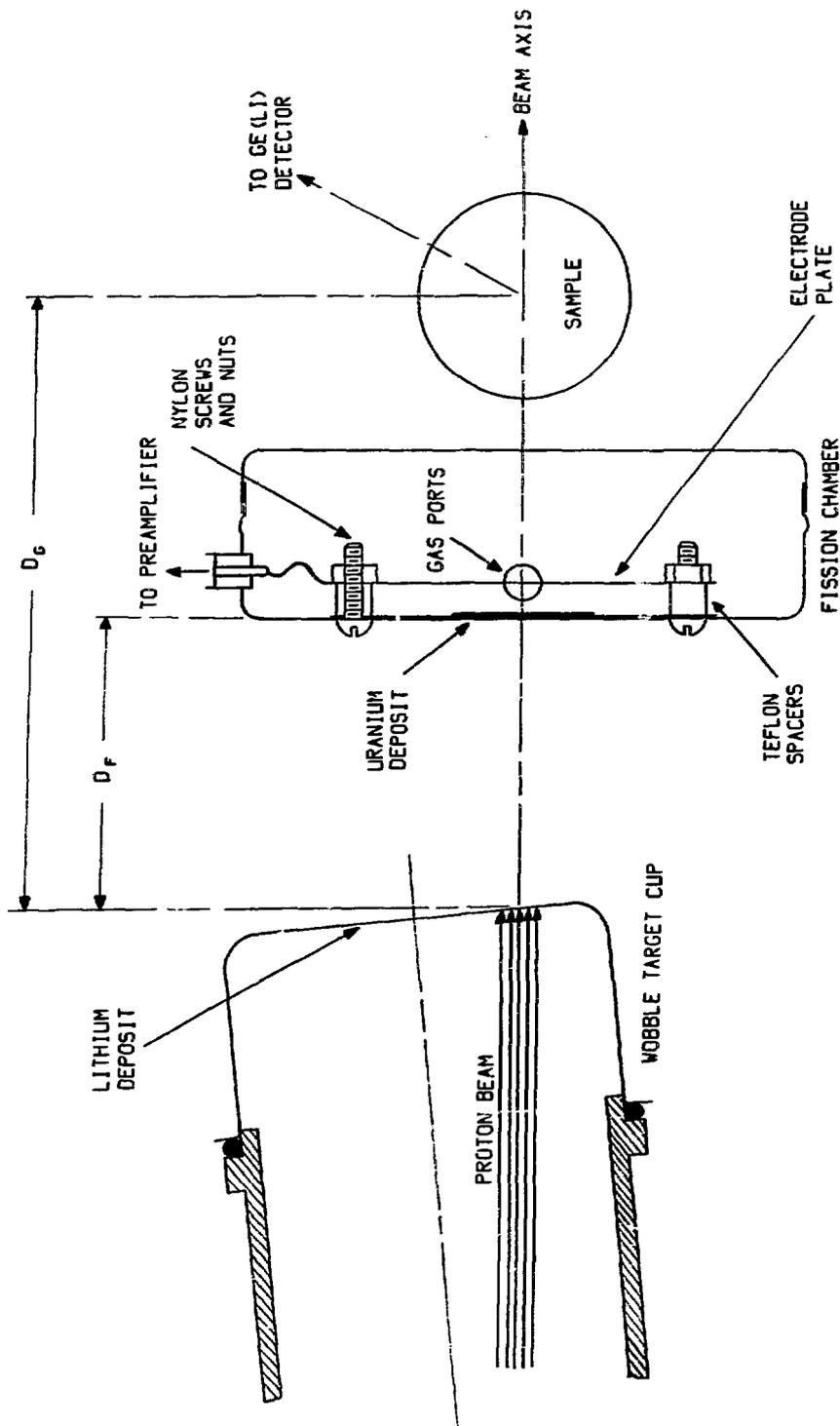
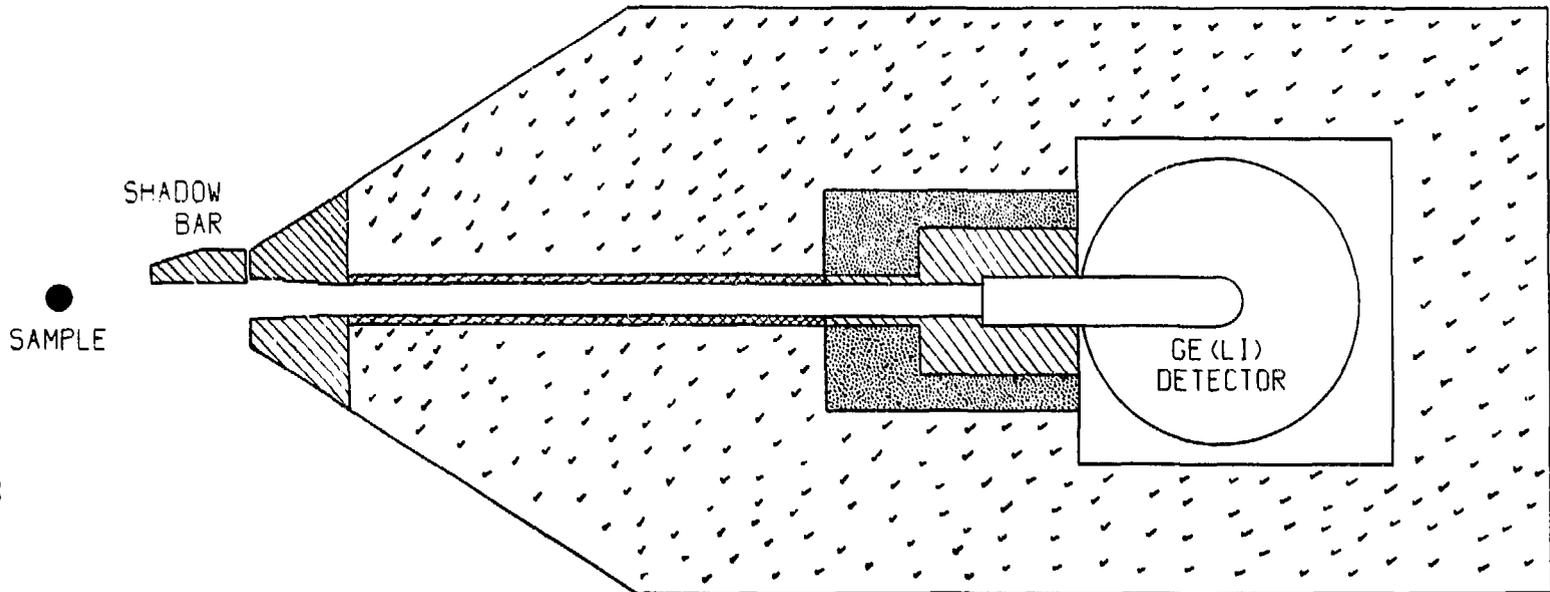


Fig. 5

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SAMPLE

SHADOW
BAR

GE (LI)
DETECTOR

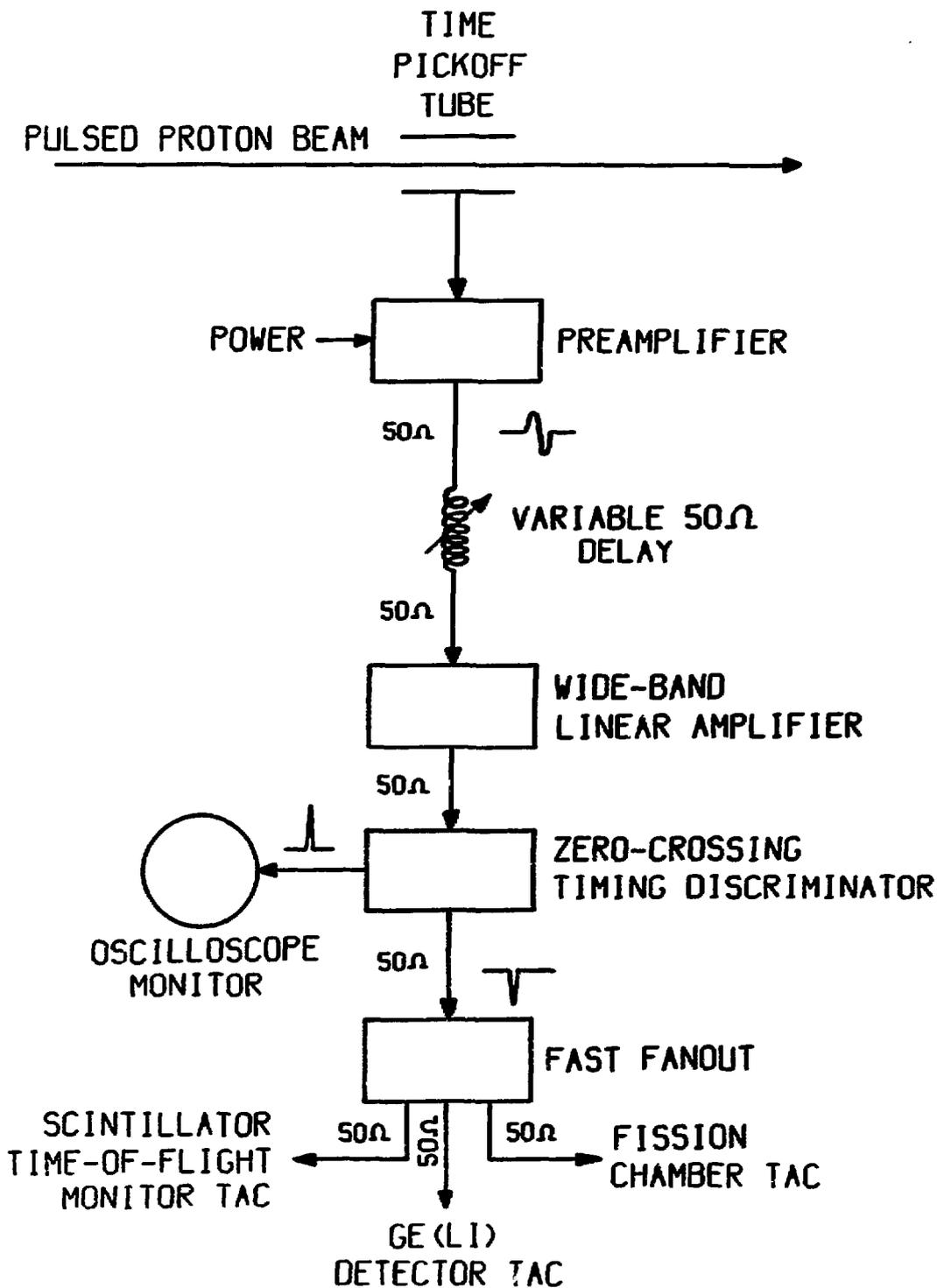
 LEAD

 50% LITHIUM CARBONATE
+ 50% PARAFFIN

 LITHIUM CARBONATE POWDER

 LITHIUM HYDROXIDE
MONOHYDRATE POWDER

Fig. 7



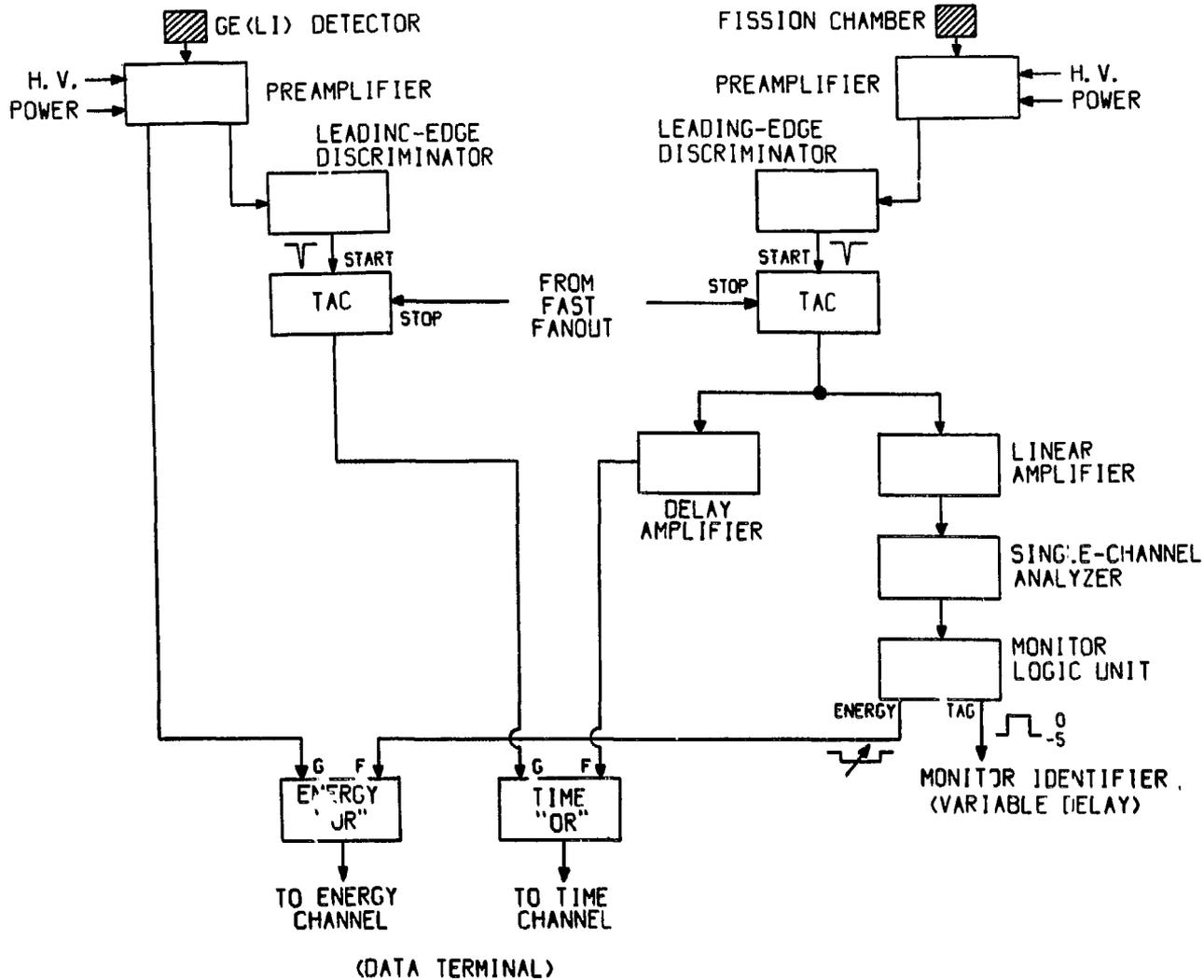
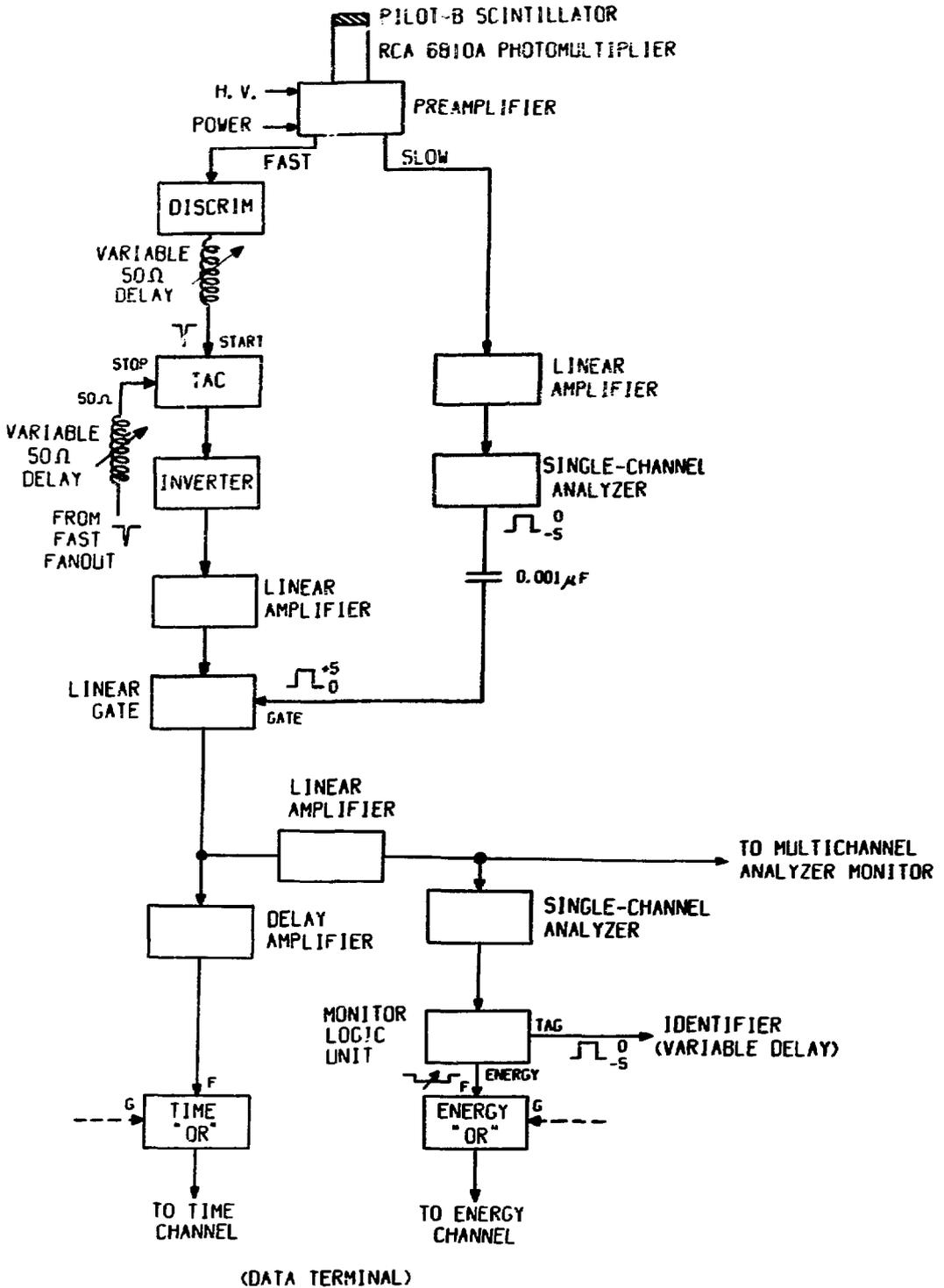
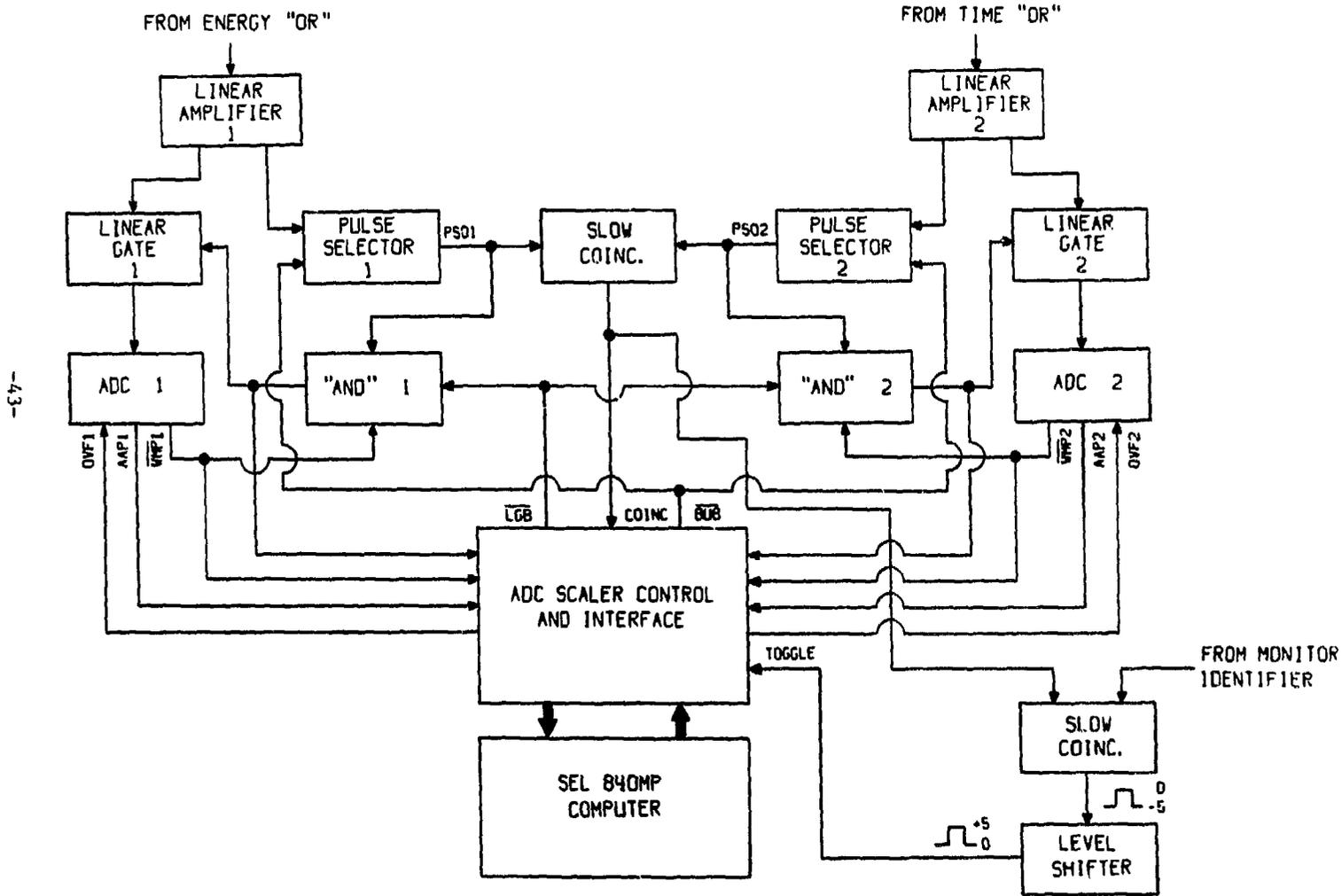


Fig. 9





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Fig. 10

Fig. 11

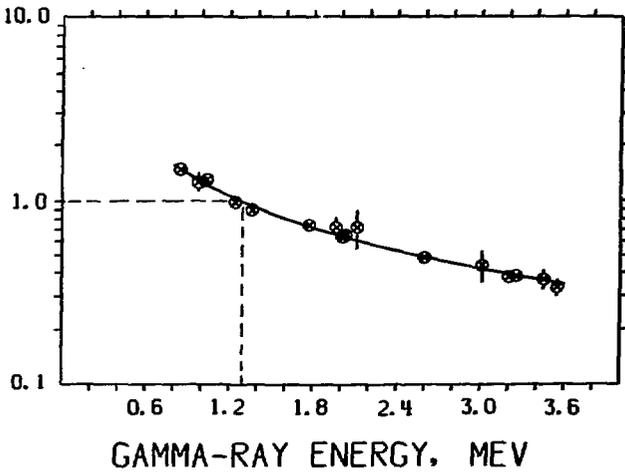
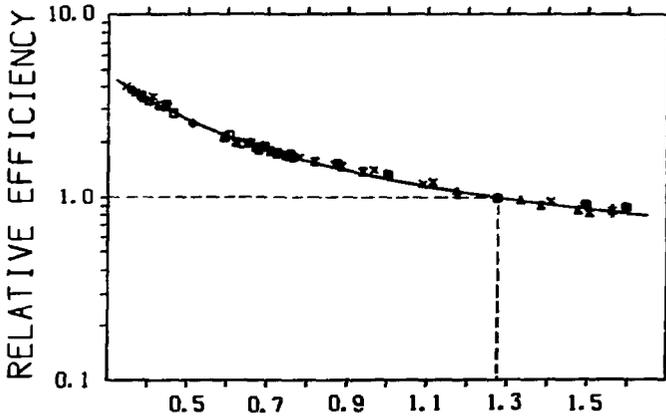
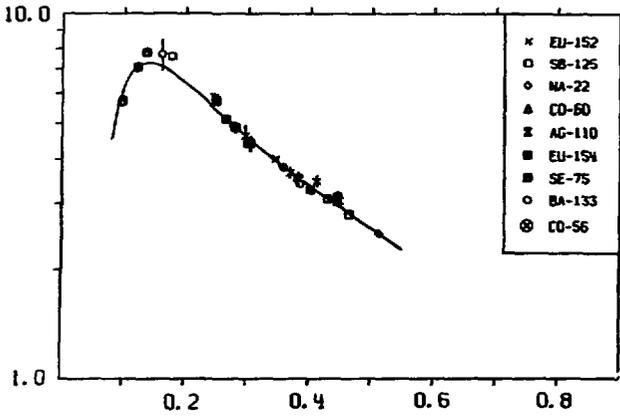
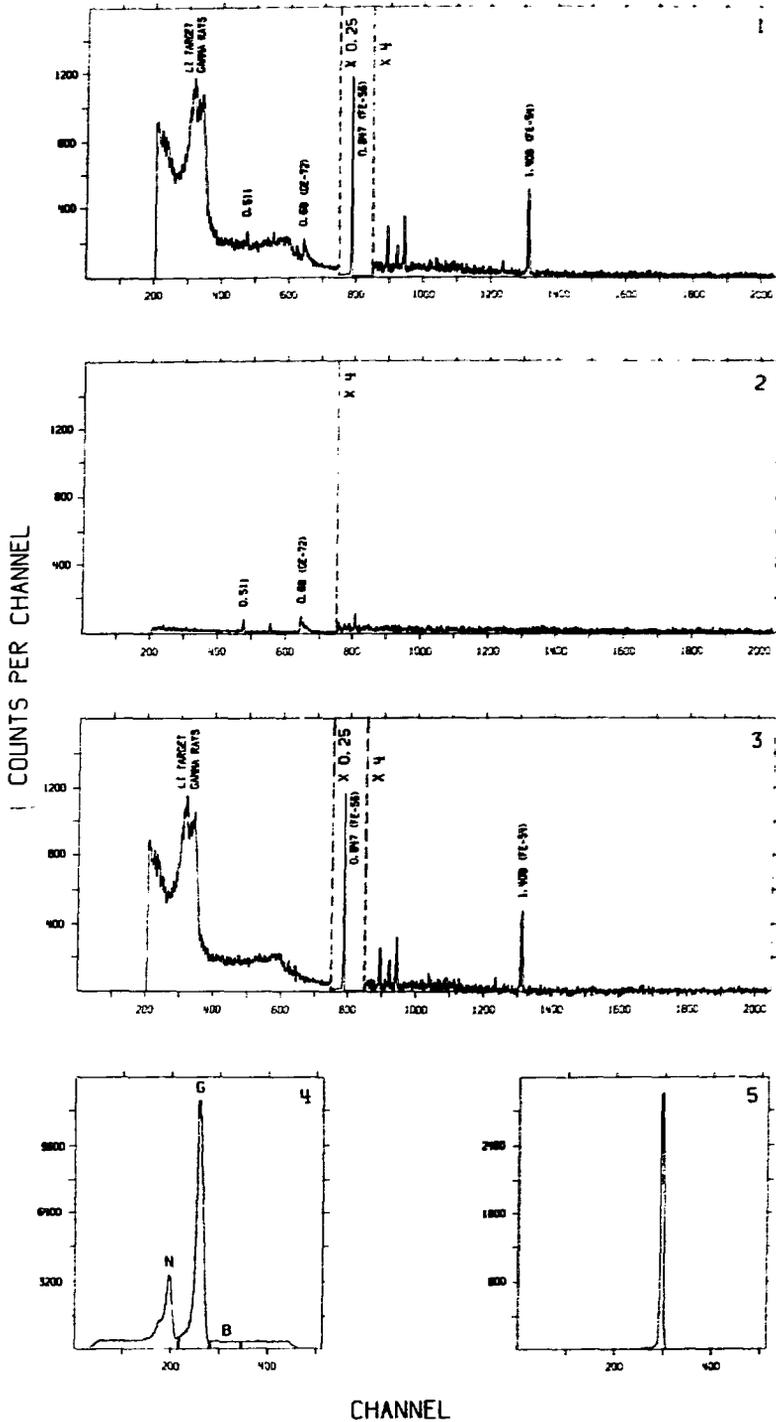
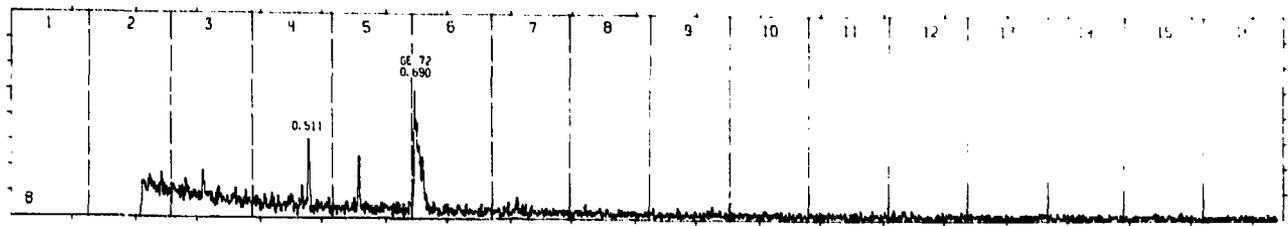
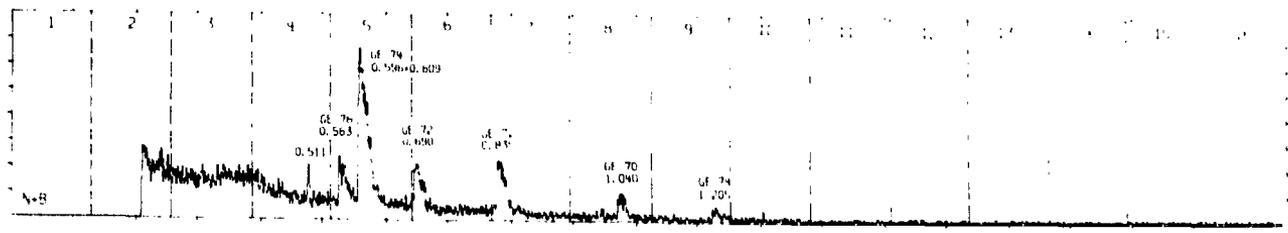
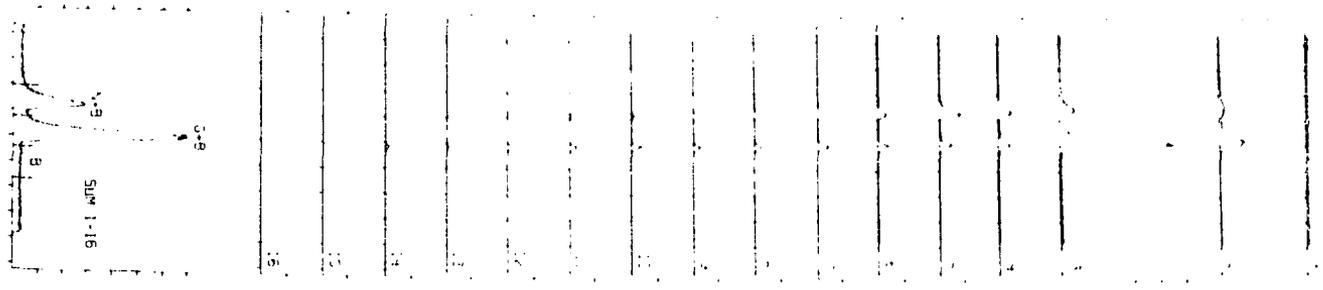


Fig. 12





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Fig. 13