ENERGETIC-NEUTRON SPECTROMETRY

Annual Progress Report

for the period from

1 April 1973 to 31 March 1974

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ABSTRACT

Initial steps have been taken to modify a self-contained time-of-flight spectrometer for unidirectional neutrons in order to extend its capability to measure omnidirectionally incident neutrons. To measure the spectrum of omnidirectionally incident neutrons, it is necessary to measure two parameters, namely, the energy of the recoil-proton in the first detector in addition to the energy of the scattered neutron. The principle of the two-parameter measurement technique was confirmed in a measurement of the neutron spectrum produced at 0° from 71-MeV deuteron bombardment of a thick carbon target at the University of Maryland cyclotron. This measurement established also an improved technique for subtracting backgrounds in unidirectional spectral measurements. To measure omnidirectionally incident neutrons from 5 to about 150 MeV, it was necessary to design and construct an improved linear gate and stretcher with a potential dynamic range of 600 to 1, to design and procure a large 10 in. by 10 in. by 4 in. (NE-102 plastic) first detector, and to design and construct a 10 in. by 10 in. by 4 in. aluminum chamber for encapsulating the NE-228 liquid first detector. The ability of the spectrometer to measure omnidirectionally incident neutrons was tested in a simulated omnidirectional spectral measurement at the University of Maryland cyclotron using the neutron beam produced at 0° from 82-MeV deuteron bombardment of a thick beryllium target. To simulate a spectral measurement of omnidirectional neutrons, measurements were made with the neutron

beam incident on the spectrometer at angles of 20° , 45° , and 75° .

These data are presently being analyzed.

1. Introduction

This report describes progress made during the past year under Contract No. AT(11-1)-2231 with Kent State University. The overall objectives of this program are the development of a spectrometer for measurement of neutrons in the energy region from a few MeV to several hundred MeV and the measurement of energetic-neutron spectra at particle accelerators. Previously, Madey and Waterman (1973 a,b, 1974) and Waterman and Madey (1973) have developed the spectrometer to measure the spectrum of neutrons incident unidirectionally on the spectrometer over the energy region from about 1 MeV to 1 GeV and have used the spectrometer to measure thick and thin target neutron spectra at particle accelerators.

In addition to continuing needs for measurements of unidirectional neutron spectra, a need exists also for an instrument system that can determine the flux and energy spectrum of omnidirectional neutron radiation in the energy region from a few MeV to a few hundred MeV. The need for such an instrument arises in connection with accelerator radiation dosimetry and shielding measurements involving the transport of energetic-neutrons.

The spectrometer developed previously for measuring unidirectional neutron spectra measures a single parameter, namely, the time-of-flight of a neutron scattered between two scintillation counters. To measure the spectrum of omnidirectionally incident

neutrons, it is necessary to measure two parameters, namely, the energy of the recoil-proton in the first detector in addition to the energy of the scattered neutron. During the past year, we have made progress in extending the applicability of the spectrometer to the measurement of omnidirectionally incident neutrons. Our initial objective is to develop the spectrometer for measurement of the neutron skyshine and skyshine source spectra at the Brookhaven Alternating Gradient Synchrotron (AGS). The results of the skyshine measurements will be used to develop a skyshine transport model of general applicability for accelerators. We will collaborate with Dr. R.G. Alsmiller, Jr. at the Oak Ridge National Laboratory and Mr. Carl Distenfeld at the Brookhaven National Laboratory in the interpretation of the skyshine measurements.

Our research accomplishments during the past year can be classified into the following categories:

- a. Experimental confirmation of the principle of the two-parameter measurement technique.
- b. Establishment of an improved technique for subtracting backgrounds in unidirectional neutron spectral measurements.
- c. Design and construction of a linear gate and stretcher with a large dynamic range.
- d. Design, procurement, and construction of large scintillation counters for neutron skyshine measurements.

- e. Specification, procurement, and test of a transportable on-line data acquisition system.
- f. Measurement of a simulated omnidirectional neutron spectrum with the two-parameter spectrometer.
- g. Measurement of neutron spectra of interest for neutron radiotherapy and neutron irradiation studies of biological systems.
- h. Preliminary design study for an on-line data acquisition system at LAMPF.
- i. Preliminary thin target measurements at the University of Maryland.
- j. Presentations at scientific meetings.
- k. Papers published during the past year.

The specific accomplishments in each of these categories are described in Section 2.

2. Research Accomplishments

Our research accomplishments during the past year are summarized below.

a. Experimental Confirmation of the Principle of the Two-Parameter Measurement Technique

In July 1973, we set up a two-parameter spectrometer at the University of Maryland cyclotron and measured the neutron spectrum at 0° from 71-MeV deuteron bombardment of a thick carbon target. The dynamic range of the recoil-proton energies that could be measured was limited by the available apparatus to a ratio of about 5 to 1. Since the neutron beam was unidirectional, it was possible to analyze the data by both one- and two-parameter techniques. The one-parameter measurement, which has been proven, served as a standard for comparison of the two-parameter measurement. Agreement of the results obtained by the one- and two-parameter analysis techniques confirms the principle of the two-parameter spectrometer. Appendix A is a detailed description of this experiment.

b. Establishment of an Improved Technique for Subtracting Backgrounds in Unidirectional Neutron Spectral Measurements

We have established an improved technique for subtracting carbon background from spectral measurements of neutrons incident

unidirectionally on the two-parameter spectrometer. Previously, we have determined carbon background from separate spectral measurements with NE-102 and NE-228 first detectors in the manner described by Madey and Waterman (1973a). A principal advantage of the improved technique is that only one spectral measurement is required with either scintillator type. Also, the carbon subtraction technique employing separate spectral measurements with NE-102 and NE-228 first detectors degrades the statistical uncertainty in the measurement by about a factor of 2 whereas the improved technique does not. Another advantage of the carbon subtraction technique with the two-parameter spectrometer is that it rejects also a major fraction of the background from the accidental coincidences that occur in the measurements with the one-parameter spectrometer; thus, the two-parameter spectrometer can measure unidirectional neutrons in a higher background environment or from an accelerator with a poorer duty cycle than possible previously with the one-parameter spectrometer. This improved technique is described in Section 4 of Appendix A.

c. Design and Construction of a Linear Gate and Stretcher with a Large Dynamic Range

Commercially available linear gate and stretchers do not have a dynamic range adequate to measure the recoil-proton pulse-height spectrum in an omnidirectional spectral measurement

over the neutron energy region from a few MeV to about 150 MeV. Such a measurement requires the capability to measure recoil proton energies over the region from about 1 MeV to 150 MeV. In NE-102 plastic scintillator, recoil-proton energies of 1 and 150 MeV give a light output equivalent to 0.75 MeV and 125 MeV electrons, respectively; hence, the dynamic range of the recoil-proton pulse height spectrum is about 170 to 1. A linear gate and stretcher module has been designed and constructed for this purpose that is linear for photomultiplier anode pulses from 25 millivolts to 15 volts, thus giving a potential dynamic range of 600 to 1. The development of this improved linear gate and stretcher is described in Appendix B.

d. Design, Procurement, and Construction of Large
Scintillation Counters for Neutron Skyshine Measurements

A large 10 in. by 10 in. by 4 in. thick NE-102 plastic scintillation counter was designed, procured, and tested for the measurement of neutron skyshine at the Brookhaven Alternating Gradient Synchrotron. This scintillator was used successfully in a simulated omnidirectional neutron spectral measurement at the University of Maryland cyclotron in March 1974. An aluminum chamber for encapsulating a 10 in. by 10 in. by 4 in. thick NE-228 liquid scintillator has been designed and constructed at Kent State University. This aluminum chamber is designed so that the liquid scintillator is in direct contact with the photomultiplier.

These large scintillators are described further in Appendix B.

e. Specification, Procurement, and Test of a Transportable On-Line Data Acquisition System

A transportable on-line data acquisition system was specified, procured, and tested. The system consists of a PDP 11/15 computer and extended memory with a total of 24K (16 bit) words of core memory, four analog-to-digital converters, a magnetic tape unit, and peripheral equipment including a teletype, live-time clock, control panel, and display scope. This system was successfully transported to the University of Maryland for a recent experiment. The on-line data acquisition system is described further in Appendix C.

f. Measurement of a Simulated Omnidirectional Neutron Spectrum with the Two-Parameter Spectrometer

In March 1974, we tested the two-parameter spectrometer by measuring the neutron spectrum at 0° from 82 MeV deuteron bombardment of a thick beryllium target at the University of Maryland cyclotron. To simulate an omnidirectional spectral measurement, separate measurements were made with the neutron beam incident on the spectrometer at angles of 20°, 45°, and 70°. These data are presently being analyzed. A more detailed description of the technical approach and some preliminary observations are given in Appendix D.

g. Measurement of Neutron Spectra of Interest for Neutron Radiotherapy and Neutron Irradiation Studies of Biological Systems

During the past year, we measured the spectra of neutrons produced at 0° from 71 MeV deuteron bombardment of a thick carbon target and from 82 MeV deuteron bombardment of a thick beryllium target at the University of Maryland cyclotron. Spectral measurements of these neutron beams are of current interest for potential application in neutron radiotherapy. Dr. George Harrison at the University of Maryland Medical School is currently using the cyclotron at College Park to conduct neutron irradiation studies of biological systems. The spectrum obtained from 71 MeV deuteron bombardment of a thick carbon target is shown in Fig. 10 of Appendix A.

h. Preliminary Design Study for an On-Line Data Acquisition System at LAMPF

A preliminary design study was made for an on-line spectrometer for monitoring the neutrons generated by the LAMPF beam stop. This design study was stimulated by Los Alamos personnel, particularly Dr. Walter Green, at the 1973 Summer Study Group on Practical Applications of Accelerators. Such an on-line monitor is needed for neutron radiation damage studies to be conducted at LAMPF with neutrons produced in the main beam stop. This preliminary

study indicates that the one-parameter spectrometer developed by Madey and Waterman (1973a) may be usefully applied at LAMPF. Recent progress indicates that the two-parameter spectrometer may be better suited to monitor the neutrons generated by the LAMPF beam stop. As described in item (b), the two-parameter spectrometer can measure unidirectional neutron spectra in a higher background environment or from an accelerator with a poorer duty cycle than possible previously with the one-parameter spectrometer. This advantage is particularly important for applications at LAMPF on account of the poor duty cycle there.

i. Preliminary Thin Target Measurements at the University of Maryland

A preliminary measurement of the neutron spectrum at 45° from 100 MeV proton bombardment of a $30 \text{ mg/cm}^2 \text{ Ni}^{58}$ target at the University of Maryland cyclotron indicates that it is feasible to measure neutron spectra from thin targets at this facility.

j. Presentations at Scientific Meetings

Richard Madey and F. M. Waterman, "Neutron Spectrometry from 200 MeV to 1 GeV", Bull. Am. Phys. Soc. 18, 617 (1973).

Richard Madey and F. M. Waterman, "Neutron Spectral Measurements in the Region from 5 to 724 MeV," Summer Study Group on Practical Applications of Accelerators, Clinton P. Anderson Meson Physics Facility, 27-31 August 1973.

Walter Green, Edward Knapp, Richard Madey, Tom Blewitt, Donald Cochran, and Dean Cen, Participants in a Round Table Discussion at the Summer Study Group on Practical Applications of Accelerators, Clinton P. Anderson Meson

Physics Facility, 27-31 August 1973.

Richard Madey and F. M. Waterman, "Neutron Spectra at 0° from 724 MeV Protons on Be and Cu," Bull. Am. Phys. Soc. 18, 1420 (1973).

R. Madey, F. M. Waterman, A. Baldwin, and N. S. Wall, "Neutron Spectrum at 0° from 71 MeV Deuteron Bombardment of a Thick Carbon Target", Bull. Am. Phys. Soc. 19, (to be presented at the Pittsburgh meeting, 31 Oct.-2 Nov. 1974).

k. Papers Published During the Past Year

R. Madey and R. M. Waterman, "Neutron Spectrometry from 1 MeV to 1 GeV", Proceedings of the IAEA Symposium on Neutron Monitoring for Radiation Protection Purposes, Vol. I, Vienna, Austria, 11-15 December 1972, (International Atomic Energy Agency, Vienna, 1973) pp. 113-121.

R. Madey and F. M. Waterman, "High-Energy Neutrons Produced by 740 MeV Protons on Uranium", Physical Review C 8, 2412 (1973).

F. M. Waterman and R. Madey, "Neutron Spectra at 0° from 724 MeV Protons on Be and Cu", Physical Review C 8, 2419 (1973).

Richard Madey and F. M. Waterman, "A Time-of-Flight Spectrometer for Neutrons from about 150 MeV to 1 GeV," Nuclear Instruments and Methods 114, 483 (1974).

Alan R. Baldwin and Richard Madey, "A Useful 350 Megashertz Scaler", Rev. Sci. Inst. 45, 711 (May 1974).

3. Activities in Progress

Activities in progress include the following:

a. Analysis of data from the March 1974 measurements at the University of Maryland

- (1) Simulated omnidirectional spectrum measurement using the neutron beam at 0° from 82 MeV deuteron bombardment

of a thick beryllium target.

(2) Preliminary thin target neutron spectral measurement.

b. Preparation for experiments at particle accelerators

(1) Measurement of the neutron skyshine and skyshine source spectrum at the Brookhaven AGS.

(2) Measurement of the neutron production from stopped negative pions at the Columbia University Nevis Cyclotron Laboratory.

(3) Measurement of the neutron production from proton bombardment of thick and thin targets at the University of Maryland cyclotron.

c. Preparation of manuscripts for presentation and/or publication

(1) Neutron spectrum at 0° from 71 MeV deuteron bombardment of a thick carbon target.

(2) An improved spectrometer for unidirectional neutron spectral measurements in the region from 5 to 150 MeV.

d. Studies of Spectrometer Applications

(1) An on-line spectrometer for monitoring the neutrons generated by the LAMPF beam stop.

(2) Thin and thick target neutron spectral measurements at the University of Maryland cyclotron.

(3) The leakage neutron spectrum above the Brookhaven 200 MeV proton linac water shield tank.

4. Contract Compliance

The principal investigator devoted at least 15 percent of his time during the 1973-1974 academic year and one 1973 summer session and full-time during another 1973 summer session to the project. To the best of our knowledge, there have been no failures to comply with the contract requirements.

5. Bibliography

This bibliography lists papers, presentations, preprints, and reports prepared under Contract AT (11-1) - 2231. Reprints of documents COO-2231-1 through COO-2231-10 are appended to our progress report (COO-2231-11) for the period 1 April 1972 through 31 March 1973. Reprints of documents COO-2231-12 through COO-2231-21 are appended to this progress report (COO-2231-21).

COO-2231-1

Neutron Spectrometry from 1 MeV to 1 GeV, Richard Madey and F.M. Waterman, International Atomic Energy Agency Reprint IAEA/SM-167/47, IAEA Symposium on Neutron Monitoring for Radiation Protection Purposes, Vienna, Austria, 11-15 December 1972.

COO-2231-2

Neutron Spectrometry from 1 MeV to GeV, Remarks prepared for presentation on 11 December 1972 by Richard Madey at the International Atomic Energy Agency Symposium on Neutron Monitoring for Radiation Protection Purposes at Vienna, Austria.

COO-2231-3

High-Energy Neutrons Produced by 740 MeV Protons on Uranium, Richard Madey and F.M. Waterman, Bull. Am. Phys. Soc. 17, 581 (April 1972).

COO-2231-4

High-Energy Neutrons Produced by 740 MeV Protons on Uranium, Remarks prepared for presentation by Richard Madey at the Washington, D.C., meeting of the American Physical Society on 27 April 1972.

COO-2231-5

High-Energy Neutrons Produced by 740 MeV Protons on Uranium, Remarks prepared for presentation by Richard Madey at a physics colloquium at the Los Alamos Scientific Laboratory on 4 May 1972, and also at the summer study session for the Indiana University Cyclotron Facility at Boulder, Colorado, 12-16 June 1972.

COO-2231-6

The Response of NE-228 Liquid Scintillator to 3.5, 5.8, and 10.5 MeV Protons, R. Madey and F.M. Waterman, Nucl. Instr. and Meth. 104, 253-256 (1972).

COO-2231-7

A Time-of-Flight Spectrometer for Neutrons from 1 MeV to 500 MeV, Richard Madey and Frank M. Waterman, Nucl. Instr. and Meth. 106, 89-101 (1973).

COO-2231-8

Neutron Spectrometry from 200 MeV to 1 GeV, Richard Madey and F.M. Waterman, Bull. Am. Phys. Soc. 18, 617 (April 1973).

COO-2231-9

High-Energy Neutrons Produced by 740 MeV Protons on Uranium, Frank M. Waterman, Ph.D. Dissertation Abstract, Clarkson College of Technology (May 1973).

COO-2231-10

A 350 Megahertz Decade Scaler, Alan R. Baldwin and Richard Madey.

COO-2231-11

Energetic-Neutron Spectrometry, Richard Madey and Frank M. Waterman, Progress Report for the period 1 April 1972 through 31 March 1973.

COO-2231-12

Neutron Spectrometry from 200 MeV to 1 GeV, Remarks prepared for presentation by Richard Madey at the Washington, D.C. meeting of the American Physical Society on 24 April 1973.

COO-2231-13

Neutron Spectral Measurements in the Region from 5 to 724 MeV, Richard Madey and F.M. Waterman, Proceedings of the Summer Study Group on Practical Applications of Accelerators, Clinton P. Anderson Meson Physics Facility, 27-31 August 1973 (to be published).

COO-2231-14

Neutron Spectral Measurements in the Region from 5 to 724 MeV, Remarks prepared for presentation by Richard Madey at the Summer Study Group on Practical Applications of Accelerators, Clinton P. Anderson Meson Physics Facility on 31 August 1973.

COO-2231-15

Neutron Spectra at 0° from 724 MeV Protons on Be and Cu, Richard Madey and F.M. Waterman, Bull. Am. Phys. Soc. 18, 1420 (1973).

COO-2231-16

Neutron Spectra at 0° from 724 MeV Protons on Be and Cu, Remarks prepared for presentation by Richard Madey at the Bloomington, Indiana meeting of the American Physical Society on 3 November 1973.

COO-2231-17

Neutron Spectrometry from 1 MeV to 1 GeV, R. Madey and F.M. Waterman, Proceedings of the IAEA Symposium on Neutron Monitoring for Radiation Protection Purposes, Vol. I, Vienna, Austria, 11-15 December 1972, (International Atomic Energy Agency, Vienna, 1973) pp. 113-121.

COO-2231-18

High-Energy Neutrons Produced by 740 MeV Protons on Uranium, R. Madey and F.M. Waterman, Physical Review C 8, 2412 (1973).

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Neutron Spectra at 0° from 724 MeV Protons on Be and Cu, F.M. Waterman and R. Madey, Physical Review C 8, 2412 (1973).

COO-2231-20

A Time-of-Flight Spectrometer for Neutrons from about 150 MeV to 1 GeV, Richard Madey and Frank M. Waterman, Nuclear Instruments and Methods 114, 483-487 (1974).

COO-2231-21

Energetic-Neutron Spectrometry, Richard Madey, Frank M. Waterman, and Alan Baldwin, Progress Report for the period from 1 April 1973 to 30 April 1974

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- 1973a: and F. M. Waterman, A Time-of-Flight Spectrometer for Neutrons from 1 to 500 MeV, Nucl. Instr. and Meth. 106, 89.
- 1973b: and F. M. Waterman, High-Energy Neutrons Produced by 740-MeV Protons on Uranium, Phys. Rev. C 8, 2412.
- 1974: and F. M. Waterman, A Time-of-Flight Spectrometer from about 150 MeV to 1 GeV, Nucl. Instr. and Meth. 114, 483.

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Appendix A

Experimental Confirmation of the Principle of the Two-Parameter Measurement Technique

Appendix A

Experimental Confirmation of the Principle of the Two-Parameter Measurement Technique

1. Introduction

Madey and Waterman (1973) have described previously a time-of-flight spectrometer for measuring unidirectional neutrons from 1 to 500 MeV. This spectrometer measures a single parameter, namely, the flight-time of a neutron scattered between two scintillation counters. Since the direction of the incident neutron is known, the orientation of the spectrometer axis with respect to the incident neutron direction determines the neutron scattering angle θ . Non-relativistically, the incident neutron energy T is given by

$$T = T_n / \cos^2 \theta \quad (1)$$

Here T_n is the scattered neutron kinetic energy, which is determined from the neutron flight-time.

We have modified this spectrometer to measure a second parameter, namely, the energy of the recoil proton in the first detector in addition to the flight-time of the scattered neutron. The incident neutron energy is then determined from the sum of the recoil proton energy T_p and the scattered neutron energy T_n as

$$T = T_n + T_p \quad (2)$$

As shown by Eq. (2), the measurement of the incident neutron energy is independent of the angle of incidence on the spectrometer. Since a neutron can scatter from a proton in the first detector

through an angle ranging from 0 to 90°, neutrons incident on the spectrometer in the forward hemisphere can scatter into the second detector. Thus, the spectrometer measures the spectrum of omnidirectional neutrons integrated over the forward hemisphere. The angle of incidence θ of a neutron with respect to the spectrometer axis can be determined from the kinematic relation

$$\theta = \tan^{-1} (T_p/T_n) \quad (3)$$

Since the angle of incidence for each event can be determined from the measured recoil-proton and scattered neutron energies, the events can be compiled also to give the differential energy spectra within specified angular intervals about the spectrometer axis.

In July, 1973, we set up a two-parameter spectrometer at the University of Maryland cyclotron and measured the neutron spectrum at 0° from 71 MeV deuteron bombardment of a thick carbon target. The objectives of this measurement were to confirm the principle of the two-parameter spectrometer, and to make a thick-target neutron spectrum measurement of interest to the University of Maryland biomedical program. Since the neutron beam is unidirectional, the technical approach was to analyze the data by both one- and two-parameter techniques. The one-parameter technique, which has been proven, serves as a standard for comparison of the two-parameter measurement.

For this measurement we used small $2\frac{1}{2}$ in. diam by $2\frac{1}{2}$ in. high first detectors and recorded the data on magnetic tape with the University of Maryland's IBM 360/44 on-line computer. The dynamic range of the recoil-proton energies that could be measured was limited by the available apparatus to a ratio of about 5 to 1. Also, we were limited by the dimensions of the first detector to spectral measurements in which the angle of incidence of the neutron beam on the spectrometer was small. At large angles of incidence, a significant percentage recoil-protons would escape the $2\frac{1}{2}$ in. diam first detector. If the recoil-proton escapes, the measured recoil-proton energy is less than the true energy resulting in an erroneous value for the incident neutron energy T and the angle of incidence.

2. Experimental Arrangement

Figure 1 is a diagram of the experimental arrangement at the University of Maryland cyclotron. The 71-MeV deuteron beam was stopped in a 3-inch thick carbon target. Neutrons emitted in the forward direction passed also through a $7/8$ -inch thick beryllium target located about 20-inches downstream. The beryllium target remained in place from a previous experiment. As shown in Fig. 2, the beryllium target was backed with a $7/16$ -inch thick aluminum plug and encased in an aluminum cylinder 3-inches in diameter by 2-inches thick. In addition to the beryllium target and aluminum target holder, the neutrons emitted in the forward direction passed also through a $1/8$ -inch thick aluminum vacuum window located in front of

FIG. 1 Experimental arrangement at the University of Maryland cyclotron.

FIG. 2. Diagram of the beryllium target and aluminum casing.

the entrance aperture of collimator. The neutrons emitted at 0° were viewed through a steel collimator 3 1/2 in. diam by 42 in. long embedded in the 70-inch thick cyclotron shielding wall. The deuteron beam intensity was monitored by integrating the charge deposited in the target.

The neutron spectrum at 0° was measured with a spectrometer consisting of two scintillation counters shown as D1 and D2 in Fig. 1. The D1 detector was centered in the neutron beam 6.5 meters from the carbon target. The D2 detector was positioned 2.5 meters from D1 and at an angle of 30° with respect to the direction of the incident neutrons. The D1 detector consisted of a 2 1/2 in. diam by 2 1/2 in. high NE-102 or NE-228 scintillator mounted on an Amperex 56 DVP photomultiplier by means of a 1 1/2 high tapered lucite light pipe. The D2 detector consisted of a 5 in. diam by 4 in. thick NE-102 scintillator mounted on an Amperex 58 AVP photomultiplier. The D1 detector was biased at 3 MeV proton energy; the D2 detector at 5 MeV proton energy. At a threshold of 5 MeV proton energy, the neutron detection efficiency of D2 was typically 15 percent for incident neutrons from 10 to 70 MeV.

3. Measurements

In accordance with procedures described by Madey and Waterman (1973), we made separate spectral measurements with NE-228 and NE-102 D1 detectors. Each spectral measurement included simultaneous measurements of the spectrum of neutrons plus background, and the spectrum of only the background from accidental or chance coincidences.

We shall refer to this latter spectrum as the spectrum of accidentals and the former as the spectrum of reals plus accidentals. The spectrum of accidentals was measured with a separate delayed coincidence circuit in the manner described previously by Madey and Waterman (1973):

Two-parameters were recorded for each coincidence between events in the D1 and D2 detectors. The recorded parameters were the pulse-height in the D1 detector and the time interval between the interactions in D1 and D2. These data for each event were recorded on magnetic tape at the output of the 360/44 IBM on-line computer at the cyclotron facility. The scheme for gating the D1 detector photomultiplier anode pulse has been described previously by Madey and Waterman (1972).

Measurements containing more than 50,000 real events were made with each of the above scintillator types for the D1 detector. The count rate of real events was typically 15 counts/sec with a beam current of 25 nanoamperes.

4. Backgrounds

The two primary sources of background in the spectral measurement are the neutron-carbon interactions in the D1 detector and the chance or accidental coincidences between uncorrelated events in the D1 and D2 detectors. Previously, we have determined neutron-carbon background from separate spectral measurements with NE-102 and NE-228 first detectors in the manner described by Madey and Waterman (1973). In this section, we describe an improved technique for subtracting

carbon background applicable to two-parameter spectral measurements of neutrons incident unidirectionally on the spectrometer. A principal advantage of this improved technique is that it requires only one spectral measurement with either the NE-102 or the NE-228 first detector. Also, the former carbon subtraction technique increases the uncertainty of the spectral measurement by about a factor of 2, whereas the new technique does not. Another advantage of the two-parameter carbon subtraction technique is that it rejects also a major fraction of the background from the accidental coincidences that occur in the one-parameter measurement.

In the present experiment, we measured the energy of the recoil proton T_p and the energy of the scattered neutron T_n . The geometry of the detectors define the neutron scattering angle θ_g for each event to within $\pm 1.0^\circ$. For n-p elastic scattering events, the neutron scattering angle is given also by the non-relativistic expression.

$$\theta_k = \tan^{-1}(T_p/T_n)^{1/2} \quad (4)$$

We use subscripts on the neutron scattering angle to distinguish that defined by the geometry from that calculated through the kinematic relation. The technique for subtracting background from neutron-carbon interactions consists of calculating the neutron scattering angle from Eq. (4) for each event and rejecting those events for which the calculated scattering angle does not agree with that defined by the geometry of the detectors. To meet this requirement, a neutron-carbon interaction in D1 that produces a neutron with energy

T_n detectable in D2 must be accompanied by a light output in D1 equivalent to a recoil proton with energy $T_p = T_n \tan^2 \theta_g$. In other words, to be accepted as an n-p elastic scattering event, the measured proton and scattered neutron energies must have the energy ratio $T_p/T_n = \tan^2 \theta_g$. Since carbon inelastic reactions that produce a neutron and a charged particle are many-bodied, there is no kinematic requirement for the "proton" and neutron energies to occur in the above ratio required for n-p elastic scattering; hence, it is expected that this restriction will reject most neutron-carbon background events. Later we will present experimental evidence supporting this expectation.

Also, the rejection of events that do not give a neutron scattering angle corresponding to that for n-p elastic scattering reduces the background of accidental coincidences. This reduction in the background of accidental coincidences is expected because the accidental coincidences arise from uncorrelated events in the first and second detectors which have a wide range of recoil proton and scattered neutron kinetic energies.

Figure 3(a) is a compilation of the neutron scattering angles obtained from Eq. (4) for each event in the neutron spectrum measured with the NE-228 D1 detector. Similarly, Fig. 3(b) is a compilation of the neutron scattering angles obtained for each event in the background spectrum of accidental coincidences. The distribution of neutron scattering angles for the real events is obtained by subtracting the background distribution shown in Fig. 3(b) from that shown in

FIG. 3 The distribution of neutron scattering angles given by
 (a) the spectrum of real plus accidental coincidences and
 (b) the spectrum of accidental coincidences measured with
 the NE-228 first detector.

Fig. 3(a). Figures 4(a) and 4(b) are the distributions of neutron scattering angles obtained for the real events only in the spectral measurements made separately with the NE-228 and NE-102 DI detectors. In both Figs. 4(a) and 4(b), the distribution of neutron scattering angles consists of a well defined peak centered at 29.5° with "tails" extending down to about 10° and up to about 50° .

The fact that both distributions are centered at 29.5° indicates that the second detector was positioned at an angle of 29.5° with respect to the neutron beam rather than at 30° . The full-width at half-maximum (fwhm) of the distribution shown in Fig 4(a) is about 4° ; that in Fig. 4(b) is about 3° . The difference in the widths of the distributions reflects the poorer pulse-height resolution of the NE-228 detector in comparison with the NE-102 detector. (We discuss the energy resolution of these two detectors in the next section.) For a Gaussian distribution, the fwhm is equal to 2.35 standard deviations. Assuming the distributions of neutron scattering angles are Gaussian, we find that the standard deviation of the distribution shown in Fig. 4(a) is 1.7° and that shown in Fig. 4(b) is 1.3° .

Now we describe how we established the angular interval of neutron scattering angles corresponding to n-p elastic scattering. We used the criterion that the angular interval include at least 99% of the n-p elastic scattering events. Assuming that the distribution of neutron scattering angles is Gaussian, we find that 99% of the events will occur within 2.58 standard deviations, which

FIG. 4 The distribution of neutron scattering angles for real events only in spectral measurements with (a) the NE-228 and (b) the NE-102 detectors.

, corresponds to the full-width at 0.036 of maximum. Since the data is compiled in a histogram with bin widths of 1° , it is convenient for processing the data to select angular intervals that include an integral number of bins. The intervals selected are from 25° to 34° for the distribution of scattering angles shown in Fig. 4(a) and from 26° to 33° for the distribution shown in Fig. 4(b). Each of these intervals corresponds to about 2.7 standard deviations and includes more than 99% of the n-p elastic scattering events.

By inspection of Fig. 4, we see that the tails of the distribution deviate from a Gaussian distribution. About 6% of the events in Fig. 4(a) are outside the interval from 25° to 34° . Similarly, about 15% of the events in Fig. 4(b) are outside the interval from 26° to 33° . The events outside the intervals defined for n-p elastic scattering are attributed to background from neutron-carbon interactions in the D1 detector. Since NE-228 has a higher hydrogen-to-carbon ratio than NE-102, less carbon background is expected in the spectral measurement made with the NE-228 D1 detector.

In the following paragraph, we present experimental evidence that the events which give neutron scattering angles outside the interval defined above for n-p elastic scattering can be attributed to carbon background. We deliberately made separate spectral measurements with NE-102 and NE-228 first detectors in order to calculate the carbon background from these measurements in the manner described previously by Madey and Waterman (1973). Then we compared the percentage of carbon background events calculated in this

manner from the NE-102 and NE-228 spectral measurements with the percentage of background events in each spectral measurement that give neutron scattering angles outside the interval defined for n-p elastic scattering. In Table I, we list the percentage of carbon background obtained from the NE-102 and NE-228 subtraction technique at detector thresholds of 3, 5, and 7 MeV proton energy. The uncertainties listed in Table I reflect the uncertainty in normalizing the NE-102 and NE-228 spectral measurements.

In Table II, we list for the same detector thresholds the percentage of the total number of events in the NE-102 and NE-228 spectral measurements that give neutron scattering angles outside the intervals defined for n-p elastic scattering. In Table II, the uncertainties represent the statistical uncertainty in the number of events. Except for the NE-228 spectral measurement at a detector threshold of 3 MeV proton energy, the values in Tables I and II agree within one standard deviation. This agreement indicates that those events which give neutron scattering angles outside the intervals corresponding to n-p elastic scattering can be attributed to neutron-carbon interactions. The fact that the difference between corresponding numbers in Tables I and II is small or zero indicates that the percentage of carbon background events that give neutron scattering angles within the interval defined for n-p elastic scattering is small.

TABLE I

The percentage of carbon background at detector thresholds of 3, 5, and 7 MeV proton energy determined from separate spectral measurements with NE-228 and NE-102 first detectors in the manner described by Madey and Waterman (1973).

<u>Threshold in</u> <u>Proton Energy (MeV)</u>	<u>Carbon Background (%)</u>	
	<u>NE-228 Detector</u>	<u>NE-102 Detector</u>
3	10.1 $\pm$ 1.9	17.9 $\pm$ 3.1
5	5.8 $\pm$ 1.8	10.7 $\pm$ 3.2
7	1.1 $\pm$ 1.7	2.3 $\pm$ 3.3

TABLE II

The percentage of events that give neutron scattering angles outside the intervals* defined for n-p elastic scattering.

<u>Threshold in</u> <u>Proton Energy (MeV)</u>	<u>Percentage of Events (%)</u>	
	<u>NE-228 Detector</u>	<u>NE-102 Detector</u>
3	6.1 ± 1.1	15.1 ± 0.7
5	3.1 ± 1.2	9.4 ± 0.7
7	1.4 ± 1.0	3.2 ± 0.8

*Angular intervals defined for n-p elastic scattering are: $25^\circ \leq \theta \leq 34^\circ$ for NE-228 and $26^\circ \leq \theta \leq 33^\circ$ for NE-102.

From Figs. 3(a) and 3(b), it can be seen that the rejection of all events that do not give neutron scattering angles within the interval defined for n-p elastic scattering will reject also a major fraction of the background from accidental coincidences that occur in the one-parameter measurements. In the present experiment, about 75% of the accidental coincidences are rejected in this manner. The background of accidental coincidences remaining in the n-p elastic scattering region is removed by subtracting the energy spectrum given by the accidental coincidences from that of the real events plus accidentals. This additional criterion for subtracting accidental coincidences permits the two-parameter spectrometer to measure unidirectional neutrons in a higher background environment than possible previously with the one-parameter spectrometer.

5. Energy Resolution

In this section, we compare the energy resolution of the one- and two-parameter spectral measurements. In the one-parameter analysis of the data, the incident neutron energy is determined from Eq. (1):

$$T = T_n / \cos^2 \theta \quad (1)$$

Here T_n is the scattered neutron energy and θ is the neutron scattering angle. Applying the law of propagation of small errors to Eq. (1), we find that the relative uncertainty in the measurement of the incident neutron energy can be written as

$$\Delta T/T = [(\Delta T_n/T_n)^2 + (2 \tan \theta \Delta \theta)^2]^{1/2} \quad (5)$$

Here $\Delta \theta$ is the uncertainty in the neutron scattering angle as a result of the finite dimensions of the D1 and D2 detectors, and $\Delta T_n/T_n$ is the relative uncertainty in the measurement of scattered neutron energy defined as

$$\Delta T_n/T_n = 2[(\Delta x/x)^2 + (\Delta t/t)^2]^{1/2} \quad (6)$$

Here $\Delta x/x$ is the relative uncertainty in the flight-path as a result of the finite dimensions of the detectors, and $\Delta t/t$ is the relative uncertainty in the flight-time as a result of the intrinsic time dispersion of the system.

In the two-parameter analysis, the incident neutron energy is determined from Eq. (2):

$$T = T_n + T_p \quad (2)$$

Here T_n and T_p are the measured scattered neutron and recoil proton kinetic energies, respectively. The relative uncertainty in the measurement of the incident neutron energy by the two-parameter technique can be expressed as

$$\Delta T/T = [(\frac{\Delta T_n}{T_n} \cdot \frac{T_n}{T})^2 + (\frac{\Delta T_p}{T_p} \cdot \frac{T_p}{T})^2]^{1/2} \quad (7)$$

Since $T_n = T \cos^2 \theta$ and $T_p = T \sin^2 \theta$, Eq. (7) can be rewritten as

$$\Delta T/T = [(\frac{\Delta T_n}{T_n} \cos^2 \theta)^2 + (\frac{\Delta T_p}{T_p} \sin^2 \theta)^2]^{1/2} \quad (8)$$

To calculate the energy resolution of the two-parameter spectrometer, we need a general expression for the relative uncertainty $\Delta T_p/T_p$ in the measurement of the recoil proton energy. Such an expression can be derived from the pulse-height resolution observed in the Compton spectra of monoenergetic gamma-rays in the manner described in the following paragraph.

Figure 5 is a plot of the Na-22 Compton spectrum of observed with the 2½ in. diam by 2½ in. h. NE-228 liquid scintillator. The Compton peak is taken to correspond to the maximum Compton electron energy produced by the associated gamma-ray. For Na-22, the Compton peak corresponds to the 1.06 MeV electron energy. As shown in Fig. 5, the Compton peak is located at channel 33.5 ± 1.5 ; the half-maximum at channel 42.5. In Fig. 6, we have plotted the channel numbers corresponding to peaks of Mn-54, Na-22, and Th-228 gamma-ray sources versus the corresponding electron energies of 0.64, 1.06, and 2.39 MeV respectively. The solid line drawn through the Compton peak positions gives the electron energy T_e corresponding to each channel of the pulse-height spectra. From this plot, we can determine the electron energy corresponding to the channel number of the half-maximum of a Compton peak and the corresponding pulse-height resolution $\Delta T_e/T_e$ in electron energy, where ΔT_e is the half-width at half-maximum of the Compton peak in electron energy. Table III lists the pulse-height resolutions in electron energy determined from

FIG. 5. Sodium-22 Compton spectrum observed with a 2½ in. diam by 2½ in. ht. NE-228 liquid scintillator.

FIG. 6 Plot of the positions of the Compton peaks observed with Mn-54, Na-22, and Th-228 gamma-ray sources verses the corresponding electron energy of the Compton peak.

TABLE III

Pulse - height resolution in electron energy determined from Mn-54, Na-22, and Th-228 gamma-ray sources for the 2½ in. diam. by 2½ in. ht. NE-228 and NE-102 scintillators used in the July 1973 neutron spectral measurement at the University of Maryland.

<u>Gamma Source</u>	<u>Electron Energy T_e (MeV)</u>	<u>Resolution, $\Delta T_e/T_e$ (%)</u>	
		<u>NE-228</u>	<u>NE-102</u>
Mn-54	0.64	30.0	14.7
Na-22	1.06	26.8	12.6
Th-228	2.39	24.0	10.7

Mn-54, Na-22, and Th-228 gamma-ray sources for the 2½ in. diam by 2½ in. h. NE-102 and NE-228 scintillation counters used in the present experiment.

Garlick and Wright (1952) have shown that the distribution of pulse-heights at the output of the photomultiplier may be represented by a Gaussian function with a width that varies approximately as the square-root of the mean output pulse height. In Fig. 7, we have plotted the pulse-height resolution $\Delta T_e/T_e$ in electron energy versus $T_e^{-1/2}$. As Fig. 7 indicates, the pulse height resolution in electron energy can be represented by a straight line of the form

$$\Delta T_e/T_e = a T_e^{-1/2} + b \quad (9)$$

For the NE-228 and NE-102 scintillators used in the present experiment, the constants a and b in Eq. (9) above have the following values:

<u>Scintillator</u>	<u>a</u>	<u>b</u>
NE-228	0.096	0.177
NE-102	0.068	0.061

By substituting the above values of the constants a and b into Eq. (9), we can determine the pulse-height resolution $\Delta T_e/T_e$ for any given electron energy T_e .

Figure 8 relates the electron energy to the proton energy for the same light output in an NE-102 and an NE-228 scintillator. The solid curve delineates the response of NE-102 scintillator calculated by Gooding and Pugh (1960, 1961) and verified experimentally by Madey and Waterman (1972). The dashed curve delineates the response of NE-228

FIG. 7 Pulse height resolution in electron energy of the 2½ in. diam. by 2½ in. high NE-102 and NE-228 first detectors used in the July 1973 spectral measurement at the University of Maryland cyclotron.

FIG. 8 Relationship between the electron energy and the proton energy for the same light output in an NE-102 and an NE-228 scintillator.

scintillator measured by Madey and Waterman. In Fig. 8, we illustrate the relationship of the pulse-height resolution in proton energy $\Delta T_p/T_p$ to that in equivalent electron energy $\Delta T_e/T_e$. It is evident from Fig. 8 that for the same light output, the pulse-height resolution $\Delta T_p/T_p$ in proton energy is better than that $\Delta T_e/T_e$ in equivalent electron energy.

In Table IV, we list the pulse-height resolution in proton energy of the 2½ in. diam by 2½ in. h. NE-228 and NE-102 scintillators used in the July 1973 neutron spectral measurement at the University of Maryland for 3, 5, 10, and 15 MeV recoil-protons. The values listed in Table IV were obtained by first determining the electron energy T_e corresponding to T_p from Fig. 8 and then determining the pulse-height resolution $\Delta T_e/T_e$ in electron energy from Eq. (9). The corresponding pulse-height resolution $\Delta T_p/T_p$ was then determined graphically from $\Delta T_e/T_e$ using Fig. 8.

Figure 9 is a plot of the values listed in Table IV for the pulse-height resolution $\Delta T_p/T_p$ in proton energy versus $T_p^{-1/2}$. As Fig. 9 indicates, the pulse height resolution in proton energy can be represented by a straight line of the form

$$\Delta T_p/T_p = c T_p^{-1/2} + d \quad (10)$$

where the constants c and d have the following values.

TABLE IV

Pulse-height resolution in proton energy of the 2½ in diam by 2½ in. ht. NE-228 and NE-102 scintillators used in the July 1973 neutron spectral measurement at the University of Maryland for 3, 5, 10, and 15 MeV recoil-protons.

Proton Energy, T_p (MeV)	Resolution, $\Delta T_p/T_p$ (%)	
	NE-228	NE-102
3	18.3	11.6
5	16.0	9.0
10	15.0	7.0
15	14.5	6.0

FIG. 9 Pulse-height resolution in proton energy of the $2\frac{1}{2}$ in diam by $2\frac{1}{2}$ in high NE-102 and NE-228 first detectors used in the July, 1973, spectral measurement at the University of Maryland cyclotron.

<u>Scintillator</u>	<u>c</u>	<u>d</u>
NE-228	0.079	0.124
NE-102	0.165	0.017

By substituting the appropriate values for the constants c and d in Eq. (10), we have a general expression for the uncertainty $\Delta T_p/T_p$ in the measurement recoil-proton energy. This expression can be used in Eq. (10) to calculate the energy resolution of the two-parameter spectrometer.

In Table V, we list the values of the energy resolution calculated from Eq. (5) for the one-parameter spectrometer and from Eq. (10) for the two-parameter spectrometer. Values of the two-parameter spectrometer are given for both NE-102 and NE-228 DI detectors. The values of the energy resolution listed in Table V indicate that the resolution of two-parameter measurement with the NE-228 DI detector is similar to that of the one-parameter measurement and that of the two-parameter measurement with NE-102 DI detector is somewhat better than the one-parameter measurement.

6. Analysis

Analysis of the data proceeded through five basic steps: (1) Calculation of the neutron scattering angle for each event and the rejection of those events that do not correspond to n-p elastic scattering. (2) Determination of the incident neutron energy for each event by one- and two-parameter techniques. (3) Compilation of histograms of the one- and two-parameter energy spectra. The spectra of the reals plus accidentals and that given by the

TABLE V

Energy resolution of the one- and two-parameter spectral measurements with $2\frac{1}{2}$ in. diam by $2\frac{1}{2}$ in. high NE-102 and NE-228 D1 detectors for neutron energies from 10 to 70 MeV.

<u>Incident Neutron</u>		<u>Spectrometer Energy Resolution, $\Delta T/T$ (%)</u>	
<u>Energy, T (MeV)</u>	<u>One-Parameter</u>	<u>Two-Parameter (NE-102)</u>	<u>Two Parameter (NE-228)</u>
10	4.7	4.6	5.5
20	5.2	4.5	5.5
30	5.6	4.6	5.6
40	6.0	4.8	5.8
50	6.5	5.1	6.0
60	6.8	5.3	6.2
70	7.1	5.5	6.4

The above values of the energy resolution were calculated from Eqs. (5) and (10) for the following parameters: $x = 250$ cm, $\Delta x = 5.1$ cm, $\theta = 29.5^\circ$, $\Delta\theta = 1.0^\circ$, $\Delta t = 0.8$ nsec.

accidental coincidences were compiled in separate histograms. (4)

Subtraction of the energy spectrum given by the accidental coincidences from that of the reals plus accidentals. (5) Determination of the energy spectrum in absolute units. Steps (1) through (4) have been described earlier or do not require further elaboration. In the following paragraph, we describe step (5), the determination of the spectrum in absolute units of the neutron yield $Y(T, \Omega)$ in units of neutrons/deuteron-MeV-sr.

The neutron yield $Y(T, \Omega)$ in units of neutrons/deuteron-MeV-sr for each energy interval δT of the spectrum is given by the expression

$$Y(T, \Omega) = \frac{X_T^2 R(T)}{N_d n_H \Omega V \epsilon_2(T') (d\sigma/d\Omega)(T, \theta) G(T) \delta T} \quad (11)$$

where X_T is the distance between the centers of the target and the D1 scintillator, $R(T)$ is the number of events observed in the energy interval δT centered at the incident neutron energy T , N_d is the total number of deuterons incident on the target during the measurement, n_H is the numerical density of hydrogen in the D1 scintillator, Ω is the solid angle subtended by the D2 scintillator at the center of the D1 scintillator, V is the volume of the D1 scintillator, $(d\sigma/d\Omega)(T, \theta)$ is the laboratory differential n-p scattering cross section for scattering a neutron with energy T through an angle θ , $G(T)$ is the total neutron attenuation factor for incident and scattered neutrons in D1, $\epsilon_2(T')$ is the neutron detection efficiency of the D2 detector for scattered neutrons with energy T' and δT is the energy width of the interval.

The energy spectrum in absolute units is determined by calculating the neutron yield Y for each interval of the energy spectrum from Eq. (11). The energy independent terms in Eq. (11) have the following values: $X_T = 647$ cm, $N_d = 5.7 \times 10^{14}$ deuterons, $n_H = 6.6 \times 10^{22}$ H atoms/cm³, $\Omega = 2.0 \times 10^{-3}$ steradians, and $V = 176.3$ cm³. Values of the energy dependent terms $\epsilon_2(T')$, $\frac{d\sigma}{d\Omega}(T, \theta)$, and $G(T, \theta)$ are listed in Table VI for neutron energies from 10 to 70 MeV. The determination of these energy dependent terms has been described previously by Madey and Waterman (1973).

7. Results

The absolute neutron spectra determined from one- and two-parameter analysis of the data are plotted in Fig. 10. For clarity, error bars designating the statistical uncertainty in the measurement are shown for the one-parameter analysis only. Since each spectrum contains the same number of events, the statistical uncertainty of the two-parameter measurement is equivalent to that of the one-parameter measurement. Except for the fact that the peak appears to be somewhat sharper in the one-parameter analysis, the one- and two-parameter analysis of the data are in good agreement. In each case, the neutron spectrum exhibits an approximately symmetric peak at about 31 MeV with a full-width at half-maximum of about 20 MeV. The agreement of the spectra obtained by the one- and two-parameter analysis techniques confirms the principle of the two-parameter spectrometer.

TABLE VI

Values of the energy dependent terms $\varepsilon_2(T')$, $\frac{d\sigma}{d\Omega}(T, \theta)$ and $G(T, \theta)$ for incident neutron energies from 10 to 70 MeV.

Neutron Energy, <u>T (MeV)</u>	<u>$\varepsilon_2(T')$ (%)</u>	<u>$\frac{d\sigma}{d\Omega}(T, \theta)$ (mb/sr)</u>	<u>$G(T, \theta)$ (%)</u>
10	16.1	268	49.5
20	16.5	137	56.9
30	15.3	83.1	62.7
40	14.4	56.5	68.4
50	14.8	41.7	72.9
60	15.2	32.4	76.4
70	15.1	26.3	79.2

FIG. 10. Neutron spectrum at 0° from 71-MeV deuteron bombardment of a thick carbon target analyzed by one- and two- parameter techniques.

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Appendix B

Development of the Two-Parameter Spectrometer

Appendix B

Development of the Two-Parameter Spectrometer

1. Introduction

As described in Appendix A, the principle of the two-parameter measurement technique was confirmed experimentally by a spectral measurement at the University of Maryland in July 1973. Development of the spectrometer since that time has proceeded along two lines: the development of a linear gate and stretcher with a large dynamic range, and the development of large detectors for neutron skyshine measurements. In Section 2, we describe the large first detectors for neutron skyshine measurements. In Section 3, we describe the improved linear gate and stretcher.

2. Description of Large First Detectors for Skyshine Measurements

Distenfeld (1973) estimates that the flux densities of skyshine neutrons vary with the locations selected outside the shield from about 0.1 to 1 and perhaps up to 5 neutrons/cm²-sec. To obtain a practical count rate in a low-flux environment, it is necessary to improve the spectrometer efficiency by using larger first detectors. While increasing the detector dimensions enhances the count rate, it degrades also the energy resolution of the spectrometer; therefore, the detector dimensions represent a compromise between count rate and energy resolution. Consideration must also be given to the relationship between neutron attenuation and the thickness of the first detector. The mean free-path for nuclear interactions of 10 MeV incident neutrons is 9.7 cm in NE-102 plastic scintillator and

10.13 cm in NE-228 liquid scintillator. For spectral measurements down to 10 MeV, the first detector thickness should not exceed about 10 cm to avoid severe neutron attenuation.

Based on the above considerations, the dimensions of the first detector were selected to be 10 in. by 10 in. by 4 in. thick. In Appendix A of our renewal proposal for the period from 1 September 1974 to August 31, 1975, we show that when used in conjunction with the 9 in. diam by 8 in. thick second detector and a 1.5 meter flight-path, a 10 in. by 10 in. by 4 in. NE-102 first detector will give a count rate of about 2 counts per minute for an incident neutron flux density of $0.1 \text{ n/cm}^2\text{-sec}$ above 10 MeV.

Large area first detectors also have the advantage of reducing edge effects caused by energetic recoil-protons that escape the first detector. Madey and Waterman (1974) have presented a graph of the included angle between the recoil proton and scattered neutron in the first detector for neutron energies up to 1 GeV. This included angle is about 90° independent of the energy of the incident neutron. Since neutrons that scatter from the first detector into the second detector are directed parallel to the spectrometer axis, the recoil-protons are always directed approximately perpendicular to the spectrometer axis; hence, the larger the lateral dimensions of the first detector, the smaller will be the percentage of recoil-protons that have sufficient range to escape the first detector.

Figure 1 is a sketch of a 10 in. by 10 in. by 4 in. thick NE-102 plastic scintillator procured from Nuclear Enterprises Inc.[†] As

[†]Nuclear Enterprises, Inc., 935 Terminal Way, San Carlos, California 94070.

FIG. 1 Sketch of the 10 in. by 10 in. by 4 in. NE-102 plastic scintillator and tapered lucite light pipe.

shown in Fig. 1, the scintillator is bonded to a lucite light pipe that tapers from a 10 in. by 4 in. cross section to a 4 in. by 2 in. cross section over a height of 6 inches. Figure 2 is a plot of Mn-54, Na-22, and Th-228 Compton spectra measured with the 10 in. by 10 in. by 4 in. thick NE-102 scintillator. The spectra shown in Fig. 2 were recorded with the scintillator mounted on an Amperex 58 AVP photomultiplier operated at 1.8 kv. Below, we list the radioactive gamma-ray energy, the equivalent-electron energy T_e of the Compton peak, and the pulse-height resolution $\Delta T_e/T_e$ in electron energy for each of the Compton spectra shown in Fig. 2.

Radioactive Nuclide	Gamma Energy T_γ (MeV)	Equivalent-Electron Energy, T_e (MeV)	Pulse-Height Resolution, $\Delta T_e/T_e$ (%)
Mn-54	0.84	0.64	36
Na-22	1.28	1.06	27
Th-228	2.62	2.39	20

Comparison of the above values of the pulse-height resolution with those listed in Table III in Appendix A for the 2½ in. diam by 2½ in. high NE-102 scintillator show that the pulse-height resolution of the much larger 10 in. by 10 in. by 4 in. NE-102 scintillator is only about a factor of 2 poorer than that of the 2½ in. diam by 2½ in. high scintillator. The 10 in. by 10 in. by 4 in. NE-102 scintillator was tested recently in a spectral measurement at the University of Maryland. These data are currently being analyzed.

FIG. 2 The Compton spectra of Mn-54, Na-22, and Th-228 gamma-ray sources observed with the 10 in. by 10 in. by 4 in. NE-102 plastic scintillator.

After encountering long delays in procuring a 10 in. by 10 in. by 4 in. NE-228 liquid scintillator, we decided to construct the detector at Kent State University. Figure 3 is a sketch of the aluminum chamber constructed to encapsulate the liquid scintillator. The light output of NE-228 liquid scintillator is only about 70% that of NE-102 plastic scintillator. In an effort to improve the pulse-height resolution of the NE-228 detector, the aluminum cell was designed so that the photomultiplier is in direct contact with the liquid scintillator. This design reduces the number of interfaces between the scintillator and photomultiplier and eliminates light attenuation that would occur in a light pipe. To optimize the light collection, the interior of the aluminum chamber was painted with white reflector paint. The 10 in. by 10 in. sides of the chamber are constructed of 1/8-inch thick aluminum; the 10 in. by 4 in. sides of 1/4-inch thick aluminum; and the 10 in. by 4 in. ends of 1/4-inch thick aluminum. A 3 in. diam by 1 in. high cylindrical chamber serves as an expansion chamber. The performance of this detector has not yet been tested.

FIG. 3 Sketch of the construction of the 10 in. by 10 in. by 4 in. NE-228 scintillator counter.

3. A Linear Gate and Stretcher with a Large Dynamic Range

Commercially available linear gate and stretchers do not have an adequate dynamic range to measure the recoil-proton pulse-height spectrum in a spectral measurement of omnidirectional neutrons from a few MeV to about 150 MeV. In such a measurement, the dynamic range of recoil-proton pulse-heights is expected to be about 170 to 1. In this section, we describe a linear gate and stretcher that has been designed and constructed for photomultiplier anode pulses from 25 millivolts to 15 volts, thus giving a potential dynamic range of 600 to 1.

The circuit of the linear gate and stretcher module is divided into four separate circuits: two gate and stretcher cards, a selector card, and an amplifier card. The circuit first converts the input pulse voltage to a current pulse. The current pulse amplitude will be limited by the circuit if the current exceeds a preset maximum value. The current pulse is then gated by a diode gate and linearly integrated by a low capacitance stretching capacitor. Two gate and stretcher cards are used to achieve a potential dynamic range of 600 to 1. The first card is designed for operation with input voltages from 25 millivolts to 1 volt; the second from 0.5 volt to 15 volts. The stretcher cards are linear to within $\pm 1\%$ over their respective regions. The selector card monitors the pulse-heights of the gate and stretcher cards and determines when to switch from the low level (25 millivolt

to 1 volt) output signal to the high level (0.5 volt to 15 volts) output signal. This selection is accomplished by a Schmitt trigger voltage discriminator which monitors the low level signal and switches to the high level signal at a specified voltage level. The output level of each card is matched so that the difference in gain between the two channels is less than 1%, providing a linear response over a dynamic range of input pulse heights of 600 to 1. The output amplifier card provides fixed gains of 1, 2, 4, 8, and 16 with an output impedance of 10 ohms. The linear gate and stretcher output signal is suitable for direct connection to the input of an analog-to-digital converter.

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Appendix C

The On-Line Data Acquisition System

Appendix C

The On-Line Data Acquisition System

The transportable on-line data acquisition system[†] is a computer-based system for data acquisition, display, and manipulation based on the Digital Equipment Corporations (DEC) PDP 11 computer. Peripheral modules are added to the system to perform the required functions. The UNIBUS hardware structure of the PDP-11 provides a standardized data exchange path between all system components. This UNIBUS feature permits expansion with a minimum of effort and allows the user to build the system to almost any level of sophistication.

At present, the data acquisition system contains the following major subsystems:

- a. PDP 11/15 Central Processing Unit (CPU)
- b. Core Memory
- c. Teletypewriter
- d. System Control Panel
- e. Nuclear Data Inputs
- f. Display Unit
- g. Magnetic Tape Unit

These subsystems are shown in Fig. 1 connected to the UNIBUS data path. The PDP 11/15 CPU is the operational center of the system. The

[†] Tennecomp Systems TP-5000

Fig. 1 Schematic diagram of the on-line data acquisition system.

CPU provides decision making, data manipulation, and the interfacing between the remaining subsystems. The system contains 24 thousand 16 bit words of core memory used to store data and operate programs. The teletypewriter provides a convenient path for transferring data between the user and the computer system. The system control panel provides a compact arrangement of knobs, switches, and buttons to operate the pulse-height analyzer system and to control the display unit, the nuclear data inputs, the magnetic tape unit, and other user defined operations. The nuclear data inputs are 4 analog to digital converters (ADC's). These ADC's may be used separately to record 4 single parameter spectra simultaneously or in combinations to record 2, 3, or 4 parameter spectra. The display unit provides a visual view of the data being processed by the system. A light pen permits the user to interact with the system. The tape unit provides a means of storing large amounts of data and the system programs. A single tape can store hundreds of times more data than the core memory.

The data acquisition system may be disassembled into four sections for shipping. Below, we list the weight of each of these sections.

<u>Section</u>	<u>Weight (lbs.)</u>
a. Teletypewriter	50
b. Magnetic Tape Unit	150
c. Central Processor and Memory Unit	150
d. Display, Control Panel and Data Input	300

Items c and d above may be broken down in to smaller packages less than 50 pounds in weight. The power requirement of the data acquisition system is 15 amperes at 120 volts A.C. or 1.8 kilowatts.[†] The floor space required for the data acquisition system and operator is about 8 ft. by 8 ft.. The system is 5½ ft. high.

[†] The power requirement of the data acquisition system plus the electronic apparatus of the spectrometer is 3.6 kilowatts.

Appendix D

Test of the Two-Parameter Spectrometer

Appendix D

Measurement of a Simulated Omnidirectional Neutron Spectrum with the Two-Parameter Spectrometer

In March 1974, we tested the ability of the two-parameter spectrometer to measure the spectrum of neutrons incident omnidirectionally on the spectrometer. For this test, we used a collimated beam of neutrons produced at 0° from 82 MeV deuteron bombardment of a thick beryllium target at the University of Maryland cyclotron. To simulate a spectral measurement of omnidirectional neutrons, measurements were made with the neutron beam incident on the spectrometer at angles of 20° , 45° , and 75° . The experimental arrangement for each of these measurements is shown schematically in Figs. 1 (a), (b), and (c). Only the spectrometer orientation with respect to the neutron beam was changed; all other parameters remained the same. Since the neutron beam incident on the spectrometer at angles of 20° , 45° , and 70° was the same, the final spectrum obtained from each measurement should also be the same even though the range of the recoil-proton and scattered neutron energies in each measurement are significantly different; for example, a 50 MeV neutron incident at an angle of 20° produces a 6 MeV recoil-proton, whereas a 50 MeV neutron incident at 70° produces a 44 MeV recoil-proton. Figure 2 is a trace of the one-dimensional time-of-flight spectra obtained with the neutron beam incident at angles of 20° , 45° , and 70° . The different spectral shape obtained for each measurement reflects the different range of scattered neutron energies present.

FIG. 1. The experimental arrangement used at the University of Maryland cyclotron to simulate an omnidirectional spectral measurement. Spectral measurement were made with the neutron beam incident on the spectrometer at angles of (a) 20°, (b) 45°, and (c) 70°.

FIG. 2. One-parameter neutron time-of-flight spectra recorded with the neutron beam incident on the spectrometer at angles of 20, 45, and 75°.

The fact that each measurement must give the same final result provides a severe test of the system and of the ability to correct for the energy and angular dependence of the spectrometer efficiency. These data are currently being analyzed.