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The Elastic Scattering of Fast Neutrons
By Deuterons

by

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I. INTRODUCTION

A. Theoretical and Practical Value of the Measurement

Many theoretical and experimental investigations have been made of the scattering of nucleons by deuterons. This provides evidence of the importance attached to these reactions in the eventual understanding of nuclear forces. Since a direct study of the interaction of two neutrons is experimentally unfeasible, one is forced to use indirect methods for measurements concerning the neutron - neutron interaction. The least indirect reaction in which this interaction is expected to participate is in the scattering of neutrons from deuterons. Nucleon - deuteron scattering also provides the simplest example of an inelastic scattering process.

Because of the large radius of the deuteron ($\sim 4.3 \times 10^{-13}$ cm)¹⁾, it is expected and experimentally verified that the scattering of neutrons or protons by deuterons occurs with orbital angular momentum greater than zero at quite low energies. This result is to be contrasted with the predominantly s-wave scattering that has been observed in the scattering of neutrons by protons at energies up to 15 MeV. Thus it is expected that the influence of the neutron - neutron interaction in elastic n-d scattering

at low energies will be through s-states if at all.

Phase shift analyses of nucleon - deuteron angular distributions have been made at low energies. It is easy to show, however, that a measurement of the angular distribution alone does not suffice in principle to define a unique set of phase shifts without the introduction of auxiliary assumptions. Making the somewhat unrealistic but necessary assumption that the total spin of the system and its z-component are conserved (neglect of spin-orbit and spin-spin forces), then the scattering for any orbital angular momentum ℓ can occur with $s = \frac{3}{2}$ or $\frac{1}{2}$, thus leading to quartet and doublet scattering. The differential cross section can be expressed in terms of the scattering amplitudes as²⁾:

$$\frac{d\sigma}{d\Omega} = \frac{1}{k^2} \left[\frac{1}{3} \left| \sum_{\ell} (2\ell+1) {}^2A_{\ell} P_{\ell}(\cos\theta) \right|^2 + \frac{2}{3} \left| \sum_{\ell} (2\ell+1) {}^4A_{\ell} P_{\ell}(\cos\theta) \right|^2 \right] \quad (1)$$

where ${}^{2,4}A_{\ell} = e^{i {}^{2,4}\delta_{\ell}} \sin {}^{2,4}\delta_{\ell}$ is the complex scattering amplitude for partial waves associated with orbital angular momentum ℓ , the superscript on A_{ℓ} represents the spin multiplicity, and δ is the scattering phase shift. If the maximum ℓ that enters into the scattering is denoted by L , then there are in all $2L + 2$ phase shifts to be determined since for each ℓ there is a doublet and a

quartet phase shift. Thus the maximum l that occurs in a Legendre Polynomial fit to the experimentally determined cross section of the form

$$\frac{d\sigma}{d\Omega} = \sum_{l=0}^{L_{\text{Max}}} a_l P_l(\cos \theta) \quad (2)$$

is given by $L_{\text{Max}} = 2L$. After carrying out the squaring operation in (1) and expressing each of the Legendre Polynomial products in terms of a series of Legendre Polynomials, the coefficients of corresponding polynomials in equations (1) and (2) can be equated. It is seen that a total of $2L + 1$ relationships are obtained for the determination of $2L + 2$ quantities. Thus some additional assumption must be made in order to determine the phase shifts from the cross section measurements.

Various assumptions have been used in the past in order to allow the determination of a unique set of phase shifts from angular distribution measurements.²⁾ Probably the most reasonable of these analyses is that used by Latter and Latter.³⁾ They analyzed conjointly both an n-d and a p-d angular distribution that were taken at equivalent energies, allowance being made for the coulomb energy difference. A spectrum of n-d phase shifts was determined from the n-d angular distribution. These were compared with the spectrum of p-d phase shifts that were obtained from the

p-d distribution in a similar manner. Under the assumption of charge independence the regions of overlap of the two phase shift distributions were examined, and a consistent set was indicated. It is conceivable that with improved data for both angular distributions this technique could yield a unique set of phase shifts under the assumptions leading to equation (1).

The phase shifts obtained in this manner can be compared with those that have been calculated from the many theoretical approaches used in the past.⁴⁾ Christian and Gammel⁵⁾ have made an extensive calculation for nucleon - deuteron scattering using the Born approximation for the calculation of the P- and D-wave phase shifts. While their results yield excellent fits to the data, several assumptions were made in their calculations. They used the zero range approximation and very simple forms of the nucleon - nucleon potentials. They concluded from their calculations that the elastic scattering is not very sensitive to the neutron - neutron interaction. The reason for this is that the primary process in the elastic scattering for $l \geq 1$ is the pickup of a proton by the incoming neutron, and this process is mainly dependent on the n-p interaction. For S-states in n-d scattering, the direct process and the knockout process

contribute approximately equal amounts to the scattering, which leads to cancellation of the terms containing odd parity potentials. The quartet S-phase shifts do not depend on the even parity n-n potential, and the doublet S-state contributes very little to the scattering.

The present experimental investigation represents one step in a comprehensive theoretical and experimental program here at Rice for the study of few nucleon processes. The measurements that are planned as an extension of the results reported here are discussed in Section VI. The theoretical investigation is being carried out by Duck⁶⁾ and Khanna.⁷⁾

An indication of the practical importance attached to the n-d cross section is given by the fact that it has been a priority I measurement for several years.⁸⁾ Deuterium is one of the best moderators for nuclear reactors⁹⁾, and in order to calculate carefully the neutron economy of a reactor the scattering and capture cross sections of all the materials in the reactor must be known accurately. This becomes more important as the mean neutron energy of a reactor is increased. Accurate scattering cross section measurements are needed over the entire range of the fission spectrum in order that theories may be devised that can be used to provide reliable predictions of the cross section in

the regions where measurements do not exist. Also in the field of weapons the n-d cross section is of primary importance.

B. Previous Measurements

Although there have been several previous measurements of the differential cross section for elastic n-d scattering, the energy range covered by these measurements has been limited to incident energies below 5.5 MeV with the exception of two experiments performed at 14 MeV. Relative angular distributions of n-d scattering have been measured over a wider energy range, but the uncertainty involved in the normalization of these distributions to the total cross section seriously limit their usefulness for comparison with theoretical predictions. A brief summary of the cross section measurements that have been performed and the techniques involved is given in the remainder of this section.

A variety of techniques has been employed with varying degrees of success in the measurements that have been reported. These techniques fall into the following categories: 1) pulse height analysis of the spectrum from a deuterium - filled proportional counter, 2) use of a counter telescope in which recoil deuterons from a radiator containing deuterium are observed, 3) use of BF_3 counters immersed

in an oil moderator behind a massive collimator to detect the scattered neutrons, 4) the pulsed beam time-of-flight technique, and 5) detection of recoil deuterons with nuclear emulsions. The majority of the measurements that have been made have utilized the first two of these techniques, which suffer from the fact that forward angle measurements are extremely difficult to perform.

Using a recoil proportional counter and correcting for end and wall effects, Allen, Ferguson, and Roberts¹⁰⁾ measured n-d angular distributions at 100 and 200 keV. By normalizing to the n-p cross section, they found an almost isotropic distribution in the center-of-mass system at 100 keV, but the departure from isotropy was quite marked at 200 keV, with the backward scattering rising to almost a factor of 3 greater than the forward scattering minimum. This is to be contrasted with the data of Adair, Okazaki, and Walt²⁾ at 220 keV. Using the same technique as Allen, et al.¹⁰⁾, with the exception of normalizing the data to the total n-d cross section, they found an isotropic cross section at this energy. The same group reported data at other energies of 0.5, 0.75, 1.0, 1.5, 2.0, and 2.5 MeV. Although they quoted a probable error of as much as 15%, their distributions in general are more isotropic than that

of other experimenters in this energy range.

Elwyn, Lane, and Langsdorf¹¹⁾ used BF_3 counters placed at five angles to measure the polarization and differential cross section of n-d scattering at incident energies of 0.5, 1.0, and 1.95 MeV. They used the partially polarized neutrons at 51° from the $\text{Li}^7(\text{p},\text{n})\text{Be}^7$ reaction. A thin scatterer was used, and a magnet precessed the spins of the incoming neutrons by 180° for the spin up and spin down measurements. Their result for the polarization in n-d scattering was consistent with $0.0 \pm 3\text{-}4\%$ at these energies. Their elastic cross sections were normalized to the neutron - carbon differential cross section.

The pulsed beam time-of-flight technique was used by Seagrave and Cranberg¹²⁾ to measure the n-d cross section at incident energies of 2.45 and 3.27 MeV. The scattering sample was a deuterated polyethylene cylinder and the data were normalized to the n-p cross section. Their measurements are possibly the most accurate to date; their estimate of the overall accuracy was 3%.

Wantuch¹³⁾ used a counter telescope and gas recoil counter to obtain angular distributions at 4.5 and 5.5 MeV. The angular range of recoil deuterons was from 0° to 60° in the lab, which corresponds to neutron scattering angles

from 180° to 70° in the center-of-mass system. The data were normalized to the n-p angular distribution.

Allred, Armstrong, and Rosen¹⁴⁾ used nuclear emulsions to detect the recoil deuterons from a radiator of deuterated paraffin for a neutron energy of 14.1 MeV. This data is in very good agreement with that of Seagrave¹⁵⁾ at the same energy, who used a recoil counter telescope and did particle identification by means of two $\frac{dE}{dx}$ proportional counters and a scintillation counter to measure the particle energy.

Smooth curves through all the data summarized above are given in Fig. 1, taken from Ref.¹⁶⁾.

The present investigation was undertaken with the immediate objective of filling in the region between 5.5 and 14 MeV, where no data has previously existed. The technique that was developed to perform the measurements is explained in the following section.

Figure 1. Summary of the data from previous experiments on the elastic scattering of neutrons from deuterons. This figure is taken from Ref.16).

1D

II. TECHNIQUES

A. General Outline of the Method of Measurement

The measurement of the differential cross section for the elastic scattering of neutrons by deuterons requires in principle only a monoenergetic source of neutrons, a scattering sample, and a means of detecting the elastically scattered neutrons or deuterons with a known efficiency as a function of angle. In the present experiment, the neutrons were obtained from the $D(d,n)He^3$ reaction (See Section II B). The scattering sample was a benzene ($C_6 H_6$) scintillator in which the benzene was enriched to 99.5% in the deuterium isotope. The detector was a plastic scintillator coupled to a fast photomultiplier tube. In order to differentiate between the neutrons from the $D(d,n)He^3$ reaction that were elastically scattered from deuterons in the scatterer into the detector and the neutrons from other processes (See Section II B), the time of flight of the neutrons from the scatterer to the detector was measured. This flight time measurement was accomplished by measuring the time difference between the pulse from a photomultiplier tube coupled to the scattering scintillator, detecting the scintillation caused by the recoil deuteron, and the pulse from the detector which was placed approximately one meter away. The experimental

arrangement is shown in Fig. 2. The shielding around the detector minimized the detection of neutrons and γ -rays incident on the detector from directions other than that defined by the flight path. The shadow cone provided extra shielding for the detector from the neutrons incident from the direction of the source, thus lowering the accidental counting rate in the detector.

In order to formulate the problem more clearly, let us consider the quantities that must be measured in order to allow the extraction of the required cross section. The differential cross section can be written as

$$\frac{d\sigma_{nd}}{d\Omega} = \frac{C'_{nd}}{\epsilon'(E_{nd}) N_d \psi} \quad (3)$$

where $\frac{d\sigma_{nd}}{d\Omega}$ = the differential cross section for the scattering of neutrons by deuterons,

C'_{nd} = number of primary source neutrons elastically scattered from deuterons and recorded by the detector per second,

$\epsilon'(E_{nd})$ = the absolute efficiency of the detection apparatus for the detection of neutrons of energy E_{nd} ,

E_{nd} = the energy of a neutron, of incident energy E_0 , scattered from a deuteron through the angle ψ ,

N_d = the number of deuterons in the scattering sample,

ψ = the flux of monoenergetic neutrons incident on the scattering sample.

Figure 2. Experimental arrangement used for the
present measurements of n-d scattering.

Since N_d remains constant for a given scattering sample, and γ can be taken to be proportional to the counting rate in a monitor detector, then

$$\frac{d\sigma_{nd}}{d\Omega} \propto \frac{C_{nd}}{\epsilon(E_{nd}) M} \quad (4)$$

where C_{nd} = the total number of elastically scattered neutrons recorded during a given time,

M = the total number of pulses recorded by a flat response monitor counter in the same time,

and $\epsilon(E_{nd})$ = the relative efficiency of the detection apparatus.

Thus a relative angular distribution can be obtained by measuring the number of elastically scattered neutrons that are recorded by the detection apparatus as a function of scattering angle for a given total number of neutrons detected by the monitor counter, taking into consideration the relative efficiency of the neutron detector at each angle.

A block diagram of the electronic apparatus is shown in Fig. 3. The timing pulses from the scatterer and the detector were taken from the anodes of the two photomultiplier tubes and fed into pulse shapers. Each anode signal greater than some lower limit selected by an adjustable discriminator on the pulse shapers triggered a negative 0.5 volt pulse that was then fed into a time-to-pulse-height converter. Because

Figure 3. Block diagram of the electronics used for the two parameter measurements. The single parameter spectra reported in the text were taken without the fast linear gate and its associated equipment.

of the high counting rate in the scatterer (on the order of 200 kc) these pulses were delayed an appropriate amount and used as stop pulses for the converter. The output of the converter was amplified by a double delay line clipping amplifier and then analyzed by a multichannel analyzer. The dynode pulses from the detector were fed into a cathode follower and then amplified. A single channel analyzer was used to define the lower limit on the recoil pulse spectrum from the detector (Section II D). The particular time-to-pulse-height converter used in these measurements had the undesirable property of giving a full scale pulse out for each start pulse not associated with a stop pulse. In order to eliminate this full scale instrumental peak, a single channel analyzer was used on the output of the converter. A slow ($\sim 2 \mu\text{s}$) coincidence was required between the outputs of the two single channel analyzers, and the multichannel analyzer was gated by the output of this coincidence circuit.

For a given scattering angle of the neutron, the recoil deuteron has a corresponding specified energy. The pulse output of the scatterer is approximately proportional to this recoil energy. Because of the high counting rate in the scatterer, however, a conventional amplifier and multichannel analyzer is not suited for pulse height analysis of

these pulses. The following method was devised to circumvent this difficulty. The anode pulses from the scatterer were fed through appropriate delay and attenuation into a fast linear gate that was normally closed, but was opened each time that a pulse was recorded at the start input of the converter. Thus the fast linear gate selected from the high counting rate in the scatterer all those pulses associated with a pulse in the detector. This not only reduced the counting rate from the scatterer so that conventional pulse height analysis was possible, but also had the advantage that it retained each of the pulses associated with a scattered neutron.

The data were accumulated on a two parameter analyzer; the x coordinate was proportional to the time of flight of the scattered neutron, and the y coordinate was a measure of the recoil energy deposited in the scatterer. The two parameter technique had the advantage of spreading accidental coincidences out over two dimensions as well as resolving background and tertiary neutrons (Section II E) in both dimensions, thus enhancing the signal to background substantially.

The technique outlined above allowed the measurement of the number of neutrons elastically scattered from deuterons.

The normalization to a constant incident flux was made by using a shielded long counter of standard design¹⁷⁾ as a monitor. The long counter was positioned approximately 1.5 meters from the source of neutrons at an angle of -35° to the beam and the number of counts registered by the long counter during each run was recorded. The relative efficiency of the detector was measured separately as explained in Section II D. Thus a relative angular distribution was obtained at a given neutron energy. In order to establish an absolute basis for the relative measurements, the technique outlined in the following paragraphs was used.

If instead of a deuterated benzene scintillator, a benzene scintillator containing a known ratio of deuterium to hydrogen is used as the scatterer, then it can be shown that the differential cross section for n-d elastic scattering can be expressed in terms of the well known n-p differential cross section and other measurable quantities. Consider equation (3) above and the corresponding equation for n-p scattering

$$\frac{d\sigma_{np}}{d\Omega} = \frac{C'_{np}}{\epsilon'(E_{np}) N_p V} \quad (5)$$

where the symbols are defined as for equation (3). Then

the result of dividing equation (3) by equation (5) is

$$\frac{\frac{d\sigma_{nd}}{d\Omega}}{\frac{d\sigma_{np}}{d\Omega}} = \frac{C_{nd}}{C_{np}} \frac{E(E_{np})}{E(E_{nd})} \frac{N_p}{N_d} \quad (6)$$

Since the n-p cross section is isotropic in the center-of-mass system for neutron energies below 10 MeV, then in the laboratory coordinate system,

$$\frac{d\sigma_{np}}{d\Omega} = \frac{\sigma_T(E_0) \cos \psi}{\pi} \quad (7)$$

where $\sigma_T(E_0)$ is the total cross section for n-p scattering at an incident neutron energy of E_0 , and ψ is the laboratory scattering angle. Hence, the expression for the n-d elastic scattering cross section becomes

$$\frac{d\sigma_{nd}}{d\Omega} = \frac{C_{nd}}{C_{np}} \frac{E(E_{np})}{E(E_{nd})} \frac{N_p}{N_d} \frac{\sigma_T(E_0) \cos \psi}{\pi} \quad (8)$$

Thus a measurement of the ratio of the number of counts recorded from n-d and n-p scattering, the ratio of the relative efficiency of the detector at the two neutron energies, and the scattering angle ψ are sufficient to define the absolute differential cross section for n-d elastic scattering, when combined with a knowledge of the n-p total cross section at the incident neutron energy and the specified composition of the scatterer.

The measurement of the absolute cross section can be made only in the forward hemisphere since n-p scattering does not occur at angles greater than 90° in the laboratory. However, the relative angular distribution obtained as outlined in the first part of this section can then be normalized to the absolute points at the forward angles.

B. The Source of Neutrons

1) The $D(d,n)He^3$ Reaction

The $D(d,n)He^3$ reaction was used as the source of monoenergetic neutrons. Since the Q-value of the reaction is positive by 3.27 MeV, it is a convenient neutron source for neutrons of energy greater than approximately 3.5 MeV. At bombarding energies greater than that necessary for the breakup of a deuteron, 4.44 MeV, the neutrons from the D-D reaction are no longer monoenergetic. The reaction

contributes a continuum of neutrons of energies from 0 to $E_0 - 5.5$ MeV, where E_0 is the primary neutron energy.

Since the energy separation between the primary and most energetic of the tertiary neutrons is 5.5 MeV, the time-of-flight technique is capable of distinguishing the primary neutrons.

2) The Target

At the outset of the experiment, both a gaseous deuterium target and a solid deuterated titanium target were tested for the present application. Since the solid target has at best a deuterium to titanium ratio of 2:1, a gas target contains more deuterium per unit energy loss in the target than does a solid target. Thus for a given neutron yield from both targets, the dispersion in the neutron energy due to target thickness is less for a gas target. Another limitation of solid targets is that the deuterium evaporates from the target at temperatures on the order of 200° C. For moderate beam currents of about 1 μ a, these temperatures are readily attainable. This would necessitate careful cooling of a solid target with the resultant complications. These considerations led to the adoption of a gas target for the present experiments.

The design of the gas target was based on that developed at Harwell.¹⁸⁾ A cross sectional view is shown in Fig. 4. The length of the cell could be made either 1, 2, or 3 cm. by interchanging the outer cylinder. For these experiments, the 3 cm. length was used.

The entrance foil was a 0.0001" nickel foil, carefully soldered to the rim of the inner cylinder. The entire

Figure 4. The gas target. The suppressor was connected to a rod leading through the insulator to the outside. The nickel entrance foil was soldered to the rim of the inner cylinder.

assembly was helium leak tested before installation and was found to be dependable during months of use.

3) Energy Loss Corrections

The incident neutron energy is determined by the beam energy at the target, the Q-value of the reaction, and the angle at which the scatterer is placed with respect to the beam direction. The deuteron beam was obtained from the Rice University Tandem Van de Graaff Accelerator. The energy was selected by bending the beam through an angle of 90° with a calibrated magnetic analyzing system. The beam energy was accurate to approximately ± 10 keV.¹⁹⁾ The energy lost in passing through the 0.0001" nickel entrance foil was calculated using the graphs of specific energy loss vs. deuteron energy for various elements given by Marion.²⁰⁾ Since it was desired to know the beam energy at the center of the gas target, the specific energy loss of a deuteron beam in a gaseous deuterium target, also given by Marion²⁰⁾, was used. The pressure of deuterium in the gas cell was approximately 1.0 atm. for all the measurements reported here, and no correction was made for the variation of the temperature of the cell from the 15° C for which the tabulations of Marion was made. Thus, given the deuteron energy at the center of the target, the 0°

neutron energy can be calculated from the kinematics of the reaction. However, a convenient tabulation of the kinematics of the $D(d,n)He^3$ reaction has been made by Blumberg and Schlesinger.²¹⁾

For a deuteron energy of 2.680 MeV incident on the entrance foil, the energy loss in traversing the foil is 231 keV. The energy loss in 1.5 cm. of deuterium gas at a pressure of 1 atmosphere is 69 keV. Consequently, the mean deuteron energy at the center of the gas target is 2.380 MeV. The zero degree neutron energy is thus 5.635 MeV.

The dispersion in the beam energy due to straggling in the foil and gas can be calculated from the tabulation of Marion.²⁰⁾ For the case considered above, the straggling in the foil is 7.2 keV and in the gas, 2.2 keV.

C. The Scatterer and the Detector

The benzene scintillators that were used as the scattering samples in the present experiment were constructed by Nuclear Enterprises Ltd.^{a)} Each of the scintillators had the same physical dimensions, 1" diameter by 1" long. They were encapsulated in a bubble free aluminum cell with a reflective coating and had two viewing faces covered with glass.

a) Address: 550 Berry Street, Winnipeg 21, Canada

After some of the initial data had been analyzed, it was discovered empirically that although the partially deuterated (mixed) scintillator had been ordered with a D/H ratio of exactly 60/40, the actual ratio appeared to be just the inverse of that which was ordered. In order to verify this suspicion, another was ordered and tested, and by taking the new one to have the specified D/H ratio of 59.2/40.8²²⁾, it was shown that the one that was initially used had the ratio 40/60 (not 60/40!) within the accuracy of the present experiment.

The plastic scintillator that was used as the detector was constructed by Pilot Chemicals, Inc.^{a)} The dimensions were 1.75" diameter by 2" long.

An estimate of the total amount of multiple scattering that occurs in the target scintillator can be obtained from the technique given in Ref. ²³⁾. A calculation for the hydrogenated benzene scintillator yields an upper limit of approximately 20%. This will actually be decreased because of the fact that in the present experiment the requirement of proper neutron energy at a given angle as well as the proper pulse height from the target scintillator will cause

a) Address: 36 Pleasant Street, Watertown 72, Massachusetts

many of the multiple scattered pulses to be outside the singly scattered neutron peak. The actual correction to the data, however, can be made to a high degree of accuracy by using the Monte Carlo program discussed in Section VI B.

The efficiency of the plastic scintillator for neutron detection is discussed in Section II D.

The photomultiplier tubes that were used with both scatterer and detector were of the type 56 AVP.^{a)} The voltage distribution that was used for all of the measurements reported here was the Philips B type, specified by the manufacturer. Since the present measurements, however, a new distribution²⁴⁾ has been tried. It was found that this distribution has the advantage of providing faster timing signals at the anode, and of optimizing the linearity of the anode signal so that the anode signal can be used for energy analysis. The physical design of the base is such that little or no heating of the tube can occur, and the shielded anode signal lead is connected directly to the anode pin at the base of the tube. Reflections are also minimized in the new base design.

The optical coupling of the scintillators to the PM tubes was accomplished by using D-C 200 fluid^{b)} which had

a) Distributed by Amperex Electronic Corporation, Hicksville, L. I., N. Y.

b) Manufacturer: Dow Corning Corporation, Midland, Michigan

a viscosity of 1,000,000 cs. at 25° C. The scintillators were then wrapped with aluminum foil that had been smoked with magnesium oxide in order to insure a high reflectivity from the walls, and covered with electrical tape to insure a light tight seal. A Co-netic^{a)} metal magnetic shield was then placed around the PM tube.

D. Determination of the Efficiency of the Detector

1) General

The efficiency of the detector for neutrons of a given energy can be defined as the ratio of the number of pulses recorded by the detector to the number of neutrons incident on the detector. For the case of a plastic scintillator coupled to a photomultiplier tube, neutron detection is accomplished by conversion of the energy of the recoil proton into light in the scintillator which is converted into an electrical signal by the photomultiplier tube. Therefore, the detection efficiency is a function of the n-p scattering cross section and the physical dimensions of the scintillator. The pulse height for a given proton recoil in the detector is approximately proportional to the recoil energy. Since the differential cross section for n-p scattering is isotropic in the center-of-mass system for neutron energies

a) Manufacturer: Perfection Mica Company

below about 15 MeV, then the number of recoil protons having energy between E and $E + dE$ is a constant for neutrons of incident energy E_0 . This follows from the fact that the laboratory differential cross section for n-p scattering is

$$\frac{d\sigma_{np}}{d\Omega} = \frac{\sigma_T(E_0) \cos \psi}{\pi}.$$

$$\therefore d\sigma_{np} = \frac{\sigma_T(E_0)}{\pi} \cos \psi \sin \psi d\psi d\phi,$$

and since

$$E_\psi = E_0 \cos^2 \psi,$$

$$dE_\psi = -2E_0 \cos \psi \sin \psi d\psi,$$

then

$$I_0 d\sigma_{np} = N(E) dE = -I_0 \sigma_T(E_0) \frac{dE_\psi}{E_0}, \quad (9)$$

where I_0 is the incident intensity. Thus the pulse height spectrum of the recoil protons for monoenergetic incident neutrons will be rectangular²³⁾, extending to the maximum recoil energy, E_0 . In practice, however, the spectrum deviates from rectangular because of the finite resolution of the detector and also because of the phototube noise. Other effects, such as multiple scattering, non-linearity of the phototube and edge effects, combine to make the deviation even more noticeable. It is always necessary to set a lower bias to define the minimum acceptable pulse height above the phototube noise. The effect of the bias is to set a lower limit on the energy of neutrons that the

detector is capable of detecting. Hence, the efficiency falls to zero at some neutron energy determined by the bias, but rises to approach asymptotically the maximum set by the n-p scattering cross section and the physical dimensions of the scintillator.

Because of the technique used in the present experiment, only the relative efficiency of the neutron detector was required (Section II A).

Since the bias setting determines the shape of the efficiency curve at neutron energies close to the threshold, it is important to have a method of establishing and reproducing the bias setting. The technique that was used for the present experiments consisted of a determination of the pulse height from the detector that corresponded to the Compton energy of a 511 keV γ -ray and then setting the bias at some fraction of this pulse height by means of a single channel analyzer. By displaying on a multichannel analyzer the Compton spectrum resulting from bombardment of the detector by Na^{22} 511 keV γ -rays, the channel corresponding to the Compton edge of the γ -rays could easily be determined. By then gating the analyzer with the output of the single channel analyzer, the position of the bias could be set to the desired fraction of the Compton edge. This provided a

convenient means of setting the bias at the beginning of an experiment and allowed checks to be made at frequent intervals to insure that no gain shifts had occurred in any of the electronics.

As explained in Section II A, the present experiment required a measurement of the relative efficiency of the detector, but not necessarily the absolute efficiency. The energy range of interest was from approximately 0.5 to 9 MeV. The various techniques that were employed for the relative efficiency determination are explained in the following sections.

2) n-p Scattering

The relative efficiency of the neutron detector can be measured by utilizing the knowledge of the differential scattering cross section for neutrons on protons. Using the same technique as outlined in Section II A, a benzene scintillator containing only normal benzene was used as the scattering sample. In this way the number of neutrons scattered from protons could be measured. For this case, equation (5) of Section II A is applicable:

$$\frac{d\sigma_{np}}{d\Omega} = \frac{C_{np}}{\epsilon'(E_{np}) N_P V} .$$

Thus

$$\epsilon'(E_{np}) = \frac{C'_{np}}{\frac{d\sigma_{np}}{d\Omega} N_p V} \quad (10)$$

and since the n-p scattering cross section is isotropic in the CM system (equation (7) of Section II A), then

$$\epsilon'(E_{np}) = \frac{\pi C'_{np}}{\sigma_T(E_0) N_p V \cos \psi} \quad (11)$$

Written as a proportionality, this becomes

$$\epsilon(E_{np}) \propto \frac{C_{np}}{M \cos \psi} \quad (12)$$

where M is the total number of counts recorded by a monitor detector, and $\epsilon(E_{np})$ is the relative efficiency of the detector for neutrons of energy E_{np} . Thus by measuring as a function of angle the number of counts recorded in the elastically scattered neutron peak for a given total incident flux, the relative efficiency for neutrons of all energies less than the incident energy can be measured. Since the background conditions of a monitor counter do not change for measurements taken at different angles of the scintillation counter, the total incident flux can be taken as proportional to the counts recorded by a flat response long counter, the monitor, placed near the neutron producing target.

The relative efficiency curve obtained by the technique outlined above is shown in Fig. 5. The data were analyzed

Figure 5. The relative efficiency obtained for the neutron detector from the n-p scattering measurements. The curve is merely a smooth curve drawn through the data points. The error bars on the data give the statistical accuracy for each point.

according to the procedure given in Section III A. The incident neutron energies that were used as well as the numerical values obtained are given in Section IV A. The errors indicated are due to the point statistics only.

It was noticed that a form of internal consistency check could be made for the absolute (mixed scintillator) cross section measurements. After extracting the number of proton-scattered neutrons from a spectrum, this number, combined with the monitor counts and the ratio of the number of protons in the mixed scintillator to the number of protons in the normal benzene scintillator, could be used to check the relative efficiency as measured above. This was done for all the absolute points that were measured, and the agreement was required to be within the statistical accuracy of the measurement in order to be accepted.

3) Comparison with a Long Counter

Another method that was used for the detector efficiency determination was a direct comparison of the desired efficiency with that of a flat response long counter. In order to accomplish this, monoenergetic neutrons from an energy of 1.148 to 2.624 MeV were obtained from the $T(p,n)He^3$ reaction. The proton beam was obtained from the Rice University 5.5 MeV Van de Graaff, and the target was zirconium

tritide deposited on a copper backing.^{a)} The long counter was placed at an angle of $+30^\circ$ to the beam direction and a distance of 150 cm. from the target, while the detector was positioned at an angle of -30° and a distance of 100 cm. After the side channel bias had been established for the neutron detector, the number of counts registered by the long counter and the detector was recorded for various neutron energies. Although no correction was applied for either the slight variation in the long counter efficiency or the background arising from stopping the beam, the relative efficiency curve that was obtained agreed very well with that obtained in the preceding section. The data are presented in Fig. 6. The curve through the data in this figure is the same smooth curve that is drawn through the n-p data in Fig. 5. Only a limited energy range was covered, but the agreement between the two independent methods is good.

4) Calculation of the Efficiency

The theoretical efficiency of the plastic scintillator can be calculated quite simply if secondary effects such as multiple scattering, edge effects, and nonlinearity of response are neglected. Consider an incident beam of

^{a)} Obtained from Texas Nuclear Corp., Austin, Texas.

Figure 6. The relative efficiency measured for the neutron detector by comparison with a long counter. The dots represent the ratio of the scintillation counter efficiency to that of the long counter. The curve through the data is the same curve as that drawn through the n-p data in Figure 5. The normalization to the present scale was accomplished by taking an average normalization factor over the region of overlap of the two sets of data.

neutrons of energy E_0 and intensity N_0 neutrons/cm.² striking the face of a plastic cylinder of length L . The decrease in the intensity, $N(x)$, between the distance x and $x + dx$ from the face of the scintillator is given by

$$dN(x) = - [\eta_H \sigma_H(E_0) + \eta_C \sigma_C(E_0)] N_0 dx ,$$

where

η_H = the number of protons/cm.³,

η_C = the number of carbon nuclei/cm.³,

$\sigma_H(E_0)$ = the n-p cross section at energy E_0 ,

and $\sigma_C(E_0)$ = the neutron - carbon cross section at

E_0 .

Thus
$$N(x) = N_0 e^{- [\eta_H \sigma_H(E_0) + \eta_C \sigma_C(E_0)] x}$$

gives the number of the incident neutrons/cm.² which remain unscattered at the distance x in the scintillator. The number of recoil protons/cm.² produced in the scintillator is given by

$$\begin{aligned} N_p(E_0, L) &= \int_0^L N(x) \sigma_H \eta_H dx , \\ &= N_0 \eta_H \sigma_H \left[\frac{1 - e^{-(\eta_H \sigma_H + \eta_C \sigma_C)L}}{\eta_H \sigma_H + \eta_C \sigma_C} \right] . \end{aligned}$$

The efficiency of the plastic scintillator is given by²³⁾

$$\epsilon'(E_0, L) = \frac{N_p(E_0, L)}{N_0} .$$

Since in any practical situation a bias must be set on the pulse height spectrum from the photomultiplier, it is necessary to take account of this bias in the calculation. One method of including the effect of the bias is to assume a rectangular pulse height distribution from the detector for monoenergetic incident neutrons. If this is done, then the measured efficiency should be

$$\epsilon(E_0, L) = \epsilon'(E_0, L) \left[1 - \frac{B}{E} \right]$$

where B is the neutron energy which causes a maximum pulse height equal to the bias setting.

From the n-p efficiency measurements, it can be seen that the efficiency falls to zero at a neutron energy of 700 keV. Because of the resolution of the detector, as well as the resolution in the experimental arrangement, the point at which the measured efficiency falls to zero is less than the actual bias. For this reason, a value of 1 MeV was taken as the bias for the calculation of the efficiency.

The calculated curve is shown in Fig. 7. The n-p data were normalized to the calculated curve over the flat portion and are shown on the same figure.

5) Discussion of the Efficiency Determinations

The agreement at the higher neutron energies between the calculated and measured efficiency lends credence to

Figure 7. Theoretical calculation of the detector efficiency. The n-p data were normalized to the calculated curve. The dashed line is the smooth curve through the n-p data from Fig. 5.

the n-p measurements. The fact that the n-p determination was corroborated by comparison with the long counter provides additional proof of the validity of the n-p scattering technique for efficiency measurements.

For the n-d cross section determinations, the relative efficiency values were read from the smooth curve drawn through the n-p measurements shown in Fig. 5.

E. Resolution Requirements and Calculations

1) Requirements

Since the neutrons from the D-D reaction are not mono-energetic above deuteron energies of 4.45 MeV, it was necessary to use a neutron spectrometer of sufficient resolution to differentiate between the primary neutrons arising from the $D(d,n)He^3$ reaction and the continuum of neutrons from the breakup reaction, $D(d,n)pD$. An additional complication is the possibility of a continuum of neutrons from the inelastic scattering process $D(d,np)n$ in the scatterer. This becomes energetically possible at an incident neutron energy of 3.3 MeV. These neutrons are also separated in energy from the primary elastic process.

There are other possible sources of background neutrons, however. Neutrons are produced whenever a high energy deuteron beam is stopped. Although a platinum blank was

used as the beam stopper in the present experiments (Section II B), a sizable background was recorded by the monitor counter at deuteron energies above 6 MeV. These neutrons could also be due to reactions occurring in the entrance foil. That there was not an excessive background due to driven-in deuterium in the platinum blank can be seen from the results of a gas in-gas out experiment that was run at a beam energy of 3 MeV. The counting rate with no gas in the target was less than 4% of the counting rate with 1 atmosphere of deuterium in the target. This could easily be attributed to the normal background from the sources mentioned above.

The resolution of the time-of-flight spectrometer must be good enough to provide distinct separation between the primary elastically scattered neutrons and the neutrons from the other processes. A thorough discussion of the factors that determined the experimentally observed resolution for the measurements reported here is given in the following section.

2) Calculations

The sources of imperfect resolution for the specific experimental arrangement used in the present measurements can be divided roughly into four categories. In the

following four sections, each of these sources will be discussed separately.

a) Flight Path Indetermination

The indetermination in the length of the flight path due to the finite width of both the scatterer and the detector contributes to the imperfect resolution of the spectrometer. Fig. 8a is an illustration of the quantities involved.

If we let ΔX_s = the length of the scatterer in the direction of the flight path,

ΔX_d = the length of the detector in the direction of the flight path,

and R = the length of the flight path,

then the indetermination in the measured flight time that results from the r.m.s. indetermination in flight path can be expressed as

$$\frac{\Delta t_x}{t_R} = \sqrt{\frac{\Delta X_s^2}{R^2} + \frac{\Delta X_d^2}{R^2}} = \frac{\sqrt{\Delta X_s^2 + \Delta X_d^2}}{R}$$

where Δt_x is the time indetermination and t_R is the time of flight from the center of the scatterer to the center of the detector. Since the energy of a neutron is related to its time of flight by

$$E = \frac{(72.4)^2}{t^2}$$

Figure 8.

- a) The pertinent dimensions for the calculation of the resolution due to the indetermination in flight path.
- b) The dimensions determining the resolution due to the finite spread in scattering angle.

where E is expressed in MeV and t in nanoseconds, then

$$dE = -2 \frac{(72.4)^2}{t^3} dt$$

or

$$\frac{dE}{E} = -2 \frac{dt}{t}$$

where the minus sign signifies the inverse relationship between energy and time. Thus we have that

$$\frac{\Delta E_x}{E_R} = -2 \frac{\Delta t_x}{t_R} = -\frac{2}{R} \sqrt{\Delta X_s^2 + \Delta X_d^2}$$

which gives the energy resolution arising from the flight path indeterminations.

For the present experiment the following dimensions were used: $\Delta X_s = 1.00''$, $\Delta X_d = 1.75''$, and $R = 1.00$ meter.

For this experimental arrangement the calculation yields

$$\frac{\Delta E_x}{E_R} = 10.2\%.$$

b) Scattering Angle Indetermination

The angles were measured initially with a transit to an estimated accuracy of 0.2° . Permanent indentations were made on the floor at the calibrated angles, and plumb bobs hung from the shield were aligned over the indentations. The overall accuracy of the angle measurement was on the order of $\pm 0.5^\circ$.

Because of the variation of scattered neutron energy with angle, the finite angle subtended by the scatterer at

the source and by the detector at the scatterer gives rise to a range of scattered neutron energies, which in turn contributes to the resolution of the spectrometer. The solid angles subtended by both the scatterer and detector must be folded together to obtain the total angular spread of the scattered neutron. The experimental arrangement is illustrated in Fig. 8b.

If we let $\Delta\psi_s = \frac{\Delta x_s}{R_s}$ = angle subtended by the scatterer at the target, and $\Delta\psi_d = \frac{\Delta x_d}{R}$ = angle subtended by the detector at the scatterer, then

$$(\Delta\psi)^2 = (\Delta\psi_s)^2 + (\Delta\psi_d)^2 .$$

The spread in the neutron energy arising from the r.m.s. indetermination in scattering angle can be calculated from the kinematics of the reaction. The case of neutrons scattered from protons is not only easier to calculate, but also the energy variation with scattering angle is greater than for neutrons scattered from deuterons. Since the scattering of neutrons from both protons and deuterons was measured in the present experiment then the consideration of the n-p angular resolution provides the worse case as far as error is concerned for the measurements of interest.

For neutrons of incident energy E_0 scattered from protons into an angle ψ , then the scattered energy E_ψ is given by $E_\psi = E_0 \cos^2 \psi$. The variation of neutron energy with

laboratory angle is given by

$$\Delta E_{\psi} = -2 E_0 \cos \psi \sin \psi \Delta \psi$$

The energy resolution is given by

$$\begin{aligned} \frac{\Delta E_{\psi}}{E_{\psi}} &= - \frac{2 E_0 \cos \psi \sin \psi}{E_0 \cos^2 \psi} \Delta \psi , \\ &= - 2 \tan \psi \Delta \psi , \end{aligned}$$

where
$$\Delta \psi = \sqrt{(\Delta \psi_s)^2 + (\Delta \psi_d)^2} .$$

This expresses the contribution to the resolution of the spectrometer arising from the scattering angle indetermination.

The source to scatterer distance R_s used in the present experiment was 10.5 cm. Using the other dimensions given at the end of the preceding section, then $\Delta \psi = .25$ radian. For a scattering angle of 40° , the contribution to the energy resolution for n-p scattering due to angular spread is $\frac{\Delta E_{\psi}}{E_{\psi}} = 43\%$. At the same angle for n-d scattering, the corresponding energy resolution is 22%. Hence this was the primary source of resolution in the measurements reported here. Since these measurements were made, the distance R_s has been increased to 50 cm., with a corresponding improvement in

resolution. For the n-p case, the resolution decreased to 12.1% and for the n-d case, 6.3%.

c) Incident Energy Spread

The spread in the incident neutron energy is determined by two principal sources: 1) the thickness of the gas target, and 2) the variation in the energy of the source neutrons with the angle of emission. The thickness of the gas target is calculable from a knowledge of the specific energy loss of the beam particles in the target gas, given the temperature and pressure of the target. The specific energy loss for deuterons in deuterium has been tabulated as a function of deuteron energy by Marion.²⁰⁾ The variation of the source neutron energy with reaction angle is calculable from the kinematics of the reaction. Since the scatterer subtends a finite angle at the target, the variation of neutron energy across the face of the scatterer is the quantity of interest. For the $D(d,n)He^3$ reaction, the neutron energy is a slowly varying function of angle around the 0° direction to the beam. This information has been tabulated in Ref.²¹⁾.

The calculated energy spread at a deuteron energy of 6 MeV for the arrangement used in the present experiment was 72 keV from the target thickness and 24 keV due to the

finite angle subtended by the scatterer.

d) Electronic Resolution

Aside from the various sources of imperfect resolution arising from the geometry, there is a fundamental limit on the resolution attainable by a time-of-flight spectrometer that is set by the resolution of the electronic circuitry and the detectors. The sources of this electronic resolution are many, but one of the primary causes is the timing uncertainty of the pulse shapers as a function of input pulse height. This electronic "walk" is minimized for constant input pulse height, and is worst for pulses that are only slightly greater than the bias level. Thus the side channel bias on the detector pulse spectrum (Section II A) was adjusted so that the minimum pulse height accepted by the side channel was always greater than the lower limit set by the pulse shaper discriminator. This had two beneficial effects: 1) it provided an accurate and easily reproducible lower bias, and 2) it minimized the electronic walk in the pulse shaper on the start input due to pulses close to the bias level. In the stop side, the discriminator was always set lower, and usually much lower, than the pulses from the recoil deuterons or protons of interest. The fact that the recoil pulses of interest were also

approximately uniform in pulse height decreased still further the timing uncertainty.

Another source of electronic resolution was in the time "jitter" of the photomultiplier tube which is due to statistical fluctuations in the transit time of the pulse through the tube. The PM tubes that were used are constructed so that the jitter is minimized. The manufacturer states that this time fluctuation is less than 2 ns , for the 56 AVP tube.

A test of the electronic resolution was made. By positioning the two scintillators so that they were on opposite sides of a Na^{22} source and detected the coincident annihilation γ -rays, a zero time peak was accumulated in the time spectrum. The full width at half maximum of this peak is the electronic resolution. The side channel and discriminators were set as in the actual experiment, and a mock-up of the experimental conditions for the stop side was made by setting a side channel window over a selected portion of the stop pulse spectrum. Such a spectrum is shown in Fig. 9.

Figure 9. A single parameter time spectrum illustrating the electronic resolution. For this spectrum, 1 channel = .143 ns. Consequently, the FWHM of the peak is 2 ns.

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III. REDUCTION OF THE DATA

A. Background Subtraction

Some of the data were taken before the two parameter technique was instigated. These data were accumulated as single parameter time-of-flight spectra. Analysis of the single parameter data was made difficult by the necessity of background subtraction. At scattering angles that were large enough so that a recoil carbon ion in the benzene scintillator had enough energy to trigger the pulse shaping network, a carbon scattered neutron peak appeared in the time-of-flight spectrum. Because of the poor resolution of the scintillator and the fact that the recoil energy of the carbon ion was slightly below or very close to the discriminator setting of the pulse shaper, the walk in the triggering circuit caused the carbon peak to be smeared out in the time spectrum. This smearing of the carbon peak frequently caused an overlap of the deuteron and carbon peaks, thus making background subtraction from the leading edge of the deuteron peak rather difficult.

In addition, there was not always a clear distinction between the tertiary neutrons elastically scattered from deuterium and the primary scattered neutrons. This complicated the subtraction of background from the trailing edge

of the deuteron peak.

As an example of the technique that was devised for the situation described above, a series of spectra taken at an incident energy of 5.635 MeV with the deuterated benzene scintillator as scatterer are shown in Figure 10. With decreasing scattering angle the carbon peak appears to move further under the deuteron peak, and is finally almost obscured. The raw data were plotted on semilog¹ paper in order that the effect may be seen more clearly. The semilog paper also allowed the superposition of one spectrum over the other, and the carbon peak could be followed from one spectrum to the other.

With the incorporation of the two parameter technique, the difficulty with the carbon peak was overcome because the carbon recoils were separated from the deuteron or proton recoils. The tertiary neutrons were also separated in recoil energy from the primary elastic group. This provided an important improvement in the accuracy of the data. An illustration of the features of a two parameter spectrum for the mixed scintillator is given in Fig. 11. Although separation of the proton and deuteron peak in the single parameter time spectra for angles more forward than about 45° was not possible, it was found that with the two

Figure 10. A series of time spectra taken with the deuterated scintillator as scatterer. The incident neutron energy was 5.635 MeV, and the scattering angles were those indicated on the graphs. As the angle is decreased, the carbon peak shifts under the deuteron peak. Only a portion of each spectrum was plotted; the γ -peak is off the spectrum to the right in each case. Each of the spectra begin with a different channel number; hence, the time shift of the peaks with the energy of the scattered neutron is not shown.

Figure 11. Diagram showing the relative positions in a two dimensional spectrum of the deuteron- and proton-scattered neutron peaks. The γ -flash is spread along the recoil axis since the energy deposited in the scatterer is not uniquely determined. The tertiary neutrons from the source are of lower energy than the neutrons from the $D(d,n)He^3$ reaction, hence the energy deposited in the scatterer is smaller, in addition to their having a longer flight time. The discriminator bias level was set by the shaper discriminator on the scatterer.

Time of Flight

parameter technique the separation could be achieved at smaller angles.

A photograph of the computer printout of a two dimensional spectrum taken with the mixed scintillator at an incident energy of 9.035 MeV and a scattering angle of 50° is shown in Fig. 12.

As remarked in Section II E (2), an improvement in the time resolution was accomplished by increasing the source to scatterer distance from 10.5 cm. to 50 cm. Some preliminary data have been taken with this improved time resolution at an incident neutron energy of 11.952 MeV. Only absolute points have been measured, but a typical spectrum is shown in Fig. 13. Whereas the time required for a typical spectrum with the poorer resolution was on the order of one to three hours, the new spectra required a factor of two or three longer. The improvement in resolution more than compensates for the increase in data accumulation time.

The technique that was used for background subtraction in the two parameter spectra was as follows. An average accidental background was derived from the part of the spectrum between the γ -flash and the neutron peak for each channel along the recoil energy axis. Then a channel by

Figure 12. A typical spectrum taken with the mixed scintillator as the scatterer. The incident neutron energy was 9.035 MeV; the scattering angle was 50° . See the text for details.

Figure 13. A two dimensional spectrum taken with improved time resolution as explained in the text. The incident energy was 11.952 MeV, and the scattering angle was 40° .

[illegible]

channel subtraction of the background from the area on the two dimensional map that encompassed the peak was made. The channels in this area were summed, as well as the total background that was subtracted. The number of counts (minus background) was taken as C_{np} , and the statistical deviation of both C_{np} and the background was calculated.

B. Absolute Normalization

After the data for a relative angular distribution had been reduced to the form given by equation (4), they were transformed into the center-of-mass system. The absolute points, all in the forward hemisphere, were also transformed to center-of-mass cross sections. At the angles where the data overlapped, an average normalization factor was derived by dividing the absolute cross sections by the corresponding relative number. This factor was then applied to the relative numbers to transform the angular distribution into cross sections.

If there was insufficient overlapping of the absolute and relative data, say the data were taken at slightly different angles, then a smooth curve was drawn through each of the spectra, and a normalization factor was derived from the curves.

C. Accuracy Estimate

In order to make a realistic estimate of the accuracy of the cross sections obtained with the technique described here, it is necessary to consider the various quantities entering in the measurement. For the absolute (mixed scintillator) data, it is seen that the accuracy depends on 1) the accuracy with which the relative number of proton- and deuteron-scattered neutrons can be extracted from the spectra, 2) the accuracy of the relative efficiency measurement, 3) the accuracy of the D/H ratio supplied by the manufacturer, and 4) the accuracy with which the total n-p scattering cross section is known.

For the single parameter data, the two peaks were not completely resolved at all angles. For these points the shape of the peaks were taken from the measurements made with the unmixed scintillators at the same energy and angles for the relative distribution and efficiency measurements. These peak shapes were then superimposed on the mixed scintillator data and the two peaks were unfolded. This technique was probably less accurate than that used for the two parameter data. Hence a greater probable error must be assigned to the single parameter data. A reasonable estimate of the probable error incurred from (1) above for

the single parameter data is 6%, and for the two parameter data, 4%. These figures were derived from the differences in the extracted counts that occurred when different methods of background subtraction were used. With the improved time resolution these figures should be lower by a sizable factor.

For the relative efficiency measurement, a probable error of 2% for each point is assigned. Since a consistent technique for background subtraction was used, this seems to be a reasonable value to allow for any constant errors due to the background subtraction.

The D/H ratio is probably known to within 0.5% in view of the care with which the second of the two mixed scintillators was prepared.²²⁾ Measurements at 11.952 MeV were made using first the mixed scintillator with the ratio of 59.2/40.8 and second the mixed scintillator with an assumed ratio of 60/40 as scatterer. The cross sections differed by 1.46%, well within the statistical accuracy of the measurement.

The uncertainty in the total n-p cross section was taken to be 1%. The experimental data in the energy region of interest is quoted to have this accuracy. Interpolation between the experimental points is provided by a formula given by Gammel.²⁵⁾

For the relative angular distributions, the problem with the background subtraction was not so severe. However, the error due to the normalization probably compensates for this.

In order to illustrate the relative magnitudes of the various contributions, a calculation will be made for the absolute measurement at a scattering angle of 33.3° and an incident energy of 9.035 MeV. The various errors are (1) 4% for background subtractions, (2) 2% for the relative efficiency measurement, (3) 0.5% for the uncertainty in the D/H ratio, (4) 1% for the n-p cross section uncertainty, and (5) 4% for the sum of the statistical uncertainties in C_{np} , C_{nd} , and the background counts subtracted from each of these. The r.m.s. of these five quantities is 6.1%.

IV. DATA

A. n-p Measurements

The efficiency data from n-p scattering were analyzed according to the procedure given in Section III. All the efficiency measurements were taken before the two parameter technique was instigated. The data are given in Table I.

For different bombarding energies, the ratio of primary source neutrons to background neutrons recorded by the monitor detector was not the same. It was desirable, however, to use different bombarding energies to cover the energy range of interest, even though in principle all scattered energies below the primary energy could be obtained by varying the scattering angle. For the large angle measurements, however, the angular range subtended by the detectors makes these measurements inaccurate for high incident energy because of the rapid variation of neutron energy with scattering angle. Thus the large angle measurements were taken with a low incident energy. These data were then used to normalize the high incident energy measurements. The normalization factor was calculated from the region of overlap of the two groups of measurements.

The graph of the data given in Table I is shown in Fig. 5 of Section II D (2).

Table I. The data obtained from n-p scattering on the relative efficiency of the detector. The definitions of the symbols in the table are as follows:

E_{np} = the energy of a neutron of the tabulated incident energy scattered from a proton through the indicated scattering angle,

C_{np} = the number of neutrons scattered from protons and detected for a given total number of neutrons created at the target,

M = the number of counts recorded by a monitor counter, and

$\epsilon(E_{np})$ = the ratio of the indicated quantity, which is the relative efficiency.

TABLE I. EFFICIENCY MEASUREMENTS

INCIDENT ENERGY (MEV)	SCATT. ANGLE (DEG.)	E_{np} (MEV)	C_{np}	M ($\times 10^{-3}$)	NORM. FACTOR	$\epsilon(E_{np}) =$ $\frac{C_{np}}{M \cos \psi} \times N.F.$
5.984	27.3	4.72	5299	300.13	1.00	19.90
	33.3	4.18	4936	300.09		19.70
	39.1	3.60	4524	300.18		19.40
	44.0	3.10	7007	500.02		19.50
	48.9	2.59	6815	500.09		20.73
	53.9	2.08	5291	500.14		17.94
	58.6	1.62	6254	801.54		14.99
	63.6	1.19	4551	1013.72		10.08
	68.4	.81	1124	1000.15		3.04
9.035	48.9	3.91	6624	599.26	1.120	18.82
	44.0	4.68	8874	724.04		19.08
	39.1	5.44	11366	853.70		19.22
	33.3	6.31	11267	780.09		19.35

B. Cross Sections

Angular distributions were obtained at incident energies of 5.635 and 9.035 MeV. The 5.635 MeV data were taken with the single parameter technique, and is deficient in measurements near 100° in the center-of-mass system. The 9.035 MeV data were taken with the two parameter technique, and is a reasonably complete angular distribution. Unfortunately all the data reported here were taken with the source to scatterer distance smaller than the optimum value.

The mixed scintillator data are given in Table II. The counts extracted from the spectra, C_{nd} and C_{np} , as well as the center-of-mass cross sections are tabulated. The transformation to the CM system was facilitated by the tables of Marion, et al.²⁶⁾. The probable error represents the root-mean-square of the estimate of the contributions from the various error sources given in Section III C and the statistical error associated with each point.

The relative angular distribution data are given in Table III. Column 5 gives the relative numbers obtained, and Column 6 gives the center-of-mass cross sections resulting from the normalization to the mixed scintillator data. The quoted probable errors were derived in the same manner as those quoted for the absolute data.