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EXPERIMENTALLY DETERMINED PROTON-RECOIL SPECTRA IN TISSUE-EQUIVALENT MATERIAL FROM 3 AND 15 MeV NEUTRONS

G. F. Stone
J. H. Thorngate

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EXPERIMENTALLY DETERMINED PROTON-RECOIL
SPECTRA IN TISSUE-EQUIVALENT MATERIAL
FROM 3 AND 15 MeV NEUTRONS*

G. F. Stone and J. H. Thorngate

ABSTRACT

An experiment was conducted to measure the energy spectrum of charged particles produced as a function of position in a tissue-equivalent phantom irradiated with monoenergetic 3 or 15 Mev neutrons. The charged particles were measured with semiconductor detectors that were covered with a thin coating of Marvethane to protect them from the sugar-urea tissue-equivalent solution. One detector was a surface barrier transmission type, and the other was a Li-drifted Si detector in the shape of a cube. The second detector had four sides which had no dead layer so that recoil O, N, and C ions were measured as well as recoil protons. Data obtained are consistent with theories of neutron moderation. Careful measurements were made to determine the contribution of n,p and n, α reactions in the detectors and the effects of neutrons scattered from the walls and floor surrounding the experimental set up. These contributed less than 10% under worst case conditions. The data obtained will be compared with the results of a computational program now underway to verify the calculations.

1. INTRODUCTION

One of the best known methods of determining the actual energy liberated in hydrogenous materials by fast neutrons involves observing the recoil protons produced. Since the distribution of proton energies is related to the incident neutron energy and the geometry of the system, the amount of energy lost by a neutron as it traverses a given distance in the hydrogenous material can be determined by obtaining the spectral distribution of the recoil protons along its track.

*Research sponsored by the U. S. Atomic Energy Commission under contract with the Union Carbide Corporation.

In the past, a number of experimental and theoretical studies of the proton-recoil technique were conducted using proportional counters and parallel-plate ion chambers [Rossi and Staub (1949)]. Perlow (1956) conducted experimental and theoretical proton-recoil studies for neutron energies between 0.05 Mev and 1 Mev, using methane-filled proportional counters. Johnson and Trail (1956) studied the proton spectra produced by neutrons in the energy range from 2 Mev to 20 Mev, using proportional counters and a scintillation detector. Barr and Hurst (1954) have used proportional counters inside a tissue-equivalent phantom to determine the depth-dose distribution due to neutrons from a polonium-beryllium source.

In recent years, attention has been given to the use of semiconductors to study recoil protons produced by neutron interactions in tissue or tissue-equivalent materials. The advantages of using semiconductors over proportional counters or scintillation detectors are their high resolution and compact size. Davy and Peshori (1966) have reported on an absolute neutron dosimeter in which a polyethylene radiator is placed in contact with a semiconductor and irradiated by monoenergetic neutrons and fission neutrons. Eldridge, Flusser, and Ritchie (1962) used a digital computer code to calculate the proton-recoil energy losses from neutron irradiation of hydrogenous systems exhibiting plane geometry. In both investigations, the results were applicable to the generalized concept of radiation dosimetry developed by Hurst and Ritchie (1962).

The objective of this work was to measure the recoil-proton spectra produced by 3 and 15 Mev monoenergetic neutrons from the $^2\text{D}(\text{D},\text{n})^3\text{He}$ and $^3\text{T}(\text{D},\text{n})^4\text{He}$ reactions respectively. Spectra were obtained by inserting specially adapted semiconductors into a tissue-equivalent phantom irradiated

by neutrons produced by a 200 kv particle accelerator. Two semiconductor detectors of different sensitive depths were used in order to span the proton energy spectrum from approximately 0.2 Mev to 14 Mev.

2. THEORY

When neutrons of energy less than 20 Mev undergo collisions in tissue, the predominant interaction is elastic scattering with protons. In soft tissue, this interaction is predominant because: (1) most of the tissue atoms are hydrogen (almost two thirds); and (2) the scattering cross section for hydrogen is larger than for any other element in tissue [Hine and Brownell (1956)]. Consequently, between 85% and 95% of the energy transferred to tissue by neutrons is due to the recoil protons from hydrogen.

2.1 Mechanism of Neutron-Proton Interaction

The actual mechanism of the recoil-proton event is indicated by the vector diagram given in Fig. 2.1. In the laboratory coordinate system, a neutron of velocity V_o and energy E_o undergoes a scattering collision and is deflected at some angle ϕ , with velocity V_n . The initial energy of the unscattered neutron is given by

$$E_o = \frac{1}{2} M V_o^2. \quad (1)$$

The resulting recoil proton moves out in the direction θ with a velocity V_p .

In the center of mass coordinate system (indicated in Fig. 2.1 by the primes), if the particles have equal mass, conservation of energy and momentum requires that the two colliding particles go out with equal velocity in opposite directions. Since for the case of hydrogen, the masses of the incident neutron and the target nucleus are almost equal, the velocity

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Fig. 2.1. Recoil Proton Vector Diagram.

of the center of mass system can be expressed by:

$$V_g = \frac{1}{2} V_o = V'_p = V'_n \quad (2)$$

so that $\theta' = 2\theta$. In the laboratory system, however,

$$V_p^2 = V_p'^2 + V_g^2 + 2V'_p V_g \cos \theta' \quad (3)$$

from the law of cosines.

Equation (3) can be written as

$$V_p^2 = \frac{1}{4} V_o^2 + \frac{1}{4} V_o^2 + 2 \left(\frac{V_o}{2} \right) \left(\frac{1}{2} V_o \right) \cos \theta' \quad (4)$$

using the equalities in (2).

Simplifying (4) gives

$$V_p^2 = \frac{1}{2} V_o^2 + \frac{1}{2} V_o^2 \cos \theta' \quad (5)$$

$$= \frac{1}{2} V_o^2 (1 + \cos \theta') \quad (6)$$

$$= \frac{1}{2} V_o^2 (1 + \cos 2\theta). \quad (7)$$

$$\text{Since } \cos 2\theta = 2 \cos^2 \theta - 1, \quad (8)$$

$$V_p^2 = V_o^2 \cos^2 \theta. \quad (9)$$

Now if both sides of equation (9) are multiplied by one-half of the particle mass, the energy of the recoil proton is obtained as

$$E(\theta) = E_o \cos^2 \theta. \quad (10)$$

2.2 Energy Distribution of Recoil Protons in Hydrogen

Zimmerman et al. (1962), in their work with semiconductor spectrometers for neutron detection, developed an analytical treatment for the energy distribution of recoil protons from hydrogen alone. To find the energy distribution, one assumes that the scattering angle θ' , as shown in Fig. 2.1, is random. (Since $\phi' = \pi - \theta'$, then ϕ' must be random in the same manner.) Let the volume of hydrogenous radiator be a solid sphere of unit radius as indicated by Fig. 2.2, and let the protons emerge isotropically from the center of the sphere. The fraction of protons passing through the solid angle defined by the cone $d\theta'$ about θ is just the ratio of the areas of the element of cone area $2\pi r \sin \theta' d\theta'$, and the total surface area of the unit sphere. Hence for a sphere of unit radius

$$N(\theta') d\theta' = \frac{2\pi \sin \theta' d\theta'}{4\pi} = \frac{\sin \theta' d\theta'}{2}. \quad (11)$$

Transforming from the center of mass system to the laboratory system, one obtains the fraction of protons produced in $d\theta$ about θ as

$$N(\theta) d\theta = N(\theta') \frac{d\theta'}{d\theta} d\theta = \frac{\sin 2\theta}{2} d\theta \quad (12)$$

$$= 2 \sin \theta \cos \theta d\theta. \quad (13)$$

The energy distribution is readily obtained by making use of equations (10) and (13) since

$$E = E_0 \cos^2 \theta. \quad (14)$$

Then

$$dE = -E_0 2 \cos \theta \sin \theta d\theta, \quad (15)$$

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Fig. 2.2. Cone of Solid Angle.

and

$$\frac{d\theta}{dE} = - \frac{1}{E_0 2 \cos \theta \sin \theta} \quad (16)$$

Hence

$$N(E) dE = N(\theta) \frac{d\theta}{dE} dE \quad (17)$$

$$= - \frac{2 \sin \theta \cos \theta d\theta}{E_0 2 \sin \theta \cos \theta} \quad (18)$$

$$= - \frac{dE}{E_0} \quad (19)$$

2.2.1 Range-Energy Relationship

An empirical range-energy relationship of the form

$$R = K E_0^\gamma \quad (20)$$

was used by Hurst et al. (1951) in their study of recoil protons from polyethylene and paraffin. R is the proton range in centimeters, E_0 is the initial proton energy in Mev, and K and γ are constants. Zimmerman and his co-workers used this empirical expression to develop theoretical treatments of emitted recoil-proton spectra from plane polyethylene radiators for two specific cases: (1) an isotropic monoenergetic neutron fluence, and (2) a collimated, monoenergetic neutron fluence of normal incidence. For purposes of brevity, only the first case will be discussed.

2.2.2 Isotropic Monoenergetic Neutron Case

A proton liberated in some hydrogenous material such as polyethylene has an initial energy E_0 . After traveling some distance d , it will have

sufficient energy to go an additional distance $R-d$. Then from equation (2)

$$(R-d) = KE_1^Y \quad (21)$$

or, using both equations (20) and (21), one obtains the distance the proton travels as

$$d = K(E_0^Y - E_1^Y). \quad (22)$$

If a plane hydrogenous radiator is placed in a neutron flux $\phi(E_n)$, assumed to be constant throughout the material, the number of recoil protons produced per unit volume of the radiator is

$$n = N\phi(E_n)\sigma \quad (23)$$

where N is the number of protons per unit volume and σ_H is the elastic scattering cross section for hydrogen.

A proton produced with energy E_0 at a depth x in the radiator at an angle θ with the normal will be emitted from the surface of the radiator with energy E_1 satisfying the equation [making use of equation (22)]

$$\frac{x}{\cos\theta} = K(E_0^Y - E_1^Y) \quad (24)$$

provided $\frac{x}{\cos\theta} < KE_0^Y$.

Since the case under discussion involves isotropic, monoenergetic neutrons, the protons produced will be emitted in all directions in the radiator with equal probability in the center of mass system and thus with energies which follow the cosine squared law, varying from $E = 0$ to $E = E_0$ in the laboratory system. This condition can be expressed as the emission rate of protons produced per unit area of radiator in an element dx about x ,

within an angle $d\theta$ about θ , and in the energy range dE about E , or

$$N(x, \theta, E) dx d\theta dE = \frac{n}{2E_0} \sin \theta d\theta dx dE. \quad (25)$$

Now in order for a proton to emerge from the radiator's surface and be detected, it must be produced initially with energy $E_0 \geq E_1$ and at a depth no greater than

$$x = K \cos \theta (E_0^\gamma - E_1^\gamma). \quad (26)$$

Then the total rate of protons emitted from one surface of the radiator with energy $E_0 > E_1$ can be found by integrating equation (25) over appropriate ranges of E , θ , and x , or

$$N(E_0 \rightarrow E_1) = \int_{E_1}^{E_0} N(E) dE. \quad (27)$$

Putting in appropriate limits of integration, we have

$$\int_{E_1}^{E_0} N(E) dE = \int_{\theta=0}^{\frac{\pi}{2}} \int_{E=E_1}^{E=E_0} \int_{x=0}^{x=K \cos \theta (E^\gamma - E_1^\gamma)} N(x, E, \theta) dx dE d\theta \quad (28)$$

$$= \frac{n}{2E_0} \int_0^{\frac{\pi}{2}} \int_{E_1}^{E_0} \int_0^{K \cos \theta (E^\gamma - E_1^\gamma)} \sin \theta dx dE d\theta \quad (29)$$

$$= \frac{nK}{4E_0} \left[\frac{E_0^{\gamma+1}}{\gamma+1} + \frac{\gamma E_1^{\gamma+1}}{\gamma+1} - E_1^\gamma E_0 \right]. \quad (30)$$

The rate of production of protons between energy E and some energy $E + dE$ can be found by taking the negative derivative of equation (30) with respect to E_1 , or

$$N(E) = \frac{d}{dE} N(E_0 \rightarrow E_1) \quad (31)$$

$$= \frac{\gamma n K}{4 E_0} (E_0 - E_1) E_1^{\gamma-1}. \quad (32)$$

Equation (32) is the differential form of the proton spectrum which might be anticipated from an infinitely thick hydrogenous radiator. This equation, although used by several previous investigators, is based on the assumption that all of the protons liberated in the radiator are due to elastic scattering in hydrogen alone. To a first approximation, this assumption gives good agreement with experimentally determined spectra. For tissue, a better approximation of the energy spectrum involves taking into account the heavy ion recoils from carbon, oxygen, and nitrogen, and the n,p reactions with atoms of oxygen and nitrogen, both of which make up a large portion of the human body. Secondly, if a silicon detector is used to measure the proton spectra produced by neutrons of energy greater than 6 Mev, n,p and n, α reactions in the detector itself must be considered. Both of these factors were taken into account in this experiment and are discussed in Chapters 5 and 6.

3. EXPERIMENTAL APPARATUS AND PROCEDURES

3.1 Method of Irradiation

Fast neutrons for the spectrum measurements were produced by a Texas Nuclear Corporation Model 9999 neutron generator. The neutron generator produces monoenergetic fast neutrons by means of bombarding either a tritium or deuterium target with deuterons accelerated through a potential of about 200 kv. Fast neutrons are produced by the following reactions:

Using the deuterium target, the D-D reaction produces 3.0 Mev neutrons, and with the tritium target, the D-T reaction produces 15 Mev neutrons at 0° with respect to the incident proton beam. Figure 3.1 is a photograph of the neutron generator and target area with the phantom in position.

The phantom consisted of a 30-cm-diam by 60-cm-high cylindrical tank fabricated from 1/8-in. aluminum sheet. This size was selected to approximate the size of the torso of an average man. It was filled with a solution of sucrose, urea and water in proportions that resulted in an atomic composition very near that of average wet human tissue [Barr and Hurst (1954)]. A comparison of the percent by weight composition of the phantom solution and that reported by Lea (1947) for average wet tissue is given in Table 3.1.

3.1.1 Phantom Arrangement and Reference Grid

For irradiation, the tank was located in reference to the source of neutrons as shown in Fig. 3.2. In the production of 3.0 Mev neutrons, there are both energy and intensity losses as a function of the center of mass scattering angle shown in Fig. 2.1 [Fowler and Brolley (1956)]. However, for the accelerating energies used, the loss in either energy or intensity is only a few percent. The 15 Mev neutrons were assumed to be isotropic from the target.

A grid over the top of the phantom was established to position the detectors for irradiations. The grid (shown in the inset in Fig. 3.2) consisted of six reference points on 5-cm centers along the beam axis and

Fig. 3.1. Accelerator and Target Area.

Table 3.1. Compositions of Phantom Solution
and Average Wet Human Tissue

Element	Phantom Solution Percent by Weight	Average Wet Tissue Percent by Weight
Oxygen	74	73
Carbon	12	12
Hydrogen	10	10
Nitrogen	4	4
All other elements: (Na, P, S, etc.)	0	1
Total	100	100

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Fig. 3.2. Arrangement of Phantom for Irradiation.

perpendicular thereto. Thus, volume elements 5 cm in diam by 60 cm long were formed, varying in depth from 2.5 cm to 27.5 cm in the phantom. Measurements were made with the detectors inserted into each of these volume elements, at varying heights, from the top of the phantom downward. Irradiations were made for each of the neutron energies given previously, and each irradiation was normalized using a modified long counter [Auxier (1963)] as a counting standard. To determine the contribution from neutrons scattered from the floor and shielding walls of the generator target area, a shadow cone, made of borated paraffin, was inserted in the line of the direct neutron beam to block all primary neutrons from the phantom and detector array. Measurements were made with and without the shadow cone in place for each neutron energy.

3.2 Detectors

When a charged particle enters a silicon semiconductor detector, it creates free electron-hole pairs by losing energy at the rate of 3.6 electron volts per electron-hole pair. This rate of charge carrier formation is nearly independent of particle energy and ionization density over a wide range of energies; therefore, the detector response is linear to an equally wide range of energies provided the sensitive depth of the detector exceeds the range of the particle, and the applied electric field is sufficient to prevent recombination. The electron-hole pair in semiconductors is analogous to the negative-positive ion pair in gases, so that the semiconductor can be thought of as a miniature ion chamber.

3.2.1 Basic Semiconductor Detector

A typical semiconductor detector is illustrated in Fig. 3.3. In the figure, D is the effective diameter corresponding to the active area of the detector; W is the depth of the sensitive or depletion region; and L is the total thickness of the silicon wafer. A totally depleted detector is one in which the sensitive region extends the full thickness of the device so that the detector is sensitive to ionizing radiation entering from either side.

3.2.2 Experimental Detectors

In this experiment, two specially adapted semiconductor detectors were used to detect the recoil protons. An Edgerton, Germeshausen and Grier Model DSG diffused-junction silicon wafer, with an active area of 3 cm^2 and a sensitive depth of 200μ , was obtained to detect protons in the energy range of 210 kev to 2 Mev. A 1.5-mm, lithium-drifted silicon cube, obtained from the National Bureau of Standards, was used to detect the protons produced by 15 Mev neutrons. The selection of the thicknesses and sizes of the two detectors was based on range-energy considerations. Using a dE/dx value of 18 kev per μ for 3 Mev protons in silicon, it was found that a $200\text{-}\mu$ -thick detector would completely stop the most energetic protons produced by the 3 Mev neutron interactions. Electrons, which are always present in neutron irradiation, would only deposit a maximum energy of 210 kev in the same thickness of silicon [ORTEC (1965)]. Thus, the 210 kev point becomes the threshold, below which any proton pulses produced in the thin detector cannot be seen because of the electron contribution.

The 1.5-mm, lithium-drifted cube detector was selected to extend the sensitive volume or depletion depth beyond the cutoff point in the case of

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Fig. 3.3. Basic Semiconductor Detector.

the thin detector described above. By using a 1.5-mm-thick lithium-drifted detector, the most energetic protons anticipated from the 15 Mev neutron interactions could be completely "stopped" in the detector, using the same range-energy reasoning given previously. However, attendant with the increased energy-measuring capability of the thicker device, there is the disadvantage of increased electron interactions which tend to mask the lower energy proton detection capability of the cube detector. This increased electron noise contribution results in masking out protons of energy below about 1.0 Mev. Thus by overlapping the capabilities of the two detectors, the entire range of recoil protons from threshold (210 kev) to 15 Mev should be obtained.

The two detectors are shown schematically in Fig. 3.4. Both devices were mounted on tissue-equivalent plastic rods fabricated from Shonka plastic [Shonka, Rose, and Failla (1958)]. This type of mount was chosen rather than the conventional ceramic-metal mount so that perturbation of the proton fluence immediately around the detector would be minimized; that is, any neutrons interacting in the mount would produce recoil protons in the same manner as if the interaction occurred in the phantom solution. The composition of the tissue-equivalent plastic is given in Table 3.2.

3.2.3 Detector Surface Coating

Because of the high capacitance characteristic of semiconductors, any extraneous materials touching the sensitive surfaces (gold or aluminum coatings) cause leakage currents and seriously inhibit the detector's performance. Since the nature of this work involved the complete immersion of the detectors in a tissue-equivalent solution with a resistance of 25,000 ohms/cm, it was necessary to coat all exposed

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(a) 200 MICRON DETECTOR (b) 1.5 mm CUBE DETECTOR

Fig. 3.4. Experimental Detectors Showing Mounting Details.

Table 3.2. Composition of Tissue-Equivalent Plastic

Material	Percent by Weight
Carbon	13.50
Polyethylene (C_2H_4)	52.10
Nylon ($C_{12}H_{22}N_2O_2$)	28.20
Silica	2.20
Calcium Fluoride (CaF_2)	4.00

detectors and the conducting plastic mounting rods with an insulating film. The coating chosen was "Marvethane," a polyurethane resin, because of its good insulating properties and because its composition of hydrogen, oxygen, and nitrogen approximates the composition given previously for tissue. The atomic composition of this material is given in Table 3.3. Very thin

Table 3.3. Composition of Marvethane

Element	Atoms per Molecule
Carbon	131
Hydrogen	214
Oxygen	26
Nitrogen	2

coatings (approximately $100 \mu\text{g}/\text{cm}^2$) were applied to all exposed surfaces of each detector assembly following a method used by Muggleton and Parsons (1963).

Each detector was tested under normal operating bias voltages by immersing them in tap water and in a sample of the tissue-equivalent phantom solution. Only a slight increase in the noise level of the detectors was observed.

Since almost all semiconductor detectors are light sensitive, due to photon interactions in the thin surface coatings, it is necessary to operate them in a light tight enclosure. To overcome this difficulty, the entire phantom and detector assembly was shielded from extraneous light by placing a black plastic lid over the phantom top and sealing all crevices with electrical tape. As an added precaution, the assembly was operated with all room light extinguished.

3.3 Electronic Components and Circuitry

As in the case of most detectors of nuclear radiations, the output pulses from a semiconductor detector are small. For example, a 1 Mev proton passing through a typical 1-mm-thick silicon detector produces about 10^5 electron-hole pairs. If the particle transit time is of the order of 10^{-8} sec, the output current from the detector will be of the order of 10^{-6} amp [Price (1964)]. The output currents from different detectors will vary with detector capacitance, applied voltage and type of radiation. To amplify the low-current pulses produced by a semiconductor detector with a high signal-to-noise ratio, it is necessary to use a low-noise preamplifier connected in close proximity to the detector. A charge-sensitive preamplifier makes signal height insensitive to variations in detector capacitance, thus resulting in a more stable drift-free operation.

3.3.1 Basic Detector Circuit

The equivalent circuit for a typical silicon surface-barrier detector together with the first stage of the associated preamplifier is shown in Fig. 3.5. In the figure, C_d is the capacitance of the detector, R_L is the reverse leakage in the detector, and R_s is the diode series resistance, including any contact resistance and the effects of undepletion. R_b is the load resistor through which bias voltage is applied to maintain the necessary electric field across the diode for charge collection. C_s represents all of the stray capacitance in cables, connectors, etc., and C_A is the effective input capacitance of the preamplifier. The signal, produced by a given ionizing event in the diode and a net current flow between the plates of C_d , appears as a pure current source in parallel with C_d .

3.3.2 Data Acquisition

A block diagram of the electronic components used for data acquisition in this experiment is given in Fig. 3.6. Pulse signals from the detector were amplified by a Tenelec Model 100 B preamplifier and model TC200 main amplifier. Bias voltage for the detector was obtained from the main amplifier and was adjusted with a 0- to 500-v, ten-turn potentiometer. Plate and filament voltages for the preamplifier were obtained from +270-v and +6-v regulated power supplies, respectively. Output signals from the main amplifier were analyzed by a Nuclear Data Model ND-130AT, 512-channel analyzer. Accumulated data were read out on punched tapes or typed by an electric typewriter coupled to the analyzer. An ORNL Model Q-1212 Mercury relay pulse generator was used for calibration purposes.

ORNL DWG 66-7044

Fig. 3.5. Equivalent Circuit for Semiconductor Detector.

ORNL DWG 66-7045

Fig. 3.6. Block Diagram of Electronic Components.

3.4 Energy Calibration

A multichannel analyzer is calibrated for a typical uncoated semiconductor detector by exposing the detector to a point-source radionuclide with a discrete particle energy, such as ^{241}Am ($E_{\alpha} = 5.46 \text{ Mev}$) and thus obtaining a reference point in terms of kev/channel with which to compare peaks from radionuclides of unknown energies. Noise level and resolution are also obtained from the recorded pulse-height distribution.

In order to obtain an energy calibration for this experiment, it was necessary to use a "cross-calibration" technique. Since both detectors used were coated with a thin film of insulating material, the normal method of direct calibration would result in errors due to alpha particle energy losses in the film. To overcome this difficulty, an uncoated detector (ORTEC Model SBCJ150) was connected to the experimental system and exposed to a point source of ^{241}Am alpha particles, as shown in Fig. 3.7. Output pulses from the source were analyzed and the pulse information stored in the analyzer. A mercury relay pulser was connected to the system and calibrated at exactly 1.5 v, using a precision potentiometer. The pulser was then used to generate test pulses equivalent to an energy level slightly higher than the ^{241}Am peak. Data from both the source and pulser were then printed out, and the 5.46 Mev α peak and the pulser peak were plotted as shown in Fig. 3.8. By comparing the known energy peak from the alpha standard with the pulser peak, exact placement of the pulser signal peak in terms of kev/channel could be made. Thus the pulser pulse-height setting dial was used as a scale in Mev and became a "secondary standard" with which to compare each spectrum measurement made by the coated detectors.

ORNL DWG 66-7048

Fig. 3.7. Detector-Source Arrangement for Cross Calibration.

Fig. 3.8. Relative Locations of Pulser and Source Peaks.

4. PRESENTATION OF DATA

4.1 Analyzer Operation

Before any of the spectrum measurements were made, all electronic components in the system were balanced and carefully checked for sensitivity and excessive noise. Due to the high detector capacitance in the case of the 3-cm² detector and the attendant preamplifier and cable capacitance, a zero suppression equivalent to 20 channels in the analyzer was used for all measurements made with this detector to overcome excessive analyzer operation on the noise signals. Since the neutron yield from the $^2\text{D}(\text{D},\text{n})^3\text{He}$ reaction was of the order of 10^8 neutrons per sec, each measurement with the 3-cm² detector in the phantom required approximately 60 min of run time. The 1.5-mm cube detector was used for all measurements made with 15 Mev neutrons. Because of its smaller volume, the noise level was much lower in this detector, consequently it was necessary to bias only nine channels of the analyzer. The amplifier gain was lowered by a factor of two, giving each analyzer channel a value of 64 kev for the 15 Mev neutron spectra measurements. The neutron yield in the $^3\text{T}(\text{D},\text{n})^4\text{He}$ reaction was almost 10^{11} /sec, so that shorter run times were achieved for these measurements. Figures 4.1 and 4.2 show the channel displacement for each detector and the value of each channel in kev.

4.2 Experimentally Determined Spectra

4.2.1 3 Mev Neutrons

The results of irradiating the phantom with 3 Mev neutrons are shown in Figs. 4.3 and 4.4. Measurements were made with the detector on the midplane of the phantom, at each of the six reference positions in the

Fig. 4.1. Analyzer Channel Displacement--3 cm² Detector.

Fig. 4.2. Analyzer Channel Displacement--1.5 mm
Cube Detector.

Fig. 4.3. Spectra Variation with Axial Depth in Phantom--3 Mev Neutrons.

Fig. 4.4. Spectra Variation with Lateral Depth in Phantom--3 Mev Neutrons.

grid. The phantom was traversed both axially and normally; that is, measurements were made from front to back and side to side, on 5-cm intervals. Only three positions are shown in Fig. 4.4 for the normal, or side-to-side, traverse. Due to symmetry, measurements made at the first three positions (i.e., positions 1, 2, and 3) were almost identical (within statistical limits) of those for the last three (positions 4, 5, and 6). Since the 3-cm² detector is a thin disc, thereby exhibiting a smaller target for recoil protons incident parallel to its sensitive surfaces, measurements were made with this detector with the larger sensitive surfaces oriented both normal and parallel to the neutron beam. The results of a typical measurement with the detector at a depth of 2.5 cm in the phantom are given in Fig. 4.5. Data for all of the spectrum curves appear in the Appendix. In each of the data tables, the analyzer channel numbers run progressively from 1 to 256 beginning with the second set of digits in the top row. The first set of digits in the top row represents analyzer live-time.

4.2.2 14 Mev Neutrons

Results of measurements made with the 1.5-mm cube detector inserted in the phantom and irradiated by 15 Mev neutrons are given in Figs. 4.6 and 4.7. Again, measurements were made at 5-cm intervals through the phantom, both axially and normal to the neutron beam. It was found that placement of the detector at various heights in the phantom whether at the extreme top or bottom resulted in little change in the spectrum shape. Hence, all spectra shown were taken with the detector located at the phantom midplane.

Fig. 4.5. Directional Response of 3 cm² Detector.

Fig. 4.6. Spectra Variation with Axial Depth in Phantom--15 Mev Neutrons.

Fig. 4.7. Spectra Variation with Lateral Depth
in Phantom--15 Mev Neutrons.

As in the case of normal traverses made with the 3-cm² detector for 3 Mev neutrons, Fig. 4.7 shows the spectra obtained with the 1.5-mm cube detector moved through three positions normal to the neutron beam. The three outer-most positions gave almost identical results to these first three positions.

5. ANALYSIS AND DISCUSSION

5.1 Analysis of Spectra

5.1.1 3 Mev Neutron Case

The lack of useful information in the energy region below 640 kev in the case of the spectra obtained with the 3-cm², 200-μ detector was disappointing. This detector size was chosen originally with the purpose of extending the low energy spectrum measurements to as low as 200 kev. However, the detector proved to be high in leakage-current noise. Figure 4.4 shows a progressive degrading of the energy spectrum by the phantom when irradiated by the lower energy neutrons. The first three depth positions show a steady drop in the spectrum. The three deepest positions (i.e., 17.5 cm, 22.5 cm, and 27.5 cm) show a wider variation in the spectrum shape. This is thought to be due to a combination of moderation, less than desirable detector resolution, and poor statistics. In the latter case, the standard error was typically about 38% for the three deepest positions. This error could have been reduced to some extent by increased neutron-proton interactions in the phantom but would have required prohibitively long accelerator run times. The dotted portions in the curves in all of the figures are drawn to denote uncertainty in the statistical accuracy of low count rates.

5.1.2 15 Mev Neutron Case

The experimental curves shown in Figs. 4.6 and 4.7 show good symmetry and progressive degrading of the proton spectrum for both axial and lateral penetration in the phantom. It is clear from the reduction of the average "hardness" of the spectrum in both Figs. 4.6 and 4.7 that the phantom moderated the higher energy neutrons progressively with depth of penetration. This is in agreement with the theory of neutron moderation found in most good nuclear physics texts [Goldstein (1959)].

Because of the higher neutron yield for the D,T reaction, counting statistics were much better for the 15 Mev case than for the 3 Mev case. The maximum probable error for the 15 Mev case was about 22% over the entire energy range of .64 to 15 Mev. In both Figs. 4.6 and 4.7 the increase in the number of events in the energy region below about 2 Mev is thought to be due to the heavy ion recoils of oxygen, nitrogen, and carbon. Although heavy ion recoils from the phantom solution could not penetrate the detector coating, the coating itself had a significant abundance of carbon, oxygen, and nitrogen. Hence, recoils from neutron interactions with these atoms could enter the detector and deposit all their energy in a short path-length. Analysis and application of this part of the energy spectra could be quite useful in tissue-dose studies. The 1.5-mm cube detector had much better resolution and considerably lower noise than the 3-cm² device, which contributed significantly to the smoothness of the curves for the 15 Mev case.

5.2 Analysis of n,p and n, α Contributions

An indication of the contribution to the total energy spectrum from the n,p and n, α reactions occurring in the silicon cube is shown in

Figs. 5.1 and 5.2. Figure 5.1 shows a comparison of measurements made with the polyurethane-coated cube detector and an uncoated cube detector inserted in the phantom at a depth of 2.5 cm. (In this position the neutron fluence is moderated less than at deeper positions.) The uncoated detector was sealed inside a nonhydrogenous Teflon container with 0.3-in.-thick walls, so that detection of recoil protons occurring outside of the detector would be eliminated. Figure 5.2 is a comparison of measurements made with the two detectors inserted at a depth of 27.5 cm (back side of the phantom). From these figures, it can be seen that the n,p and n,α contributions to the total proton spectrum are less than 10 percent for the 2.5-cm depth position, and less than 2 percent for the deeper, 27.5-cm position. These percentages compare favorably with values obtained by Dearnaley et al. (1962).

5.3 Scattering Measurements

Figure 5.3 shows the placement of the shadow cone relative to the phantom and accelerator target. The cone was designed so that the phantom would be totally enveloped by the "neutron shadow" created by the cone. Measurements were made with the cone in position both for 3 Mev and 15 Mev neutrons for the positions considered to be most sensitive to scattered neutrons. Figures 5.4 and 5.5 show the comparisons of measurements made with and without the shadow cone in position. It was concluded that there was less than one percent scatter for the 3 Mev neutron case and less than 5 percent scatter for the 15 Mev neutron case. These values compare favorably with similar measurements made with proportional counters in the accelerator target area by Johnson (1966).

Fig. 5.1. Comparison of n, p and n, α Contributions--2.5 cm Depth.

Fig. 5.2. Comparison of n,p and n, α Contributions--27.5 cm Depth.

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Fig. 5.3. Arrangement of Phantom and Shadow Cone for Scattering Measurements.

Fig. 5.4. Contribution Due to Scatter--3 Mev Neutrons.

Fig. 5.5. Contribution Due to Scatter--15 Mev Neutrons.

6. CONCLUSIONS AND RECOMMENDATIONS

It is concluded that the 1.5-mm lithium-drifted detector, properly insulated, can be used to measure the proton-recoil spectra in tissue-equivalent material from neutrons up to 15 Mev. The spectra obtained are useful over all energies from 640 kev to about 15 Mev, and the upper energy limit could perhaps be extended with improved detector resolution. The lower energy end of the spectra shows strong evidence of heavy ion recoils resulting from neutron interactions with nitrogen and oxygen and carbon atoms. The spectra show good distribution for both normal and axial detector positioning in the phantom.

By making measurements with a coated detector and an uncoated detector of similar size, the contribution to the total energy spectrum from n,p and n, α reaction due to the 15 Mev neutrons in the silicon can be evaluated and subtracted from the spectrum if necessary.

Use of the 3-cm², 200- μ detector for measurements of the spectra in the energy region below 3 Mev gave reasonably good results. In the low energy region (below 640 kev) excessive noise made it impossible to detect the lower energy protons. It is felt that this difficulty could be overcome by using a detector of smaller sensitive surface area and improved electronic circuitry, including lower capacitance cables and connectors.

Further work in the refinement of detector coating is necessary to minimize leakage currents and still maintain good resolution. The lithium-drifted cube detector could be imbedded directly in tissue-equivalent plastic of the Shonka (1958) type for future measurements.

It is recommended that spectra measurements of this type be extended to other neutron energies and the HP RR fission spectrum. It is also recommended that a computer code be developed, using Monte Carlo techniques, to calculate theoretical spectra so that comparisons with the experimental spectra can be made. If the comparisons show good agreement, computer codes can be developed for numerous applications of proton-recoil energy distributions in tissue-depth-dose studies.

ACKNOWLEDGMENTS

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APPENDIX

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APPENDIX

Table A.1

Analyzer Energy Calibration Data
 Americium-241 Alpha Source
 ORNL Q-1212 Pulser

10200	001571	000593	000338	000295	000234	000188	000205
000166	000160	000117	000104	000074	000060	000049	000049
000058	000044	000049	000038	000043	000028	000040	000046
000040	000042	000048	000043	000042	000030	000041	000041
000047	000041	000039	000041	000039	000045	000043	000048
000028	000025	000046	000038	000031	000042	000036	000048
000047	000044	000036	000051	000038	000044	000041	000040
000040	000041	000057	000060	000053	000048	000055	000041
000059	000039	000045	000062	000061	000063	000045	000068
000068	000052	000052	000069	000056	000055	000060	000075
000058	000056	000062	000060	000060	000075	000083	000079
000072	000069	000067	000088	000083	000062	000076	000088
000088	000108	000095	000084	000075	000099	000120	000095
000088	000089	000103	000097	000098	000090	000119	000116
000108	000132	000130	000141	000128	000131	000138	000145
000147	000140	000172	000151	000153	000161	000167	000195
000184	000195	000202	000218	000211	000278	000247	000250
000288	000286	000335	000290	000343	000347	000358	000434
000423	000486	000510	000581	000604	000665	000762	000829
000813	000829	000862	000850	000778	000841	000925	000967
001046	001176	001352	001400	001678	001943	002327	002690
003459	004192	005185	006704	006953	003758	001090	000145
000061	000055	000055	000069	000056	000087	000083	000054
000042	000058	000061	000086	000095	000121	000167	000196
000186	000030	000003	000001	000001	000001	000002	000003
000003	000001	000000	000000	000001	000002	000003	000002
000002	000001	000002	000001	000001	000001	000002	000001
000003	000002	000001	000000	000002	000000	000002	000002
000000	000002	000001	000000	000000	000002	000001	000001
000003	000001	000001	000000	000002	000000	000001	000003
000001	000000	000003	000002	000001	000003	000001	000001
000002	000001	000003	000001	000003	000000	000000	000001

Position 2

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Table A.2 (Continued)

Position 3

400000	002519	001761	001288	000944	000755	000658	000556
000422	000346	000335	000256	000279	000222	000217	000181
000181	000140	000133	000128	000097	000088	000103	000092
000063	000084	000088	000065	000050	000053	000058	000050
000044	000035	000038	000052	000033	000032	000039	000037
000037	000022	000025	000027	000026	000028	000020	000028
000019	000024	000015	000029	000015	000013	000017	000013
000019	000018	000008	000005	000021	000014	000015	000016
000014	000011	000022	000009	000006	000003	000009	000014
000011	000001	000009	000008	000009	000008	000008	000003
000007	000005	000006	000005	000007	000001	000006	000006
000003	000006	000005	000002	000004	000002	000003	000007
000001	000005	000003	000008	000003	000006	000003	000004
000005	000002	000002	000002	000002	000004	000004	000001
000002	000005	000004	000006	000002	000002	000002	000003
000003	000002	000005	000000	000001	000001	000001	000003
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000000	000002	000000	000001	000001	000002	000001	000001
000004	000001	000003	000001	000002	000001	000002	000000
000001	000002	000000	000000	000001	000003	000001	000003
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000002	000000	000000	000001	000000	000001	000000	000001
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Table A.2 (Continued)

Position. 5

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Table A.3

Data for Figure 4.5
Normal Traverse
Position 1

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Table A.3 (Continued)

Position 2

400000	009278	006764	005180	003917	003236	002673	002215
001951	001697	001560	001287	001230	001098	000954	000849
000778	000730	000661	000629	000557	000557	000459	000462
000420	000381	000340	000350	000339	000285	000274	000273
000265	000238	000202	000205	000184	000171	000160	000146
000163	000151	000141	000108	000103	000130	000103	000091
000099	000098	000104	000084	000095	000067	000078	000083
000066	000069	000073	000067	000063	000043	000051	000051
000054	000042	000049	000041	000043	000031	000035	000032
000034	000027	000034	000026	000036	000023	000022	000026
000023	000025	000018	000024	000020	000021	000009	000015
000018	000020	000013	000019	000013	000015	000010	000013
000008	000007	000013	000012	000011	000009	000010	000009
000007	000004	000009	000013	000004	000007	000009	000007
000013	000005	000007	000009	000004	000006	000006	000005
000008	000004	000008	000010	000005	000004	000005	000002
000003	000011	000004	000005	000006	000006	000008	000003
000005	000001	000002	000003	000005	000001	000005	000001
000005	000004	000001	000003	000003	000004	000002	000004
000002	000001	000004	000004	000001	000001	000004	000003
000002	000005	000001	000001	000003	000001	000001	000003
000003	000003	000002	000002	000002	000001	000003	000000
000002	000003	000003	000002	000004	000001	000002	000001
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000000	000002	000000	000003	000001	000001	000001	000002
000000	000000	000000	000000	000002	000001	000001	000004
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000001	000001	000001	000001	000000	000003	000000	000001
000000	000000	000002	000001	000002	000000	000001	000000
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000000	000001	000000	000001	000001	000002	000000	000000

Table A.3 (Continued)

Position 3

[illegible]

Table A.4

Data for Figure 4.6
Detector Normal to Beam

100000	007996	010599	011479	011033	009264	007007	004867
003094	001740	000944	000614	000424	000368	000358	000329
000356	000342	000373	000394	000406	000455	000397	000353
000366	000376	000399	000364	000360	000369	000364	000380
000360	000344	000337	000315	000311	000307	000328	000292
000271	000303	000292	000257	000270	000239	000276	000257
000252	000258	000229	000214	000243	000228	000190	000219
000215	000206	000224	000200	000206	000182	000187	000181
000187	000198	000190	000188	000193	000177	000173	000178
000153	000143	000162	000156	000167	000143	000153	000140
000155	000142	000131	000144	000143	000123	000157	000112
000137	000130	000130	000122	000131	000121	000135	000112
000114	000136	000127	000143	000110	000124	000124	000110
000138	000125	000154	000117	000103	000117	000116	000083
000114	000113	000109	000097	000086	000085	000099	000071
000098	000078	000062	000073	000047	000055	000069	000046
000061	000061	000046	000041	000043	000040	000032	000045
000044	000039	000048	000034	000035	000031	000031	000024
000026	000023	000024	000018	000025	000019	000019	000024
000026	000018	000018	000024	000017	000015	000019	000016
000023	000026	000017	000017	000016	000020	000018	000007
000008	000019	000013	000015	000011	000009	000020	000012
000010	000007	000012	000007	000010	000010	000010	000012
000008	000009	000012	000012	000010	000010	000009	000009
000007	000014	000009	000012	000013	000008	000014	000005
000012	000008	000009	000011	000009	000007	000006	000002
000008	000008	000006	000009	000008	000007	000006	000010
000019	000003	000009	000009	000007	000007	000009	000007
000011	000007	000006	000005	000008	000005	000004	000006
000007	000005	000009	000006	000008	000002	000006	000007
000002	000004	000009	000007	000009	000003	000004	000004
000009	000004	000005	000004	000001	000008	000006	000002

Table A.4 (Continued)

Detector Parallel to Beam

100000	010823	007346	004612	002774	001610	001216	001053
000925	000823	000705	000573	000404	000320	000204	000188
000152	000115	000116	000098	000111	000113	000105	000111
000105	000097	000104	000117	000120	000113	000124	000101
000115	000108	000107	000136	000120	000125	000122	000119
000144	000122	000139	000141	000151	000144	000136	000137
000149	000117	000125	000146	000129	000131	000156	000130
000152	000130	000146	000120	000138	000127	000137	000131
000115	000134	000134	000119	000132	000114	000133	000138
000114	000115	000123	000120	000112	000133	000105	000103
000109	000122	000115	000120	000101	000113	000099	000109
000101	000099	000113	000106	000106	000092	000110	000099
000096	000088	000103	000089	000088	000086	000112	000099
000105	000099	000085	000070	000094	000083	000083	000073
000102	000088	000080	000074	000076	000079	000067	000078
000079	000066	000074	000067	000070	000068	000078	000056
000066	000052	000049	000072	000063	000068	000047	000082
000046	000049	000063	000054	000063	000054	000060	000034
000059	000051	000043	000046	000042	000039	000050	000037
000036	000058	000058	000044	000051	000051	000050	000046
000037	000045	000040	000038	000044	000029	000030	000040
000038	000027	000030	000037	000028	000026	000029	000031
000025	000025	000030	000029	000027	000027	000032	000022
000016	000024	000021	000019	000022	000033	000018	000024
000019	000024	000021	000019	000024	000031	000022	000019
000024	000024	000017	000026	000030	000016	000023	000013
000023	000013	000026	000019	000020	000020	000016	000014
000015	000026	000010	000013	000018	000017	000019	000019
000013	000014	000016	000017	000014	000016	000013	000015
000014	000009	000017	000016	000009	000008	000005	000009
000012	000007	000009	000008	000016	000007	000006	000012
000009	000012	000012	000012	000015	000008	000009	000007

[illegible]

Table A.5 (Continued)

Position 2

[illegible]

Position 3

[illegible]

Table A.5 (Continued)

Position 4

[illegible]

Position 5

1

Table A.5 (Continued)

Position 6

[illegible]

[illegible]

Position 2

[illegible]

Table A.6 (Continued)

Position 3

[illegible]

Table A.7

Data for Figure 5.2
Coated Detector

[illegible]

Uncoated Detector

[illegible]

Table A.8

Data for Figure 5.3
Coated Detector

[illegible]

Uncoated Detector

[illegible]

Table A.9

Data for Figure 5.4
Without Shadow Cone

[illegible]

Table A.10.

Data for Figure 5.5
Without Shadow Cone

[illegible]

Table A.10 (Continued)

With Shadow Cone

[illegible]

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