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MEASUREMENT OF DETECTOR NEUTRON ENERGY RESPONSE
USING TIME-OF-FLIGHT TECHNIQUES

SEPTEMBER 1973

MASTER

PREPARED FOR THE U. S. ATOMIC ENERGY COMMISSION UNDER CONTRACT NO. AT(26-1)-565.

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by H. S. Janeè

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Work performed for the Los Alamos Scientific Laboratory.

MASTER

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ABSTRACT

The feasibility of using time-of-flight techniques at the EG&G/AEC linear accelerator for measuring the neutron response of relatively sensitive detectors over the energy range 0.5 to 14 MeV has been demonstrated. The measurement technique is described in detail as are the results of neutron spectrum measurements from beryllium and uranium photoneutron targets. The sensitivity of a fluor photo-multiplier LASL detector with a 2- by 1-inch NE-111 scintillator was determined with the two targets, and agreement in the region of overlap was very good.

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1. INTRODUCTION

The measurement techniques described here were designed to determine the neutron response as a function of energy of a variety of radiation detectors that are used more or less routinely by the Los Alamos Scientific Laboratory (LASL) and the Lawrence Livermore Laboratory (LLL) in their weapons-test related efforts at Nevada Test Site. Many of these detectors incorporate some scintillator coupled to a photomultiplier or photodiode. They are primarily designed for gamma-ray detection and they are always employed in the current mode.

The requirements of a system to measure detectors like these are somewhat different from a strict counting experiment employing a scintillator and photomultiplier optimized for resolution, for which much information, such as response functions, light tables, etc., is available in the extensive literature¹⁻⁷. Since the detectors are employed in the current mode, the quantity of interest is the charge produced in the whole detector by a neutron of a given energy incident on the detector. If this is measured directly, then for those detectors employing scintillators it is not necessary to know the scintillator's response functions nor neutron detection and light collection efficiencies. What must be known, however, is an absolute measurement of the incident neutron spectrum and, since counting techniques are employed, the detector's bias to the extent that it significantly affects the total charge collected.

This method of measuring detector neutron sensitivity then has three requirements: 1) a source of neutrons of adequate intensity and energy range, 2) a method of accurately measuring the neutron spectrum at the detector position, and 3) a means of recording the detector charge per incident neutron.

The EG&G/AEC electron linear accelerator (linac) is well suited for production of neutrons in the energy range 0.1 to 15 MeV⁸⁻¹⁰ through the use of photoneutron targets such as those of beryllium and uranium used in these measurements. Accurate calibration of these targets was made possible with a 2- by 2.5-inch NE-213 liquid scintillator detector, a material whose efficiency as a function of neutron energy has been the subject of investigation by several researchers^{2-6,11}. This detector's absolute detection efficiency had been carefully established by O'Dell, et al.,¹² as a function of bias energy. The detector charge developed in response to neutrons of a particular energy was determined in a 64- by 64-channel dual parameter experiment which simultaneously sorted detector signals according to neutron time-of-flight (energy) and pulse height (charge).

As a test of the feasibility of this technique, the neutron energy response of a LASL NPM-52 detector was determined over the energy range 0.8 to 14 MeV. Direct comparisons at 2.35 and 13.9 MeV were provided by measurements of Lyons¹³. Data for other LASL detectors are available at these energies¹⁴, and qualitative comparisons are provided by measurements of Kirkbride, et al.,⁸ and Michael, et al.,¹⁵ who made measurements on MEL-150C and NE-224 scintillator detectors respectively and compared them with Monte Carlo calculations. The data of Kirkbride, et al., were analyzed by Yates¹⁶ and compared with calculations of Ankenbrandt¹⁷.

2. THEORY OF MEASUREMENTS

The basic approach to measurement of detector neutron response involves two experiments, as outlined. The first is the determination of the neutron spectrum from a given photoneutron target using a scintillator detector whose absolute detection efficiency has been accurately established over the neutron energy range of interest. The second experiment involves measurement of the charge produced by the "unknown" detector in response to neutrons in the energy interval E to $E+\Delta E$. The number of neutrons contained in this interval is determined from the known spectrum, and the sensitivity, expressed in coulomb/neutron, is obtained by dividing the measured charge by that number.

Both these measurements rely on the time-of-flight separation of neutrons according to their velocity (thus energy) over a path that is long, in terms of time, compared to the production time of the neutrons.

The next sections outline the relationships necessary to arrive at the neutron energy spectrum and detector charge from the multichannel analyzer data.

2.1 NEUTRON PRODUCTION IN Be AND U TARGETS

The mechanism for neutron production with the beryllium target is the absorption of bremsstrahlung photons and emission of a neutron with energy:

$$E_n = h\nu - E_B \quad (1)$$

where $h\nu$ is the photon energy, and E_B is the neutron binding energy. For beryllium the latter is 1.67 MeV, considerably lower than the 7- to 15-MeV range for most nuclei¹⁸. The cross-section of photoneutron production as a function of photon energy starts at zero at the threshold energy and then follows a broad resonance-shaped curve with a peak at roughly 13 MeV for a heavy nucleus like lead and above 20 MeV for light nuclei such as carbon and oxygen. The shape of the neutron spectrum from the beryllium target thus should be essentially the fold of the bremsstrahlung spectrum with the photoneutron production cross-section for a given electron energy. Figure 1 shows bremsstrahlung spectra for 2- to 20-MeV electrons calculated for the linac target used in these measurements (cited in Ref. 12).

For heavier nuclei the situation is more complex, because to the direct photoneutron process resulting in monoenergetic neutrons for a given photon energy

Fig. 1. Calculated bremsstrahlung spectra for the linac target.

is added a process which results in the formation of a compound nucleus upon absorption of a photon. The nucleus decays with emission ("evaporation process") of neutrons whose energy is essentially independent of the photon energy and peaks at around 1 MeV for heavy nuclei and photons that are several MeV above the neutron binding energy.

With uranium, neutrons are also produced by gamma-induced fission. The total yield of neutrons with gamma-ray energy increases very sharply over the region of the giant resonance (up to ~35 MeV) and thereafter increases linearly¹⁹. The absolute yield, expressed in neutrons/electron incident, is given by Barber and George²⁰ as about 96×10^{-4} at 27 MeV for a roughly 1-cm-thick target and by Burrill²¹ as approximately 110×10^{-4} for a thick target, as shown in Fig. 2. Figure 2 also gives the yield from beryllium, but target thicknesses are not known, rendering comparisons inconclusive.

Lindner²² determined the importance of the gamma-induced fission process relative to the photoneutron process and found it to be largely independent of photon energy in the region 6 to 9 MeV. Defining the quantity Γ_n/Γ_f as essentially the ratio of ^{237}U nuclei produced in the reaction $^{238}\text{U}(\gamma, n)^{237}\text{U}$ to the number of ^{99}Mo isotopes produced in the fissioning process, this value ranges from 3.4 to 5.4. Gindler, et al.,²³ found the fission branching ratio, defined as

$$\frac{\sigma_{(\gamma, f)}}{\sigma_{(\gamma, f)} + \sigma_{(\gamma, n)}},$$

to be rather constant at about 0.2 for photons in the energy range 8 to 11 MeV. In Lindner's terminology this implies a value of 4.0 for Γ_n/Γ_f .

The photoneutron production threshold energy for uranium is 6.13 MeV and the fission threshold ~5.3 MeV²³. The cross-sections rise from the threshold energies to peaks at ~12 and ~14 MeV for the photoneutron and fission processes, respectively.

2.2 DETERMINATION OF NEUTRON ENERGY SPECTRUM

The relativistic expression relating neutron energy to velocity is

$$\beta = \frac{v}{c} = (1 + mc^2/E)^{-1} \sqrt{1 + 2mc^2/E} \quad (2)$$

Fig. 2. Thick target ${}^9\text{Be}(\gamma, n)$ and ${}^{238}\text{U}(\gamma, \text{nf})$ neutron yields.

with

$$mc^2 = 939.55 \text{ MeV, and}$$

$$c = 3 \times 10^{10} \text{ cm/sec}$$

For a time-of-flight path of length L and with neutron flight time t expressed in terms of the analyzer time calibration α (nsec per channel), i.e., $t = \alpha CH$, where CH is the channel number, v in Eq. (2) is replaced by

$$v = \frac{L}{t} = \frac{L}{\alpha \cdot CH} \quad (3)$$

Combining Eqs. (2) and (3) yields the expression for the neutron energy, E , in terms of the experimental parameters L , α , and CH

$$E = mc^2 \left[\frac{1}{\sqrt{1 - (L/\alpha \cdot CH \cdot c)^2}} - 1 \right] \quad (4)$$

The datum obtained in the spectrum measurements is a differential time spectrum which is obtained from the multichannel analyzer counts/channel vs. channel data through the time calibration α :

$$\frac{dN}{dt} = \frac{1}{\alpha} \left[\frac{dN}{dCH} \right] \quad (5)$$

To get the desired energy spectrum dN/dE , the relationship

$$\frac{dN}{dE} = \frac{dN}{dt} \times \frac{dt}{dE} \quad (6)$$

is employed. From Eqs. (2) and (3), t expressed in terms of E is:

$$t = \frac{L}{c} (E + mc^2) (E^2 + 2mc^2 E)^{-1/2} \quad (7)$$

and differentiating with respect to E :

$$\frac{dt}{dE} = - \frac{L}{c} (mc^2)^2 (E^2 + 2mc^2 E)^{-3/2} \quad (8)$$

So that, from Eqs. (5) and (6), and ignoring the minus sign,

$$\frac{dN}{dE} = \frac{L}{\alpha c} \frac{1}{\epsilon(E)} \frac{1}{\Omega \cdot Q_T} (mc^2)^2 (E^2 + 2mc^2 E)^{-3/2} \frac{dN}{dCH} \quad (9)$$

in neutrons/MeV-steradian-electron (n/MeV-sr-e) where

Ω = solid angle subtended by detector

Q_T = linear accelerator target charge accumulated
(expressed in electron charges)

$\epsilon(E)$ = detection efficiency as a function of neutron energy.

Equation (9) can be rewritten by expressing E in terms of the measurement parameters L , α , and CH :

$$\frac{dN}{dE} = \frac{L}{mc^3 \alpha} \cdot \frac{1}{\epsilon(E) \cdot \Omega \cdot Q_T} \cdot \left[\frac{1}{1 - (L/c\alpha CH)^2} - 1 \right]^{-3/2} \frac{dN}{dCH} \quad (10)$$

2.3 DETERMINATION OF DETECTOR CHARGE

In the dual parameter experiment the data consist of 64- by 64-channel charge spectra for which the abscissa is in counts/channel and the i^{th} channel corresponds to a charge Q_i which has magnitude $i \cdot q$, where q is the charge calibration of the linear data chain (in coulomb/channel). The total charge in the k^{th} charge spectrum then is given by the sum:

$$Q_k = q \sum_{i=1}^{64} i \cdot n_i \quad (11)$$

where n_i is the number of counts recorded in the i^{th} channel.

The k^{th} spectrum or group corresponds to a time-to-amplitude converter (TAC) pulse height proportional to time-of-flight t_k and the time calibration of the

system yields Δt_k , the time per group (in nsec/group). Thus, the counts accumulated in the k^{th} group are due to neutrons of energies between E_k and $E_k + \Delta E_k$ obtained from Eq. (3) for the flight times t_k and $t_k + \Delta t_k$.

2.4 DETERMINATION OF DETECTOR SENSITIVITY

Having obtained the neutron spectrum and the detector charge due to neutrons in the energy interval E_k to $E_k + \Delta E_k$, it is only necessary to find the number of neutrons in that interval by integration of the spectrum over the appropriate energy interval to be able to compute the sensitivity. This interval is represented by the sum:

$$\sum_{j=m}^{j=n} \left(\frac{dN}{dE} \right)_j \Delta E_j \quad (12)$$

where m and n are the indices of the energy spectrum which correspond to E_k and $E_k + \Delta E_k$, and ΔE_j is the energy interval ΔE_k divided into $(n-m)$ slices, i.e., $\Delta E_j = \Delta E_k / (n-m)$. The number of neutrons in the interval is

$$n(E, \Delta E)_k = \Omega' Q_T' \sum_{j=m}^{j=n} \left(\frac{dN}{dE} \right)_j \Delta E_j \quad (13)$$

where

Ω' = solid angle subtended by detector

Q_T' = linear accelerator target charge accumulated
(in units of electrons)

The detector sensitivity to neutrons of energies between E_k and $E_k + \Delta E_k$ is then given by:

$$S(\bar{E}_k) = \frac{Q_k}{n(E, \Delta E)_k} = \frac{q \sum_{i=1}^{64} i \cdot n_i}{\Omega' Q_T' \sum_{j=m}^{j=n} \left(\frac{dN}{dE} \right)_j \cdot \Delta E_j} \quad (14)$$

3. EXPERIMENTAL APPROACH

The following sections discuss in some detail the facility, apparatus, and techniques employed for the two principal measurements: the spectral yield of photoneutrons from the two targets and the neutron-produced charge in a given detector obtained in a dual parameter experiment. The neutron spectra are normalized to the linac electron beam so that only a monitoring of the beam charge is required for future measurements. It is, however, extremely important to maintain the exact experimental conditions for this to be valid.

3.1 TIME-OF-FLIGHT FACILITY

The time-of-flight path in the EG&G/AEC linear accelerator facility (Fig. 3) is over 29 m, of which 27.6 m is an evacuated 12-inch-diam pipe containing 16 annular collimators, each made of 1-inch steel sandwiched between 2-inch-thick polyethylene pieces, of alternate 4 and 5 inch diameters. A slide assembly roughly at the pipe's midpoint permits uranium plates to be placed in the beam to attenuate bremsstrahlung photons generated or scattered by the photoneutron target.

The uranium target is coupled to the 90° high energy port in the linac cell (Fig. 4). The electron beam is magnetically analyzed and slits can be set to restrict the width of the electron energy distribution. The beryllium target, a 10-inch-long by 3-inch-diam cylinder, is closely coupled to the standard bremsstrahlung target, which consists of a 0.015-inch gold tungsten disk followed by a 1.25-inch aluminum filter, Fig. 5; also shown is the non-interrupting beam monitor (NIBM), essentially a loop of wire in which a signal is induced by the electron beam that passes through it. The pulse from the NIBM precedes the neutron pulse by somewhat less than 1 nsec, with the neutron beam centerline about 8 cm in from the right edge of the beryllium target. Actually neutrons are produced throughout the volume of the beryllium cylinder and the center of neutron production depends on the beam energy.

The uranium target was fabricated from a design by Profio, et al.,²⁴ and consists of a 3-inch-diam depleted uranium sphere into which a 1-inch-diam entrance hole is cut (Fig. 6). Electrons impinge directly on the uranium and the bremsstrahlung produced in turn generates neutrons through both the photoneutron and photofission processes. The entry hole depth and the uranium sphere diameter

Fig. 3. EG&G/AEC Linear Accelerator Facility (linac).

Fig. 4. EG&G/AEC Linear Accelerator high energy 90° port with uranium photoneutron target.

Fig. 5. Beryllium photoneutron target coupled to standard bremsstrahlung target.

Fig. 6. Uranium photoneutron target.

were chosen to make the centroid of neutron production coincide with the sphere center for the 28-MeV electron beam used in the Profio experiment. One would expect this to hold essentially true for our experiment in which 27-MeV electrons were used, and this is in fact borne out by preliminary data on the angular distribution from our target²⁵, shown in Fig. 27.

The linac operating parameters used during the measurements were:

Electron energy	27.0 $\pm$ 0.4 MeV
Pulse width	10 nsec FWHM
Repetition rate	360 pps
Time-of-flight path length	2915.3 cm
Bremsstrahlung target	0.015-inch Au-W with 1.125-inch Al filter
Photoneutron targets	10-inch by 3-inch diam Be cylinder; 3-inch-diam U sphere
Beam filter	1.0-inch ²³⁸ U
Effective collimation	4-inch diam

3.2 NEUTRON SPECTRUM MEASUREMENTS

The experimentally determined quantity in these measurements is a neutron time-of-flight spectrum obtained with a detector of known efficiency and a measuring circuit that permits accurate assessment of the time interval between neutron production in the photoneutron (U,Be) target and arrival at the detector at the end of the time-of-flight path. The total charge accumulated at the linac bremsstrahlung target during a run was recorded and used to normalize the neutron spectrum to a single electron. The emphasis here is on the charge measured at the linac target rather than the charge carried by the electron beam. For the uranium target the two quantities are the same; in the case of the beryllium target, however, most of the 27.0-MeV electrons (72%) are not stopped in the bremsstrahlung target. A large fraction of those that are transmitted strike the beryllium cylinder, where they produce some small amount of bremsstrahlung radiation (since their energy is degraded to a few MeV at this point, they won't contribute measurably to the photoneutron production, particularly since the cross-section for electrons is $1/\alpha$ ($1/137$) that for photons).

The beam current for the spectrum measurements was adjusted to a level which resulted in recording roughly one neutron event in the detector for every 10 linac pulses. This was done to minimize the probability of two or more neutron events

occurring in the detector at the same time. With the beryllium target, peak currents measured at the bremsstrahlung target were on the order of 50 mA, whereas about 10 mA were sufficient to produce the desired neutron flux from the uranium target.

The subsequent sections deal in detail with the particulars of the spectra measurements: the neutron detector, measurement system electronic circuitry, and characteristics of the two photoneutron targets.

3.2.1 NE-213 Fluor Detector

The NE-213 fluor detector used as the standard for neutron flux measurements, described in detail elsewhere¹², is a glass-encapsulated 2-inch-diam by 2.5-inch long NE-213 liquid scintillator optically coupled to an Amperex 56 AVP photomultiplier tube (see Fig. 7 photograph and Fig. 8 photomultiplier dynode circuit diagram). The latter shows the two detector outputs, a "fast" signal from the anode and a "slow" signal for pulse height analysis from the twelfth dynode via an emitter follower circuit.

The detector's efficiency (detector counts/incident neutron) must be known not only as a function of neutron energy (carefully established by O'Dell, et al.,¹² over the energy range 0.2 to 20 MeV*) but also of the electronic bias set on the pulse height signal during a typical counting experiment. The behavior of efficiency with neutron energy for several bias levels (30 to 100 keV) is shown in Fig. 9. These curves are results of calculations by O'Dell, et al., who, based on a single-collision model involving elastic scattering from hydrogen and carbon nuclei and the $^{12}\text{C}(n,\alpha)$ reaction, found the efficiency to be closely given by the relationship:

$$\epsilon(E_n) = \frac{1 - \exp \left[-n_H t(\sigma_H + \beta \sigma_C) \right]}{\sigma_H + \beta \sigma_C} \left[\sigma_H f(B, E_n) + \beta \sigma_C^e g(B, E_n) + \beta \sigma_C^\alpha h(B, E_n) \right] \quad (15)$$

*With an absolute accuracy of $\pm 8\%$.

Fig. 7. 2-inch-diam by 2.5-inch-long NE-213 detector for neutron energy spectra measurements.

Fig. 8. NE-213 detector electronics.

Fig. 9. NE-213 efficiency vs. neutron energy.

where

$$\beta = n_C/n_H$$

$$n_H \text{ and } n_C = \text{number of atoms/cm}^3 \text{ of hydrogen and carbon}$$

$$\sigma_H = \text{total neutron-proton cross-section}$$

$$\sigma_C = \text{carbon nonelastic cross-section}$$

$$t = \text{effective thickness of fluor } (= \frac{\pi}{2} R \text{ for cylindrical fluor irradiated side-on})$$

$$R = \text{fluor radius (1.0 inch, thus } t = 1.57 \text{ inch} = 3.99 \text{ cm)}$$

$$\sigma_C^e = \text{carbon elastic cross-section}$$

$$\sigma_C^\alpha = {}^{12}\text{C}(n,\alpha) \text{ cross-section}$$

$$f, g, \text{ and } h(B, E_n) = \text{fractions of proton recoils, } {}^{12}\text{C} \text{ recoils and alpha particles which, for neutron energy } E_n, \text{ produce observable scintillation events for a given detector bias } B$$

The bias is expressed in electron energy and the corresponding neutron (really proton) energy is determined from the scintillator's response function to monoenergetic neutrons, such as shown in Fig. 10 for the NE-213 scintillator (from Ref. 12). The electron-proton equivalence in terms of scintillation pulse heights is shown in Fig. 11 which contains data from several authors. For this present work, the data of O'Dell, et al.,¹² were used.

The detector's bias energy was determined with the circuit of Fig. 12 which employed the following instrumentation modules:

Linear Amplifiers	ORTEC 454, 450, and 410
Discriminator	EG&G TR204 Dual Updating
Gate Generator	EG&G GG-200
Multichannel Analyzer	Nuclear Data 50/50 System

A radioactive source, such as ^{137}Cs , ^{65}Zn , ^{54}Mn , or ^{60}Co , was placed near the detector and the "slow" pulses from the emitter follower circuit were stored in the multichannel analyzer which was gated by anode pulses that exceeded the bias level of the discriminator. The bias level energy was determined from the

Fig. 10. Response of NE-213 to monoenergetic neutrons.

Fig. 11. Electron and proton energies producing equal pulse heights in NE-213.

Fig. 12. Circuit for the determination of detector energy bias.

Compton edge energy which, for the examples provided in Fig. 13, is 644 keV for ^{54}Mn (840 keV gamma) and 906 keV for ^{65}Zn (1114 keV gamma). O'Dell, et al.,¹² determined that for this particular detector, the half height point of the Compton edge corresponds to 1.05 ± 0.01 times the Compton edge energy, yielding the indicated values of 676 keV and 951 keV for ^{54}Mn and ^{65}Zn , respectively. The bias energy for the two examples happens to be 26 keV, using the half height point of the leading edge of the spectrum as the bias channel.

3.2.2 Measurement of Neutron Time-of-Flight Spectra

Once the detector bias has been established via the circuit of Fig. 12, that portion of the circuit dealing with the fast anode signal becomes part of the measurement electronics used for the recording of the time-of-flight spectrum, as shown in Fig. 14. The TAC used was an Ortec-437A unit set at the 2- or 4- μsec range. The start pulse was generated at the linac target by the NIBM and after amplification by fast EG&G AN101 amplifiers was routed to an EG&G T140 zero-crossing discriminator which fed a logic pulse to the TAC for pulses exceeding a nominal level of approximately 0.4 V. The stop pulse, generated by the detector

Fig. 13. ^{54}Mn and ^{65}Zn spectra in NE-213.

Fig. 14. Circuit for the measurement of neutron time-of-flight spectra.

as a result of neutron interactions in the scintillator, was a logic pulse produced by the discriminator whenever the anode pulse exceeded the bias level. A dual output from the discriminator served to gate on the analyzer via an EG&G GG-200 gate generator. Delays were used where necessary to insure the proper timing or sequence of events. Scalers were used to store the linac pulses, valid TAC pulses, and counts from the ORTEC 439 current digitizer which monitored the target charge. The ratio of the valid TAC pulses (i.e., detector events that followed the NIBM start pulse within the range of the TAC setting) to the linac pulses served as a monitor on the beam current, which was adjusted to maintain that ratio at roughly 0.1.

A number of calibrations and checks were performed on the TAC/MCA (multi-channel analyzer) system in order to determine TAC and MCA linearities, timing resolution, and system time calibration. Some of these are described briefly.

Timing Resolution - The inherent time resolution of the electronic measuring circuit is primarily determined by the start and stop discriminators and the TAC. To determine this, the portion of the electronic circuit of Fig. 14 consisting of the NE-213 detector, NIBM chains, TAC, and analyzer was employed. The aim was to inject two pulses, fixed in time relative to each other and of a shape similar to those encountered in the experiment, into the start and stop signal chains and observe the slewing of this fixed time interval at the analyzer. This was achieved by using the uranium target and operating the linac with the 50-psec pulse. The intense bremsstrahlung flash (the uranium plates were removed from the time-of-flight pipe) produced a signal in the detector for each linac pulse and the anode signal was delayed by some small amount relative to the NIBM signal in the control room (about 20 nsec). When the TAC was expanded full scale to 50 nsec, the system time resolution was found to be on the order of 450 psec, as shown in Fig. 15. The factors contributing to this slewing are the inherent time resolution of the TAC (quoted by the manufacturer at 10 psec for this range), the discriminators' slope, and the target size. The bremsstrahlung photons arriving at the detector are most likely produced in the center region of the uranium sphere but could conceivably originate anywhere in the sphere. This fact alone introduces a maximum spread of about 250 psec into the time interval between the NIBM pulse and the gamma-ray flash and serves to

Fig. 15. Measurement of system time resolution.

indicate that the time slewing due to the discriminators and the rest of the circuitry is on the order of 350 psec. Thus the uncertainty in the overall timing is dominated by the 10-nsec pulse width, barring systematic errors in time interval measurements.

TAC Linearity and System Time Calibration - A number of methods were used to establish the linearity of the TAC over its operating range and the time calibration α (nsec/channel) of the recording system. One method used fixed cable delays which were calibrated with the aid of a sampling oscilloscope and/or a frequency generator and pulser; another used a sampling oscilloscope and pulser to time intervals between pulses. Both methods are useful in the absolute time calibration of the system (i.e., Fig. 14 circuit). However, for measurement of differential time linearity of the TAC and the slope of the time vs. channel curve, a method employing random pulses from a detector in coincidence with pulses from a precision frequency generator (Tektronix 184 time mark generator) was found to be very suitable.

This method, shown schematically in Fig. 16, produced start-stop pulses randomly separated in time by an integral number of multiples of the base time by an integral number of multiples of the base time interval, i.e., 50 nsec for a 20-MHz sine wave. The sine wave from the time mark generator produced a train of logic pulses from the EG&G T-140 discriminator which were placed in coincidence with random anode pulses from the NE-213 detector exposed to a radioisotope source. The results of such a calibration (see Fig. 17) show the system to be linear over most of the TAC range above about 160 nsec. Since time intervals of that magnitude imply neutron energies of more than 200 MeV for our experiment, this nonlinearity was of little concern.

The above assumes a linear MCA ADC, which indeed was found to be the case during checks made with the aid of an Ortec 419 precision pulse generator. For the determination of absolute time, cables of known delay were used in conjunction with a pulser to establish the time corresponding to zero channel.

3.2.3 Neutron Time-of-Flight Spectra from Be and U Targets

The gamma-ray flash from the uranium target in particular was so intense that the 1-inch-thick uranium plate had to be inserted in the time-of-flight pipe

Fig. 16. Circuit for the determination of differential time linearity.

Fig. 17. System differential time linearity.

in order to prevent saturation of the photomultiplier tube. Even then, the bremsstrahlung photon beam at the detector was intense enough that most of the stop pulses from the detector were due to photons, and thus the neutron events were in effect biased off. To remedy this situation the timing was arranged so that at the TAC the NIBM pulse occurred after the gamma-ray flash but of course before the arrival of the fastest expected neutron.

Typical raw time-of-flight spectra for the beryllium and uranium photo-neutron targets are shown in Figs. 18 and 19. The very pronounced structure in the beryllium data is due to resonant absorption in beryllium at the indicated energies of 0.61, 0.81, and 2.72 MeV, three points which serve as an excellent check on the system time calibration. The data shown took about 4 hours to accumulate with a count rate of roughly 30 cps of neutron events in the detector.

Neither of two background subtraction methods tried indicated a significant contribution to the measured spectra from random or beam-related background. The first method was simply designed to remove spurious detector events that happened to occur after a valid start pulse and within the full scale time setting of the TAC. This was easily achieved by replacing the NIBM start pulse with one not beam-related (but at the same repetition rate) and running for a time equal to that during which data were accumulated with the linac beam off and the analyzer in the subtract mode. Total counts so accumulated were typically less than 1% of the total counts with beam on. A more meaningful check of background due to events produced by non-primary neutrons, gamma-rays, or rf noise pickup was carried out at one instance by moving the beryllium target just out of the field of view of the detector. The purpose was to obtain some knowledge of the contribution of room-return gamma-rays and neutrons to the measured spectra. The results again showed a negligibly small count rate which led us to conclude that the observed spectra were indeed an accurate measure of the target neutron spectrum.

3.3 DETECTOR CHARGE RESPONSE MEASUREMENTS

Unlike the measurements described in the previous section, the determination of neutron produced detector charge did not employ a counting circuit in the strict sense since the desired information was not a scintillator pulse height spectrum or response function. Rather, the quantity measured was the charge produced by the detector per incident neutron of a given energy. This was achieved with the

Fig. 18. Raw neutron time-of-flight spectrum, beryllium target.

Fig. 19. Raw neutron time-of-flight spectrum, uranium target.

use of an EG&G LG-105 linear gate, basically a gated integrator, the output of which is a voltage pulse whose amplitude is proportional to the charge measured by the unit while gated on.

This approach to the measurement of detector neutron response is dictated primarily by the fact that the detectors of interest are used in the current mode and vary greatly in design and type. Some are fluor/photomultiplier or fluor/photodiode combinations; others incorporate photodiodes without scintillators; and still others are Compton diodes, detectors which respond directly to the charged particles and associated fields generated in the materials that constitute the active region. Since all the detectors are in general considerably less sensitive than the photomultiplier types, measurement of their neutron response may require that the charge due to a number of neutrons within an energy interval be recorded rather than the scintillation pulse height due to a single neutron.

The approach taken in previous measurements by Kirkbride, et al.,⁸ Knowlen and O'Dell⁹, and Michael, et al.,¹⁵ for example, had been to select a relatively narrow time window (100 nsec or less) and accumulate pulses occurring in that interval which was delayed with respect to the linac pulse by varying amounts to cover the desired energy range. This method has the advantage that the time windows can be adjusted in width to suit the particular energy range (that is, $\Delta E/E$ can be kept constant, within limits) but is inefficient in that only a small portion of the pulses generated by the detector are analyzed during a particular run. Using a linear gate to integrate detector charge has a further disadvantage in that linear gates cannot be gated on for arbitrarily small time intervals so that energy resolution suffers at the higher energies.

In our experiment we employed the multi-parameter capability of the Nuclear Data 50/50 system and accumulated time and pulse height information simultaneously, similar to the experiment of Pohl, et al.⁶ Thus data for the whole neutron energy range were accumulated at once, and given enough analyzer storage one can, in principle, make the time intervals arbitrarily small. The electronic circuit and detector and experimental techniques used in the neutron response measurements are described next.

3.3.1 Dual Parameter Time-of-Flight Experiment

The 4096-channel analyzer of the Nuclear Data 50/50 system was used in a 64 x 64 configuration providing 64 time groups of 64 channels each to cover the

desired neutron energy range. The measuring circuit, Fig. 20, indicates the two A/D converters and the gating of the time ADC from valid TAC pulses that exceeded a nominal bias level set slightly above the characteristic TAC pedestal that appeared at the output for each start pulse. Once the time ADC was gated on, it would store an incoming pulse from the linear gate according to its height in a time group determined by the level of the TAC pulse. All other pulses from the linear gate that did not coincide with a valid TAC pulse were stored in the first time group. The linear gate itself was gated on from the detector's dynode pulse via a discriminator and gate generator. That part of the circuit was again used to set the detector bias at a level above the detector noise with the aid of radioisotope sources which were also useful for setting the system gain.

As in the neutron spectrum measurements, the NIBM pulse was delayed by an amount sufficient to have it arrive at the TAC about 100 to 200 nsec after the gamma-ray flash pulse from the detector. Thus the first of the 64 time groups corresponded to some fixed time interval after the target pulse, and this as well as the time ADC calibration (nsec/group) was measured with the aid of a pulser and delay cables of known length.

The detector for which results are reported here was a LASL NPM-52 unit that required some modification of the circuit of Fig. 20. Since the detector had only one output from the photomultiplier mode, this signal was split at the detector via a 50-ohm divider to provide the "dynode" and "anode" signal chains indicated. Also, as will be described later, the relatively small signals of the "anode" chain required amplification in order to fall into the fixed sensitivity range of 3- to 100-pC/pulse of the LG-105 linear gate. To cover optimally the desired neutron energy range the experiment was split into two parts, covering from roughly 0.3 to 2 μ sec in the first and from 1.5 to 3.2 μ sec in the second. The beryllium target was used in the first experiment since it yields relatively more high energy neutrons than does the uranium target which was employed for measurement of the response to the lower energy neutron group.

The multichannel analyzer and scalers were tied into a central control panel that permitted all of them to be started and stopped simultaneously. Again, the ratio of valid TAC pulses to linac pulses was monitored as before, but the ratio was allowed to go higher than 0.1, since pulse pile-up is not an inherent concern of this measurement method. Run times with a given photoneutron target

Fig. 20. Circuit for the measurement of detector neutron response.

were on the order of 10 to 12 hours, during which time approximately 2×10^6 total counts or 30,000 counts per energy group were accumulated. Background runs were again carried out for equal time lengths by replacing the NIBM start pulse with a beam unrelated pulse.

3.3.2 Detector Description

The LASL NPM-52 detector, shown schematically in Fig. 21, incorporated a 2-inch-diam by 1-inch-thick NE-111 scintillator and RCA 7253 photomultiplier tube. The indicated dc calibration lamp served to maintain the detector gain at a calibrated (with a ^{60}Co source at EG&G's Las Vegas facility) value. A system consisting of a battery power supply, precision 1-ohm resistor, two 10-turn resistor pots, a precision potentiometer, and electrometer was used to set and measure that current flowing through the filament of the dc calibration lamp which would produce a 1- μA signal from the detector output at a given photomultiplier high voltage. Once these parameters were established during the ^{60}Co calibrations, detector gain was maintained at that value by adjusting the high voltage. This was done at least once a day during the course of the measurements.

During initial exposure of the detector to radioactive sources (^{60}Co , ^{65}Zn , etc.) for purposes of system gain adjustments, it was found that the detector's high noise level (i.e., low signal/noise ratio) made measurements of neutron response impossible. Cooling the detector reduced the noise to a level below approximately 700-keV neutron energy. The detector was placed inside a dry-ice filled styrofoam container whose temperature ranged between -34 to -38°F during the measurements. A hole cut in the container to permit the scintillator to protrude removed the low-Z styrofoam from the neutron path, but moisture condensing on the scintillator housing froze and thus added a thin layer of ice. It is believed this did not measurably disturb the neutron beam.

3.3.3 System Charge and Gain Calibration

The linear "anode" chain in Fig. 20, consisting of amplifiers if any, linear gate, and multichannel analyzer, must be calibrated to permit absolute determination of detector change. To do this accurately, a method employed by EG&G Las Vegas personnel, who use a number of LG-105 linear gates as part of a digital recording system, was adopted. A precision dc power supply (Power Design 2005) was connected to the LG-105 data input with 50-ohm termination. An EH 121 pulse generator,

Fig. 21. Schematic of LASL NPM-52 detector.

producing rectangular pulses at some nominal rate of a few kHz, was connected to the gate input. The output was connected to the ND50/50 pulse height ADC. The charge per pulse could accurately be determined from the dc current at the input (power supply voltage divided by 50-ohms) and width of the gate pulse or, more precisely, the gate pulse width at the 0.3-V level. For a particular gate pulse width, the dc input level was varied to generate pulses over the range 0 to 100 pC. The channels in which each appeared were recorded and are plotted in Fig. 22. This procedure was repeated for five gate pulse widths ranging from 22 to 200 nsec to assure that the calibration was not sensitive to that parameter. As the three examples of Fig. 22 show, the calibration was essentially independent of the gate pulse width.

Since, with the LASL NPM-52 detector, it was necessary to insert an amplifier (2-stage EG&G AN-101) between the detector and linear gate, gain had to be determined as well. Because the AN-101 is a pulse amplifier the above method could not be used, but the amplifier was calibrated separately with the aid of a pulser and oscilloscope. It should be noted that the measured gain with the LG-105 connected was different from that measured with the amplifier alone. Specifically, it was found that the gain measured with the two stages of the amplifier in cascade was

Fig. 22. System charge calibration.

about 40% larger than the product of the measured gains of each stage. The reason for this was not determined but the possibility suggests itself that the AN-101, to the extent that it represents a true current source, acts differently when both stages are used rather than just one.

3.3.4 Detector Charge Response Spectra for Be and U Targets

Some typical results of the dual parameter detector response measurements are shown in Figs. 23 and 24 for the LASL NPM-52 detector and the beryllium and uranium photoneutron targets, respectively. These isometric displays represent the detector response surface with the three axes being charge/pulse, counts, and time (energy). The response data obtained with the beryllium target, if viewed in the yz-plane (counts vs. time), resemble the NE-213 detector TAC spectrum of Fig. 18 in that the dip corresponding to the 2.72-MeV resonance absorption line in beryllium can be readily identified. Since the time axis extends only to 2 μ sec (approx.) the 0.81- and 0.61-MeV lines are not observed.

As presented, the data show time increasing from the origin so that the early curves correspond to high energy neutrons. These curves are thus much broader than those corresponding to lower energy neutrons and also represent more smearing of the true response function, since the energy bin widths are much larger for fast neutrons than for slower ones. The cutoff of the spectra in Fig. 24 is an artifact resulting from the use of a particular plot routine which sets the contents of the first and last channel to zero.

TIME OF FLIGHT SPECTRUM
NPM-52 DETECTOR
BERYLLIUM TARGET
RUN 1152

Fig. 23. Isometric representation of response of LASL NPM-52 detector to neutrons from Be target.

TIME OF FLIGHT SPECTRUM
NPM-10 DETECTOR
URANIUM TARGET
RUN 0252

Fig. 24. Isometric representation of response of LASL NPM-52 detector to neutrons from U target.

4. RESULTS AND DISCUSSION

4.1 Be AND U PHOTONEUTRON SPECTRA

The time-of-flight spectra for the beryllium and uranium photoneutron targets, such as shown in Figs. 18 and 19, were converted to energy spectra through the application of Eqs. (4) and (10) in Section 2.2. A computer program was written for our CDC 6400 terminal to store the raw time-of-flight data (converted from paper tape to computer cards), convert each time channel to energy, and compute dN/dE of Eq. (10) using detector efficiency data that were available on punched cards for bias energies ranging from 10- to 100-keV electron energy. The efficiency arrays for a given bias covered the range 0.05 to 20.05 MeV in 401 equal increments. Linear interpolation was used to compute the efficiency at each of the 1024 neutron energies as well as for bias energies for which data were not available. The total neutron yield, normalized to unit solid angle and one 27.0-MeV electron, was obtained by summing the products of computed spectrum value and associated energy bins.

The results of those computations are shown in Figs. 25 and 26, the beryllium and uranium photoneutron spectra obtained with 27.0-MeV electrons and filtering of the neutron beam with 1-inch uranium. Integration of the spectra led to the total yield values of 4.95×10^{-5} and 2.48×10^{-4} n/sr/e for the beryllium and uranium targets, respectively. The uranium curve (Fig. 26) also shows a plot of data obtained by Gulf General Atomic²⁴ for a uranium target after which ours is modeled. The particulars of the experiment were a beam energy of 28 MeV, spectrum measurements at 90° relative to the electron beam, and use of a 1.238-inch uranium filter. The data, presented in tabular form in the GGA report, were normalized to our measured spectra at 2.0 MeV, a purely arbitrary point. Since the experimental conditions are not exactly the same, differences in spectral shape are to be expected. However, the divergence in the two spectra below 0.5 MeV appears greater than might be expected from a purely qualitative assessment of the differences in experimental conditions. We cannot comment on the GGA spectrum which, incidentally, was measured with a scintillation detector (2- by 2-inch NE-221) down to 1.5 MeV and with a boron capture detector below that energy.

Two considerations that might explain, at least in part, the sharp rise in our measured spectra below 0.5 MeV or so are explored. The most likely error to account for the observed behavior is one in the determination of the detector bias.

Fig. 25. Neutron energy spectrum from ^9Be photoneutron target.

Fig. 26. Neutron energy spectrum from ^{238}U photoneutron target.

As the curves of Fig. 9 indicate, the detection efficiency near the bias energy varies rapidly both with energy and bias. Thus, an error of a few keV in measurement of detector bias can indeed greatly distort the low energy portion of the neutron spectrum. The discussion of measurement errors in the Appendix treats this in some quantitative manner, and it is hoped that it will be possible to analyze the errors due to detector bias inaccuracy in greater detail in future measurements. We believe that this poses perhaps the most significant difficulty for measurements of this type. A second consideration for at least some of the rise in the low energy portion of the spectrum might be the light production by capture gamma-rays resulting from neutrons thermalized in the scintillator. Yates, et al.,²⁶ calculated the ratio of delayed light (i.e., that produced by capture gamma-rays) to the prompt light (that produced by neutron elastic scattering) for a 9-inch diam NE-224 scintillator and found it to be 1.14 at 0.5 MeV and 4.2 at 0.2 MeV for a 2-inch thickness. For a zero-order approximation we assume that this ratio is linear with scintillator volume, so that for our 2- by 2.5-inch scintillator we expect the ratio to be on the order of 0.25 at 0.2 MeV and negligibly small at 0.5 MeV. From our scintillator dimensions one can estimate very crudely that the time required for the thermalization of a 0.5-MeV neutron is on the order of 1 to 2 μ sec. Thus it is possible, though unlikely, that some light produced by this mechanism by low energy neutrons would be detected in the time-of-flight spectrum measurements. Ankenbrandt¹⁷ calculated the fraction of "slow" light for a 6-cubic-inch scintillator to be about 65% at 0.2 MeV and 45% at 0.5 MeV of the total light. Here the ratio of scintillator volumes would indicate values of 0.02 or less for our case, certainly negligibly small. We conclude that the light production due to capture gamma-rays for our particular scintillator is small and within the experimental error.

Some comparisons can be made with target yields obtained by other workers although, of course, experimental conditions are never precisely the same nor always known, so that exact quantitative comparisons are ruled out. Earlier measurements by linac personnel with the beryllium target (among others) at 20.5 MeV resulted in a yield of 1.85×10^{-5} n/sr/e compared to that of 4.95×10^{-5} n/sr/e for this experiment at 27.0 MeV. From the data of Fig. 2, it is expected that the ratio of the yield at 27 MeV to that at 20.5 MeV is about 2.2 for a thick beryllium target. In order to compare the above yields, it must be pointed out that the lower energy

measurement was made without a beam filter and at a higher detector bias (about 0.5 MeV). Furthermore, since both values refer to the detected target charge, a correction for the difference between the fraction of electrons stopped at 20.5 MeV and at 27.0 MeV (0.54 and 0.28, respectively) must be applied. The fraction of neutrons transmitted by the 1-inch-thick uranium filter is very roughly 0.45 (assuming an average value of the total cross-section of 7 barns) so that, in the context of our experiment, the yield at 20.5 MeV becomes 1.60×10^{-5} n/sr/e. The ratio thus is 3.1 in the measured yields compared to the 2.2 value cited above. The fact that the bias for the low energy measurement was higher than ours suggests that the larger ratio may not be unreasonable.

For the uranium target yield the earlier cited values of 96×10^{-4} n/e of Barber and George²⁰ and 110×10^{-4} n/e of Burrill²¹ for thick uranium targets compare reasonably well with the value of 70×10^{-4} n/e that we obtain if the yield of Fig. 26 is corrected for beam filter attenuation and 4π geometry. Sandifer and Quam²⁵ measured the angular distribution of neutrons from our uranium target at 27.0 MeV (shown in Fig. 27) with sulfur foils and estimated the yield from these data to be 4.9×10^{-4} n/sr/e or, if correcting for the beam filter attenuation, 2.2×10^{-4} n/sr/e. This compares well with the yield of 2.48×10^{-4} n/sr/e for the spectrum of Fig. 26.

4.2 LASL NPM-52 NEUTRON SENSITIVITY

The detector neutron sensitivity was obtained from the dual parameter data as shown in the examples of Figs. 23 and 24 and the application of Eqs. (10), (12), and (13) of Section 2.3. The system charge calibration permitted the computation of Q , the first moment of each of the 64 charge spectra, accumulated during a given run with either the beryllium or uranium target. The time axis calibration assigned an energy and bin width to each group. The pertinent photoneutron spectrum was integrated over each of these energy intervals to yield the total number of neutrons that produced the charge Q in the detector. The detector sensitivity then is simply the ratio of the total charge to the number of neutrons for the particular energy interval designated by $(E, \Delta E)_k$.

The results of these computations are shown in Fig. 28 along with measurements of P. Lyons¹³ at 2.35 and 13.9 MeV, and a calculated curve of the neutron sensitivity of a LLL L-24 detector by Ankenbrandt¹⁷. Dr. Lyons measurements were made with the same detector with neutrons from the $d(d,n)He^3$ and $d(t,n)He^4$ reactions

Fig. 27. Angular distribution of neutrons from ^{238}U target.

at the LASL A-2 facility.* The values he obtained were 1.03×10^{-12} C/neutron (C/n) at 13.9 MeV and 3.82×10^{-13} C/n at 2.35 MeV. This compares with values of 1.3×10^{-12} and 3.5×10^{-13} C/n read from the time-of-flight data of Fig. 27.

Comparisons with some preliminary measurements on other LASL fluor/photo-multiplier detectors¹⁴, such as the NPM-2 and NPM-10, fail to provide such good agreement. The above detectors had been calibrated at 3.2 MeV and 14 MeV, and their sensitivities were expressed in C/n/cm² to permit comparisons with the ⁶⁰Co calibration (C/R). Adjusting the sensitivity values of the NPM-52 detector to these units at 3.2 MeV (4.5×10^{-13} C/n) and 14 MeV (1.3×10^{-12} C/n) and normalizing the NPM-2 and NPM-10 sensitivities to that of the NPM-52 via the ⁶⁰Co sensitivities, one gets the comparison in Table 1.

Table 1. Comparison of the Neutron Sensitivities of Three LASL Scintillator Detectors

	NPM-52	NPM-2	NPM-10
Fluor Type	NE-111	Pilot A	Pilot A
Fluor Dimensions	2" diam x 1"	5" diam x 3"	5" diam x 3"
⁶⁰ Co Sensitivity (C/R)	5.11×10^{-3}	3.0×10^{-2}	6.0×10^{-1}
Neutron Sensitivity (C/n/cm ²) - normalized to NPM-52 ⁶⁰ Co sensitivity			
3.2 MeV	9.1×10^{-12}	4.1×10^{-12}	5.7×10^{-12}
14 MeV	2.6×10^{-11}	1.1×10^{-11}	1.2×10^{-11}

The Table 1 data suggest that the ratio of neutron to gamma-ray response for the NPM-52 is more than twice as high as that of the NPM-2 and NPM-10 detectors. One argument that tends to support this trend is that the neutron cross-section is

*It should be noted that the detector, after the time-of-flight measurements, was returned to the EG&G, Las Vegas facility for recalibration. A drop in sensitivity of about 40% was observed at that time and the high voltage was increased to reestablish the original gain. Dr. Lyons at LASL found no gain-shift from the latest setting. It is believed that the cooling of the detector somehow resulted in a gain change after the detector returned to room temperature. This could have been aggravated during shipping. In any event, both neutron measurements were made at the same detector gain albeit different PM high-voltage levels.

larger than that for 1.25-MeV gamma-rays for those energies and materials, so that for a thin fluor compared to a thick one a higher fraction of the total neutrons compared to the gamma-rays will have interacted. The light output is proportional to the total number of interactions and thus the ratio of neutron light to gamma-ray light, when plotted as a function of fluor thickness, is expected to decrease with increasing thickness. Whether this argument alone explains the observed large discrepancies needs to be explored more fully.

Fig. 28. Sensitivity as a function of neutron energy of LASL NPM-52 detector.

5. CONCLUSIONS

The feasibility of using time-of-flight techniques at the EG&G/AEC linear accelerator for measuring the neutron response of relatively sensitive detectors over the energy range 0.5 to 14 MeV has been demonstrated. The measurement technique has been described in detail and two photoneutron targets, beryllium and uranium, have been calibrated and referenced to linac beam parameters. The particular detector measured was a low-sensitivity fluor photomultiplier LASL detector that required cooling and signal amplification to obtain good signal-to-noise ratio. The data obtained with the beryllium and uranium photoneutron targets agreed very well, and comparison of the sensitivity with measurements by another investigator at 2.35 and 13.9 MeV using a dc machine to generate d-d and d-t neutrons was quite good.

In comparing the ratio of neutron sensitivity to that of ^{60}Co sensitivity it was found that the values for the 1-inch-thick NE-111 scintillator of the NPM-52 detector were considerably higher than 1) ratios obtained in previous measurements, using d-d and d-t neutrons with 3-inch-thick scintillators (such as found in the LASL NPM-2 and NPM-10 detectors) or 2) the ratio computed through Monte Carlo calculations for a LLL L-24 detector incorporating a 6-inch-thick scintillator.

In the measurements of photoneutron spectra and detector charge the detector bias needs to be established accurately. Furthermore, to make exact predictions of the detector's response in the current mode the effect of the bias on the total measured charge needs to be determined. Both matters need further exploration, it is believed, to improve the quality of measurements.

The LG-105 linear gate and stretcher used in the measurements of detector charge was found to be somewhat unstable and limited in dynamic range for this application. In future measurements a unit that would be an improvement in either of these categories should be employed. Finally, the extension of this measurement technique to less sensitive detectors appears feasible, in terms of the available neutron flux and the realization that signal amplification prior to integration will be required. The severest limitation appears to be techniques that can be employed to improve signal-to-noise ratio.

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APPENDIX

ERROR ANALYSIS OF NEUTRON TIME-OF-FLIGHT MEASUREMENTS

The neutron sensitivity determined at a given energy is a function of a host of experimental parameters which are operated on and combined in a number of steps. It is thus difficult to estimate by simple inspection the contribution of an error in any one of these parameters to the overall error. For this reason the propagation of significant random errors has been developed in some detail to permit determination of the relative importance of various parameters to neutron sensitivity. Systematic errors such as arise from the presence of detector bias are not treated, and errors in the determination of bias energy are reflected in an increase in the uncertainty of the absolute detection efficiency, which is given by O'Dell, et al.,¹² as $\pm 8\%$.

The relationships developed permit calculation of the error in sensitivity at any energy and a sample calculation is provided for the 4-MeV sensitivity error.

The detector sensitivity is given by the ratio $S = Q/\Phi$, where Q is the detector charge and Φ is the total number of neutrons producing that charge. The error in S , ΔS , is then approximated by:

$$\Delta S \approx \partial S = \left[\left(\frac{\partial S}{\partial Q} \right)^2 (\Delta Q)^2 + \left(\frac{\partial S}{\partial \Phi} \right)^2 (\Delta \Phi)^2 \right]^{1/2} \quad (A-1)$$

where all quantities refer to a particular energy and associated interval. ΔQ and $\Delta \Phi$ are the errors associated with the measurement of detector charge and neutron flux, respectively.

A.1 ERROR IN DETECTOR CHARGE

From the expression for detector charge in the k^{th} time group given in Eq. (11), Section 2, it can be shown that the error in that value, ΔQ , is given by:

$$\Delta Q \approx \partial Q = \left[\left(\sum_j j \cdot n_j \right)^2 (\Delta q)^2 + \sum_j n_j (j \cdot q)^2 \right]^{1/2} \quad (A-2)$$

where j is the channel number of the k^{th} charge spectrum, n_j is the counts in that channel, and Δq is the uncertainty in the system charge calibration, q .

A.2 ERROR IN NEUTRON FLUX

The determination of the number of neutrons in the k^{th} energy bin reflects the errors in the energy and energy interval not only in the assignment of the limits over which the spectrum is integrated, but also in the value of the spectrum of Eq. (10) of Section 2. If we replace the quantity $n(E, \Delta E)_k$ of Eq. (13) with the term Φ , we have;

$$\Phi = c \sum_k \frac{dN}{dE} k \cdot \Delta E_k \quad (\text{A-3})$$

where c for the moment is a constant and equals $\Omega'Q_T$ in Eq. (13). The error in Φ can be shown to be:

$$\Delta\Phi \approx \partial\Phi = c \left[\sum_k (\Delta E_k)^2 (\Delta DN_k)^2 \right]^{1/2} \quad (\text{A-4})$$

where

$$DN_k \equiv \left(\frac{dN}{dE} \right)_k,$$

the average value of the neutron spectrum over the k^{th} energy interval. To compute the error ΔDN_k , we refer to Eq. (10) and find that the computed energy spectrum is a function of four parameters, each of which contains an error. These are: the detector efficiency, the time-of-flight path length, the system time calibration, and the counts of the measured time-of-flight spectrum. We assume the quantity $\Omega \cdot Q_T$ to be constant for the moment, and we make the replacement $D\beta \equiv dN/dCH$.

The error ΔDN_k is given by:

$$\Delta DN_k \approx \partial DN_k = \left[\left(\frac{\partial DN}{\partial \epsilon} \right)^2 (\Delta \epsilon)^2 + \left(\frac{\partial DN}{\partial \alpha} \right)^2 (\Delta \alpha)^2 + \left(\frac{\partial DN}{\partial L} \right)^2 (\Delta L)^2 + \left(\frac{\partial DN}{\partial D\beta} \right)^2 (\Delta D\beta)^2 \right]^{1/2} \quad (\text{A-5})$$

To compute the terms $\partial DN/\partial \epsilon$, $\partial DN/\partial \alpha$, etc., we introduce the quantity:

$$\gamma = \sqrt{1 - (L/\alpha\beta c)^2} \quad (A-6)$$

and upon performing the indicated partial differentiations we obtain the following:

$$\frac{\partial DN}{\partial \epsilon} = - \frac{L}{\epsilon \cdot \alpha \beta c^3} \left[\frac{1}{\gamma^2} - 1 \right]^{-3/2} D\beta \quad (A-7)$$

$$\frac{\partial DN}{\partial \alpha} = \frac{L}{\epsilon \cdot \alpha^2 \beta c^3} \left[\frac{1}{\gamma^2} - 1 \right]^{-3/2} \left\{ 3 \left(\frac{L}{\alpha \beta c} \right)^2 \left[\frac{1-2\gamma}{\gamma^2(1-\gamma^2)} \right] - 1 \right\} D\beta \quad (A-8)$$

$$\frac{\partial DN}{\partial L} = \frac{1}{\epsilon \cdot \alpha \beta c^3} \left[\frac{1}{\gamma^2} - 1 \right]^{-3/2} \left\{ 1 + \frac{3}{\gamma^4} \left(\frac{L}{\alpha \beta c} \right)^2 \left[\frac{1}{\gamma^2} - 1 \right]^{-1} \right\} D\beta \quad (A-9)$$

$$\frac{\partial DN}{\partial D\beta} = \frac{L}{\epsilon \cdot \alpha \beta c^3} \left[\frac{1}{\gamma^2} - 1 \right]^{-3/2} \quad (A-10)$$

A sample calculation was performed for the sensitivity measurement with the Be target at 4 MeV. The values of the pertinent parameters and the errors assigned were as follows:

$$\begin{aligned} t &= 1060 \text{ nsec}; \quad t + \Delta t = 1085 \text{ nsec}; \quad L = 2925 \text{ cm}; \quad \Delta L = \pm 1 \text{ cm}; \quad E = 3.82 \text{ MeV}; \\ E + \Delta E &= 4.0 \text{ MeV}; \quad \alpha = 4 \text{ nsec/channel}; \quad \Delta \alpha = 0.05 \text{ nsec/channel}; \\ \beta &= 265 \text{ channels}; \quad D\beta = 700 \text{ counts/channel}; \quad \Delta(D\beta) = \pm 26 \text{ counts/channel}; \\ \epsilon &= 0.3; \quad \Delta \epsilon = \pm 0.03; \quad Q = 1.9 \times 10^{-7} \text{ coulomb}; \quad \Phi = 3.93 \times 10^5 \text{ neutrons}; \\ S &= 4.8 \times 10^{-13} \text{ coulomb/neutron}. \end{aligned}$$

Computing the terms given by Eqs. (A-7) through (A-10) we find the smallest contribution to the error in the spectrum to arise from the uncertainty in L. The largest contribution to the error arises from the uncertainty in the detection efficiency, followed by that in the system time calibration. By combining these errors with estimated errors of 0.04% in the determination of the solid angle and 1% in that of

the measured target charge Q_T , the error in the value of the spectrum at 4 MeV is found to be $\pm 12\%$. It is expected that at lower energies this would be much worse, since the error in ϵ in the proximity of the bias is large and count rates are relatively low.

In order to obtain the error in the neutron flux, we must now integrate the spectrum DN_k over the interval $(E, \Delta E)_k$, which has an error associated with it due to the uncertainties in the measurement of time-of-flight. Remembering that for low relativistic neutrons $\Delta E/E \approx 2\Delta t/t$, we find the error in the energy interval to be about 1.5%. Applying Eq. (A-4) and combining it with this error we find the overall error in the neutron flux determination to be still $\pm 12\%$.

The error in the measurement of detector charge, computed from Eq. (A-2), is dominated by the uncertainty in the system charge calibration, since the number of counts accumulated in the charge spectrum was large. A 5% uncertainty was assigned to the charge calibration, a value that probably represents an upper limit. Systematic errors introduced as a result of the application of a detector bias are not included in the error assigned to the charge measurement.

When the errors in the charge are combined with those in the determination of neutron flux, the error in the detector sensitivity value is found to be $\pm 13\%$. This value, it should be re-emphasized, applied strictly to the 4-MeV point only. In general, it is expected that this is worse at both the low energy and high energy ends, because counts in both the time-of-flight and charge spectra are lower. Additionally, the effects of uncertainties in detector bias may strongly influence the low energy sensitivity values.

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