assuming isotropy in the center of mass system. A comparison of the observed fractional catcher yield with the calculated one is shown in Fig. 4.

Ratios below 1.0 cannot be considered inconsistent with isotropy if the average triton energy at the back angles is sufficiently lower than corresponds to the two body reaction considered above at each energy. If, on the other hand, the average is higher, an upper limit can be set by considering the reaction $D+Li^6 \rightarrow T+He^4 +H+2.51$ Mev to be isotropic for the case where the proton and the alpha particle have no relative motion. Near 0.4 Mev, this assumption barely corresponds to the observed points. This is the limiting case, and it seems likely the average is far from it. The observed effect near 0.4 Mev cannot be explained as due to greater target heating and consequent tritium loss from the targets, as much thinner targets and lower beam currents were used at this energy than above 1 Mev where the assymetry appears reversed.

A more detailed study of the angular distribution should be possible with a modified technique using several tritium catcher foils at various angles to the beam.

SUMMARY

Within the limits of experimental error, the threshold for the $Li^7(d,t)Li^6$ reaction agrees with the computed value, 1.27 Mev. The cross section rises with energy above threshold to about 95 millibarns at 2.4 Mev, and then to about 165 millibarns at 4.1 Mev. The $Li^6(d,t)Li^5$, $(p)He^4$ cross section rises to 190 millibarns near 1 Mev, then to 290 millibarns near 4 Mev. Thanks are due to many of our colleagues at the Oak Ridge National Laboratory who contributed materially to this study.

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Recoil Deuterons and Disintegration Protons from the *n-d* Interaction, and *n-p* Scattering at $E_n = 14.1$ Mev*

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A counter-telescope consisting of two proportional counters and a NaI scintillator in triple coincidence has been used to study the angular distribution of scattered deuterons and disintegration protons from the interaction of 14.1-Mev neutrons with deuterium. Charged reaction products were identified by simultaneous observation of particle energy and rate of energy loss. Thin radiators of deuterated and normal polyethylene were used, the latter to investigate the incident neutron spectrum and *n-p* scattering at 14.1 Mev.

The absolute differential cross sections observed over the recoil angular range 0 to 55 degrees in the laboratory for elastic *n-d* and *n-p* scattering are in good agreement with the recent nuclear-emulsion results of Allred, Armstrong, and Rosen, and with the theoretical results of Christian and Gammel. The anisotropy of *n-p* scattering was found to be about six percent. Protons from disintegration of deuterium were observed over the angular range of 0 to 80 degrees in the laboratory, and the integrated cross section for the forward hemisphere is larger than has been observed previously. The energy distributions appear more nearly uniform than those estimated by Frank and Gammel, and the angular distribution more strongly peaked forward.

INTRODUCTION

THE study of nucleon-deuteron interactions has been the subject of many theoretical and experimental investigations. A comprehensive survey of the general problem, together with a bibliography to 1953, may be found in a recent review article by Massey.[1] At relatively low energies (below 6 Mev), comparison of *n-d* and *p-d* scattering favors change symmetry (i.e., equivalence of *n-n* and *p-p* nuclear forces) and some type of exchange force, but experimental uncertainties have made detailed comparison difficult. At higher intermediate energies, only two *p-d* experiments have been performed, at 9.66 Mev[2] and at 20.6 Mev.[3] Several *n-d* experiments between 10 and 15 Mev have been reported[4–7] but the results have not been entirely consistent. Since *n-d* elastic scattering is highly anisotropic, it is quite essential for theoretical interpretation that absolute cross section measurements be made. Moreover, neutrons over 3.3 Mev are energetically able to disintegrate the deuteron, and this interaction, which is the simplest case of inelastic scattering and an im-

* Work performed under the auspices of the U. S. Atomic Energy Commission.

[1] H. S. W. Massey, in *Progress in Nuclear Physics*, O. R. Frisch, Editor (Pergamon Press, London, 1953), pp. 235–270.

[2] Allred, Armstrong, Bondelid, and Rosen, Phys. Rev. **88**, 533 (1952).

[3] D. O. Cladwell, University of California at Los Angeles thesis, January 1954 (unpublished).

[4] Ageno, Amaldi, Bocciarelli, and Trabacchi, Phys. Rev. **71**, 20 (1947).

[5] J. H. Coon and R. F. Taschek, Phys. Rev. **76**, 710 (1949).

[6] Griffith, Remley, and Kruger, Phys. Rev. **79**, 443 (1949).

[7] T. C. Griffith, Proc. Phys. Soc. (London) **A66**, 894 (1953).

portant problem by itself, gives rise to protons which must be taken into account and distinguished from deuterons in order to obtain even a relative angular distribution for *n-d* elastic scattering.

The most recent and detailed investigation of the *n-d* interaction was made at Los Alamos by Allred, Armstrong, and Rosen[8] at 14.1 Mev, using the monoenergetic $T(d,n)He^4$ reaction and a multiplate nuclear-emulsion camera, together with a neutron collimator, to insure good angular resolution and low background. These investigators were able to discriminate against the disintegration protons to obtain the absolute elastic differential cross section in detail for cm neutron angles between 46 and 176 degrees, and they found in particular that the differential cross section at the minimum near 120 degrees was only half as large as had been previously reported. Disintegration protons were unequivocally detected between 2 Mev, the lower limit set by track selection criteria, and the allowed maxima, but background and statistical uncertainties were large. A semiquantitative angular distribution for the disintegration protons was obtained which was forward-peaked and extrapolates to about 42 ± 12 mb/sterad for the differential cross section for protons over 2 Mev in the forward direction in the laboratory, with an integral of 53 ± 15 mb.

A new theory[9] of the *n-d* and *p-d* interactions was developed concurrently with the above experiment, which was upsetting to the hope of obtaining information about nuclear forces from analysis of intermediate-energy experiments. Close agreement with experiment was found using a formulation in which the principal physical process is a "pickup" interaction wherein the incident particle interacts with the unlike nucleon to form a "new" deuteron. The triplet even-parity *n-p* force dominates the scattering, which is nearly independent of the *n-n* and *p-p* forces. Moreover, the range, shape, and tensor nature of the *n-p* force do not affect the phase shifts in a sensitive manner. Very good agreement with the most reliable *n-d* and *p-d* scattering experiments was obtained over the energy range of 1 to 14 Mev, and except in the region of the interference minimum, with the *p-d* experiment at 20.6 Mev.[3,10] In view of this result, de Borde and Massey[11] have extended their earlier calculations[12] to include higher order phase shifts using a similar Serber-type exchange force and find reasonably close agreement.

Frank and Gammel[13] have developed a simplified theory of the disintegration process whereby a connection between elastic and inelastic cross sections could be established independent of the properties of two-body forces. Given the elastic distribution, their formulation could be used to make a prediction of both the energy and angular distribution of the disintegration protons from the *n-d* interaction. Comparison with the results of Allred, Armstrong, and Rosen[8] showed qualitative agreement, with the theory predicting somewhat larger values. No comparison energywise was possible. Even quantitatively, the agreement was better than the assumptions of the theory merit, and very much better than the more elaborate calculations of Bransden and Burhop.[14]

We are apparently forced to accept that the *n-n* interaction plays a negligible part in the elastic *n-d* scattering, but it is even more difficult to believe that it does not enter into the disintegration of the deuteron.

The present experiment was designed to investigate the energy and angular distribution of protons from the inelastic interaction of 14-Mev neutrons with deuterons in more detail than was practicable with the nuclear emulsion technique,[8] and to remeasure the *n-p* and *n-d* elastic differential cross sections in an independent manner.

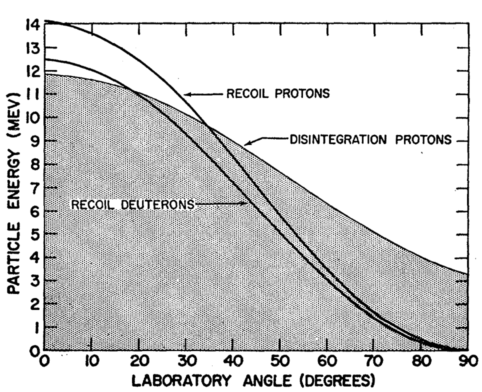

FIG. 1. Energies of charged particles arising in the *n-p* and *n-d* interactions at $E_n=14.1$ Mev, given as a function of the angle of observation in the laboratory.

METHOD AND APPARATUS

The energies of the different particles to be encountered are shown in Fig. 1, plotted as a function of laboratory angle. For elastically recoiling deuterons and protons, the function is $E_{\max}\cos^2\theta$, where $E_{\max}$ is 14.1 Mev for protons, and 12.63 Mev for deuterons when struck by 14.1-Mev neutrons. The maximum energy a disintegration proton can have may be calculated by noting that this corresponds to the two neutrons going off together in the cm direction opposite to the proton, so this limit may be treated as a two-body collision. Since the disintegration process which gives rise to the protons is in fact a three-body breakup, protons of all energies up to this maximum may be present. Inspection of Fig. 1 will show that it is difficult to discriminate

[8] Allred, Armstrong, and Rosen, Phys. Rev. **91**, 90 (1953).
[9] R. S. Christian and J. L. Gammel, Phys. Rev. **91**, 100 (1953).
[10] J. L. Gammel (private communication).
[11] A. H. de Borde and H. S. W. Massey (unpublished). See reference 1, Fig. 10.
[12] Buckingham, Hubbard, and Massey, Proc. Roy. Soc. (London) **A211**, 183 (1952).
[13] R. M. Frank and J. L. Gammel, Phys. Rev. **93**, 463 (1954).
[14] B. H. Bransden and E. H. S. Burhop, Proc. Phys. Soc. (London) **A63**, 1337 (1950).

among the different groups on the basis of energy alone, and moreover the finite angular aperture of the detecting system places a limitation on the energy resolution attainable at the larger angles. For the elastic recoils, $E=E_{\max}\cos^2\theta$, and $\Delta E/E=2\tan\theta\Delta\theta$. Particularly for the observation of the low-energy portion of the proton spectrum, observation of specific ionization or dE/dx would insure proper identification. Since the use of multiple-coincidence techniques is a practical necessity for the electronic detection of low energy charged particles in the presence of an intense fast neutron flux, a coincidence counter-telescope previously developed for this purpose by Ribe and the author[15] was readily adapted for use in the present investigation. The counter-telescope which consists of two gas proportional counters and a NaI scintillator and photomultiplier in triple coincidence has already been described in detail.[15]

In use, the gas counters were filled with about 0.1 atmos of krypton with 5 percent CO_2, which gave between 25- and 200-kev energy loss by the particles as they traversed each counter, giving a measure of dE/dx in the gas counters simultaneously with a measure of E in the crystal. The counter-telescope was mounted on an indexed stand so that its axis could be rotated in a horizontal plane about a vertical axis lying in the plane of the radiator, and the angle made by the reaction products with respect to the direction of incident neutrons read directly from the index.

The 14-Mev neutrons were obtained from the $T(d,n)He^4$ reaction by bombarding a thick zirconium-tritium target[16] with the 250-kev monatomic deuteron beam from a Cockcroft-Walton accelerator. The radiator was placed at 90 degrees with respect to the deuteron beam. At this position the incident neutrons were almost monoenergetic with an energy of 14.10 ± 0.05 Mev. The number of neutrons from the reaction was measured by counting the accompanying alpha particles emitted into a well-defined solid angle. A schematic representation of the counters and the associated electronic circuits is given in Fig. 2. The pulses resulting from the ionization in the two proportional counters and from the scintillation in the NaI crystal are amplified and fed into a triple coincidence circuit, the output of which gates open two multichannel pulse-height analyzers[17] in time to receive the (delayed) pulse-height representations of E and dE/dx, respectively. The Los Alamos Model 301 coincidence circuit[18] provides stable upper and lower discriminator settings whereby a pulse-height group of interest can be selected, and a dynamic rise-time delay together with fixed delays adjustable in steps of 0.1 μsec for each channel whereby the fast proportional counter pulses could be brought into delayed coincidence with the slower NaI scintillation pulses.

[15] F. L. Ribe and J. D. Seagrave, Phys. Rev. **94**, 934 (1954).
[16] Graves, Rodrigues, Goldblatt, and Meyer, Rev. Sci. Instr. **20**, 579 (1949).
[17] C. W. Johnstone, Nucleonics **11**, No. 1, 36 (1953).
[18] Designed by C. W. Johnstone.

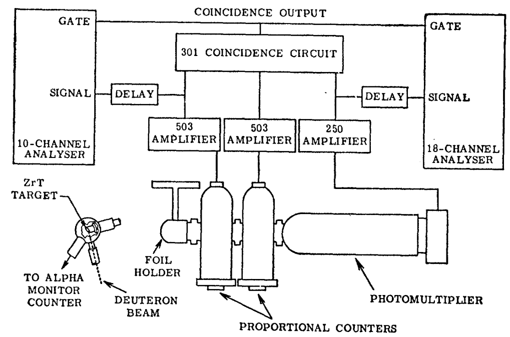

FIG. 2. Schematic block diagram of the apparatus used to study the *n-d* interaction. Preamplifiers, scalers, and counter details are not shown.

The radiators were thin foils of normal and deuterated polyethylene mounted on platinum and retained in the foil holder by a ring of 20-mil platinum (thick enough to stop 14-Mev proton recoils). On the back side of the foil holder a similar piece of platinum was mounted, so that background counts due to disintegration of the counter lining and filling could be evaluated. The deuterated polyethylene (CD_2) which was prepared by A. R. Ronzio of this laboratory had an isotopic composition of 96.5 atom percent deuterium and 3.5 atom percent hydrogen. The principal impurity was 0.3 percent oxygen (by weight) arising from the catalyst used in polymerization. Small bits of this material, and of normal polyethylene were pressed into foils a few thousandths of an inch thick. After measurement with a sensitive dial gauge, a satisfactorily uniform area of foil was selected and clamped between two cover glasses, so that a circle of known area could be cut out. The chosen radiators were then cleaned in absolute alcohol, dried in vacuum, and weighed in a microbalance. The effective diameter of the radiator was determined by the retaining diaphragm, either $\frac{3}{8}$ or $\frac{7}{8}$ in. in diameter, but the corresponding foil diameters were only slightly oversize, so the uncertainty in the surface density of the area exposed was small. In the $\frac{3}{8}$-in. diameter, CD_2 densities of 4.04, 6.55, and 10.59 mg/cm^2 were used, and in the $\frac{7}{8}$-in. diameter, also 4.04 mg/cm^2. Only one CH_2 radiator was used, $\frac{3}{8}$ in. diameter, of density 10.09 mg/cm^2. The solid-angle defining aperture, which was $\frac{7}{8}$ in. in diameter, was placed directly in front of the NaI crystal, and the solid angle subtended at the radiator by this diaphragm was 1.264 $\times 10^{-2}$ sterad. Three additional diaphragms were placed inside the counter telescope to serve as antiscattering baffles.

Tests of Spectrometer Operation

A mercury-relay precision pulser was used throughout the experiment to establish and check discriminator settings, amplifier gains and linearity, analyzer adjustment, and operation of the coincidence circuit. The coincidence circuit was operated with a resolving time of 0.35 μsec. Unfortunately, the channel delay setting could not be established with the pulser due to the differing rise times of the pulses from the scintillator and proportional counters, and it was necessary to take data of counting rate as a function of relative channel delay for the elastic recoil group to establish and check the operating point. Under some conditions, the lowest energy protons detectable were not counted when the delays were set for the recoil group, and the precaution was always taken to repeat the observations with several different delays to be sure of counting all the particles.

The individual channel and coincidence counting rates were monitored by scalers (not shown in Fig. 2) so that the accidental counting rate could be calculated; accidental coincidence counts could also be evaluated empirically by inserting an additional 1.5-μsec delay in the scintillator channel so that no true coincidences were recorded. Data was taken under conditions such that both the accidental triple coincidences and double coincidences between analyzer gating and counter singles were negligible.

Several different CD_2 targets (enumerated above) were used, to explore any possible systematic error arising from the targets. At 5° the proton data from targets ranging in thickness from 4.04 to 10.59 mg/cm^2 and in mass exposed from 4.69 to 15.4 mg were in excellent agreement.

The effect of the spectrometer aperture has been discussed previously;[15] the angles given in this paper are the mean angles of observation, and the associated uncertainties indicate the corresponding half-widths of the angular resolution functions. Thus, when the angle between the spectrometer axis and the incident neutrons was zero, the mean angle of observation with the $\frac{3}{8}$-in. diameter radiator was 3.5±2 degrees. The zero-setting of the index was determined by making observations of the sharply-peaked *n-d* angular distribution

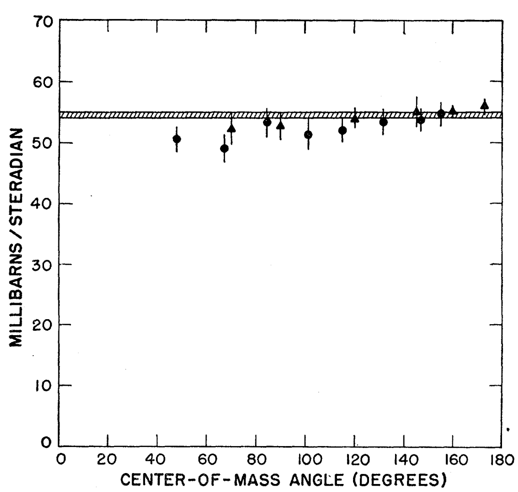

FIG. 3. *n-p* scattering at $E_n = 14.1$ Mev. (▲) This experiment; (●) Allred, Armstrong, and Rosen; shaded region is $\sigma_T/4\pi$ if one uses $\sigma_T = 689 \pm 5$ mb (Poss, Salant, Snow, and Yuan).

(see below) in the vicinity of 10 degrees to each side of an arbitrary "zero" until the corresponding measurements agreed, whereupon the true zero-setting could be inferred. The uncertainty in angular position arising from this procedure is less than one degree, which is considerably less than the half-widths of the angular resolution functions.

In order to establish the energy scale for the disintegration protons from the recoil deuterons observed simultaneously, it is necessary to know the ratio of light emitted in NaI by protons and deuterons of the same energy. Work at the University of Illinois[19] has shown that the light response to NaI to protons and deuterons is linear within a few percent between 1 and 11 Mev, and that protons give about 5 percent more light than deuterons of the same energy. This ratio was determined in the course of this experiment to be $L_p/L_d = 1.04 \pm 0.01$ for protons and deuterons between 5 and 14 Mev by mounting CH_2 and CD_2 foils on opposite sides of the foil holder and comparing pulse-height distributions for elastically scattered protons and deuterons at several laboratory angles.

n-p Scattering

A measurement of the *n-p* angular distribution was made with a normal polyethylene radiator in the counter-telescope, to serve three purposes: (1) to check on the calculation of absolute cross sections from counter dimensions and source strengths; (2) to obtain independent data to compare with previous evidence[8,20] of a slight anisotropy in *n-p* scattering at 14 Mev; (3) to observe the spectrum of neutrons incident on the target, in order to make a correction to the *n-d* spectra for deuterons recoiling from degraded neutrons.

The results of the angular distribution measurements are shown in Fig. 3, where they are compared with the results of Allred, Armstrong, and Rosen,[8] and with the assumption of isotropic scattering based on the total cross section 689±5 millibarns measured by transmission.[21] It may be seen that the present results are in good agreement with the results of the very different nuclear plate technique, and the suggestion of anisotropy is confirmed. A least-squares fit to the present results of the form $A+B\cos\theta$ gave a value for $\sigma(\pi)/\sigma(\pi/2) = 1.047 \pm 0.025$ while a fit of the form $A+B\cos^2\theta$, which has better theoretical justification, gave the value 1.060 ± 0.023. These values may be compared with the value given by Allred, Armstrong, and Rosen[8] of 1.04 ±0.05 and that given by Barschall and Taschek[20] of 1.06±0.06. The points shown for the present experiment include a correction for the effect of degraded neutrons (see below) which amounts to about twice the statistical uncertainty for the points at 70, 90, and 120

[19] Taylor, Jentschke, Remley, Eby, and Kruger, Phys. Rev. **84**, 1034 (1951).
[20] H. H. Barschall and R. F. Taschek, Phys. Rev. **75**, 1819 (1949).
[21] Poss, Salant, Snow, and Yuan, Phys. Rev. **87**, 11 (1952).

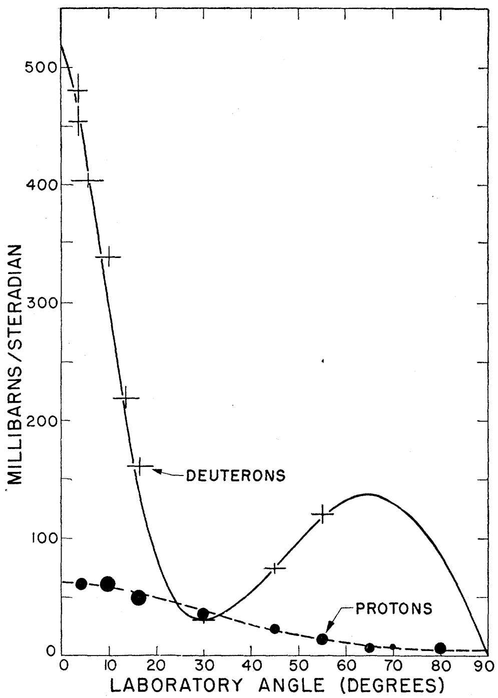

FIG. 4. Angular distribution of protons and deuterons from the n-d interaction at $E_n = 14.1$ Mev. The solid curve is the theoretical result of Christian and Gammel for elastically scattered deuterons; the dashed curve is a least-squares fit through the experimental points (●) for disintegration protons.

degrees. At these points the probable error plotted includes (arbitrarily) half of the amount of the correction; elsewhere the error shown is statistical only. It is not surprising to find anisotropy on the order of 6 percent at 14 Mev, since n-p scattering is markedly anisotropic at higher energies.[22,23] In view of the anisotropy observed, and the possibility of an up-turning of the differential cross section at small neutron angles, no correction was made to force the average value to agree with the total cross section. The disagreement is at worst no more than the uncertainty of 4 percent in the absolute neutron flux.

n-d Interaction

For clarity in the discussion to follow, the angular distributions in the laboratory system for the elastic and inelastic n-d interactions at $E_n = 14.1$ Mev as measured in this experiment are presented in Fig. 4. The distribution of elastically recoiling deuterons is strongly forward, with a sharp minimum in the vicinity of 30 degrees, qualitatively suggestive of a pick-up distribution for $L=0$. The angular distribution for protons from disintegration of deuterium is also peaked forward, but much less strongly so, and there are more protons than deuterons at 30 degrees.

EXPERIMENTAL PROCEDURE

With a CD_2 foil facing into the spectrometer, bombardments were generally made with an integrated flux at the radiator of 3.09×10^9 neutrons/cm^2, and the E and dE/dx pulse-height distributions recorded for all charged-particle pulses admitted by the particular upper and lower discriminator settings. A bombardment was then made using the same integrated flux of neutrons but with the foil holder rotated so that the platinum bank faced the spectrometer. The background so recorded, principally from disintegration of the gas filling of the first proportional counter, was then subtracted to give the net distributions attributed to the CD_2 radiator.

The principal competing reactions are $C^{12}(n,\alpha)Be^9$ and $C^{12}(n,n)3He^4$, but because of their high specific ionization, all such alphas were excluded by the upper discriminator on the proportional-counter channels. Care was taken that this limit was set below the overload level of the Model 503 amplifiers employed. The $C^{13}(n,\alpha)$ reaction was likewise excluded. The $C^{12}(n,p)B^{12}$ reaction was only 0.5 Mev above its threshold, and such protons (if any) would not have been detected. The $O^{16}(n,\alpha)C^{13}$ alphas were eliminated as above, and the 0.3 percent level of oxygen impurity reduced the contribution of $O^{16}(n,p)$ and (n,d) reactions, for which the cross sections are reported to be 35 and 15 mb, respectively,[24] to a negligible level.

The nature of the data and its treatment will be discussed with reference to Figs. 5 and 6. In Fig. 5 are

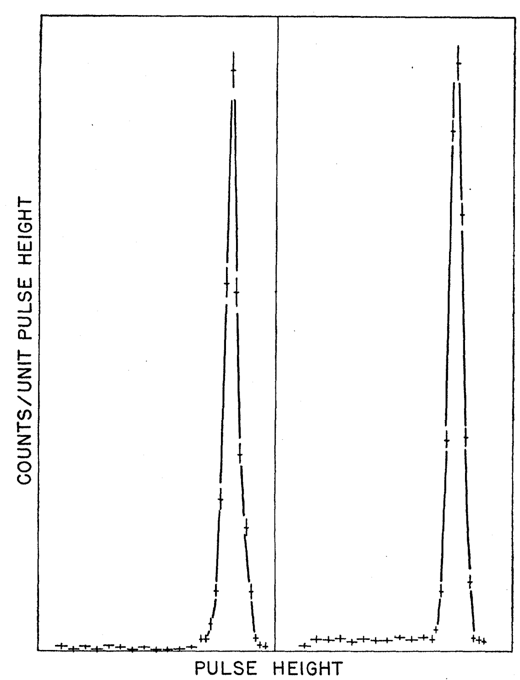

FIG. 5. Typical scintillator pulse-height distributions in the forward direction under bombardment by 14.1-Mev neutrons. On the left, CH_2 radiator; on the right, CD_2 radiator.

[22] Brolley, Coon, and Fowler, Phys. Rev. **82**, 190 (1951).
[23] Hadley, Kelly, Leith, Segrè, Wiegand, and York, Phys. Rev. **75**, 351 (1949).
[24] A. B. Lillie, Phys. Rev. **87**, 716 (1952).

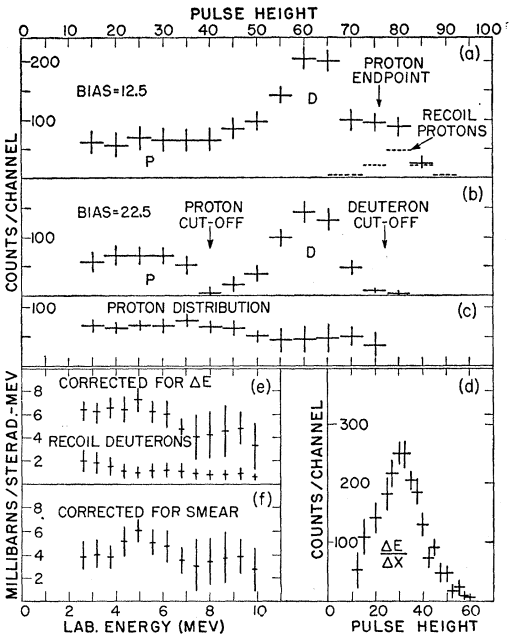

FIG. 6. Typical pulse-height distributions as the laboratory angle of 30 degrees, showing method of analysis. (a) Complete scintillation pulse-height distribution; (b) distribution with dE/dx-bias set to eliminate protons without affecting deuterons; (c) net proton distribution; (d) gas-counter pulse-height distribution; (e) proton distribution in energy, corrected for energy losses. Also shown are deuterons recoiling from degraded neutrons; (f) final proton energy distribution corrected for smearing. See text.

shown typical pulse-height distributions for the forward direction, in a form for comparison of the *n-p* and *n-d* interactions. The resolution of the system was, for 14-Mev protons, 6 percent width at half-maximum when observed with channels 2.5 percent wide. In the *n-p* case, the low-energy pulses correspond to protons recoiling from degraded neutrons present in the incident flux, and in the *n-d* case, the low-energy pulses correspond to disintegration protons, together with a few deuterons recoiling from the degraded neutrons. The manner in which protons and deuterons were disentangled is illustrated in Fig. 6, which shows the steps of analysis in the most difficult case, 30 degrees. In this case the number of protons and deuterons from the *n-d* interaction are nearly equal, and the proton distribution extends completely under the deuteron distribution which has already been broadened by the effect of finite angular aperture mentioned earlier. Moreover, the recoil protons from the hydrogen present in the "CD_2" foil are quite noticeable since the differential cross section for *n-p* scattering is more than five times as large as that for deuteron disintegration, and the recoil protons fall nearly on top of the end point of the disintegration protons. This situation is illustrated in Fig. 6(a). The dE/dx pulse-height distribution [Fig. 6(d)] at this angle cannot be used directly for diagnosis, but the peak of the distribution corresponds to dE/dx of the deuteron group of known energy and establishes the scale of dE/dx, so that other corresponding points may be calculated. As the lower limit for accepting dE/dx pulses in the coincidence circuit was progressively raised, the energy pulse-height distribution changed first by the loss of the recoil proton group, and then by progressive withdrawal of the disintegration proton group from beneath the deuteron group until the condition illustrated in Fig. 6(b) was reached, wherein the deuteron group is essentially unaffected,[25] and the protons have been removed. By comparison of (a) and (b) (and the intermediate steps not shown) the proton pulse-height distribution (c) can be deduced. When energy losses in the foil and gas are taken into account, and the measured light ratio $L_p/L_d=1.04$ (see above) is used, the pulse-height position of the recoil protons can be referred to that of the recoil deuterons. The width of the distribution was taken from the 30-degree data on *n-p* scattering. The amplitude corresponds to the H/D ratio of 3.6 percent given by mass-spectrographic analysis of the deuterated ethylene gas before polymerization. When the amplitude of the recoil-proton distribution was adjusted to give best fit to the data, the H/D ratio was found experimentally to be 4±2 percent. Since this determination is limited statistically by the difficulty of obtaining data at this most sensitive point, the value of 3.6 percent was accepted and used throughout the experiment. The distributions of Fig. 6 (a), (b), and (c) represent the analysis of but one run of several. The average of all such runs was used in plotting Fig. 6(e) which gives the proton *energy* distribution in millibarns per sterad-Mev. Included in this graph is the distribution of recoil deuterons arising from degraded neutrons (discussed below). When these are subtracted, the proton distribution is obtained except for one final correction, the distortion arising from the fact that the energy loss of low-energy particles is larger than that of high-energy particles, so that when the spectrum is observed with channels of constant width, and the counts per channel are replotted at the mean energy of each channel, as in Fig. 6(e), there is a piling-up in lower channels. Or, to say it another way, the lower channels are wider *in energy*, so to get the differential cross section *per* Mev, one must reduce the cross section per channel in proportion to the energy-width of the channel. For a mathematical formulation of this "smearing," let $n(E)=d^2\sigma/d\Omega dE$, the desired distribution of events per unit energy. Since these take place throughout the radiator, particles lose energy according to both their initial energy and their position, so it is necessary to integrate $n(E)$ over the thickness of the foil in units of equal energy loss, as follows. Let E_1 be the emergent energy and $n_1(E_1)$ the corresponding

[25] A small correction for high-energy deuterons lost due to finite dE/dx resolution was applied. See reference 26.

distribution function. Then

$$n_1(E_1)=\frac{1}{X}\int_{E_1}^{E_1+\Delta(E_1)}\frac{n(E)dE}{(dE/dx)},$$

where X is the thickness of the foil and $\Delta(E_1)$ is the energy lost in passing completely through the foil by a particle *emerging* with energy E_1. When $\Delta(E_1)\ll E_1$, as was generally the case in this experiment, the integral may be replaced by a product of averages, so $n_1(E_1)=n(\bar{E})[\Delta(E_1)/\Delta(\bar{E})]$, where $X\langle dE/dx\rangle_{\text{Av}}=\Delta(\bar{E})$ and $\bar{E}$ is the mean energy in the foil. The resulting equation may readily be solved for $n(\bar{E})$, which is the desired distribution function. Since the energy loss in the gas was small compared to that lost in the foil, and all the particles passed through all the gas, the correction for smearing in the gas was negligible, and was not applied, although the mean energy loss in passing through the gas was of course taken into account.

In order to make a correction to the disintegration proton spectrum for deuterons recoiling from degraded incident neutrons, one must in principle know the incident flux, both as to energy and angle of incidence, and the highly anisotropic *n-d* differential cross section for all energies. This is a good deal more information than is available. The "tails" of the spectra obtained with a CH_2 radiator are reproduced in Fig. 7, where they are plotted as apparent differential cross sections, or as if they resulted directly from interaction of the target material with the primary 14-Mev neutrons, it being assumed that the degraded flux is proportional to the primary flux. The regions where data are absent are those covered by the primary recoil protons. The last distribution shown in Fig. 7 is the average of applicable data for all five angles, and the shaded region covers this average and an (arbitrary) uncertainty of plus and minus one-half its value. This same shaded region has been replotted over the data for the five angles, and purports to show that in view of the statistical uncertainty of the individual data points, this average is a fair representation of the collective data at the several angles. Were this exactly so, or were the data in better support of this hypothesis, it would mean that the secondary neutron flux was isotropically incident on the radiator. Consider now what could be expected of neutrons proceeding directly from the neutron source, imagined to arise from inelastic scattering in the zirconium, silver, tungsten, and steel of the target assembly. Given a characteristic shape to the recoil spectrum at 0 degrees, the prominent features of the distribution should move down in energy as $\cos^2\theta$ when θ is increased. It is difficult to discern any such effect in the data of Fig. 7. The total amount of degraded flux amounts to about 4 percent of the primary flux. One can account for the order of 1 percent scattering in the target assembly from known cross sections. If there were this much straight from the target it would be

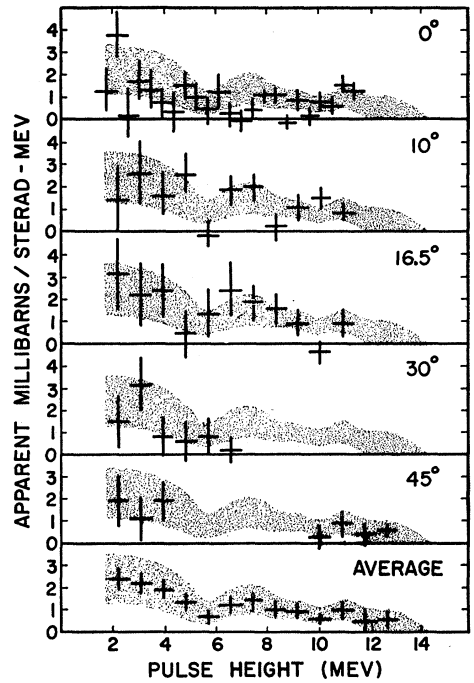

FIG. 7. Distribution of proton recoils from CH_2 radiator arising from degraded neutrons present in the incident flux. The shaded area is a smoothed average over angles with an associated uncertainty of $\pm$ half its value. See text.

indistinguishable in the presence of the isotropic 3 percent, but if there were more, it should exhibit dependence on $\cos^2\theta$. A similar problem of course arose in the nuclear-emulsion investigation[8] of the *n-d* interaction, except that there was more evidence to treat the secondary flux as arising primarily from small angle scattering in the aperture of the collimator-shield used; a summary of measurements of *n-d* angular distributions at low energies is presented in that paper. That information was used by the present author to prepare a smoothed logarithmic plot of $d\sigma_{n-d}/d\sigma_{n-p}$ against neutron energy and recoil angle (not shown) as an aid to evaluating a correction for recoil deuterons based on the data for recoil protons. Now if the incident flux were known in detail, or could be unequivocally deduced from the recoil proton distributions, one could proceed to evaluate the recoil deuteron distribution at a given angle of detection by averaging $d\sigma_{n-d}/d\sigma_{n-p}$ over the range of neutron energies which could give rise to the particular choice of angle and recoil energy. For orientation, the correction factor N_d/N_p (E_d,θ) was calculated by averaging in the manner indicated for two assumptions consistent with the data, (1) uniform flux, and (2) one-third direct from the target, two-thirds uniform. In case one, which is in best agreement with the data but hard to accept implicitly, the factor was between 0.7 and 1.0 for all energies and angles. For case two, which is probably more realistic, the factor range from 0.5 to 1.5, being highest for small

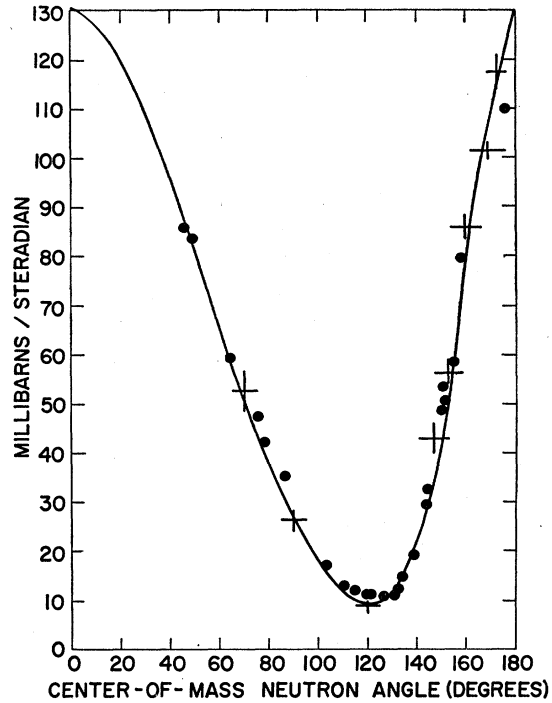

FIG. 8. n-d elastic scattering at $E_n = 14.1$ Mev. The solid curve is the prediction of the theory of Christian and Gammel, which is compared with the results of this experiment (+) and the results of Allred, Armstrong, and Rosen (●).

angles and large energies and least for large angles and intermediate energies, and in the vicinity of 1.0 for all angles at the lowest energies detected. These calculations merely indicate that the errors likely to be incurred through ignorance of the neutron flux in complete detail are within reasonable bounds, and are in general comparable with the statistical uncertainty of the data. Accordingly, the correction factor was set equal to 1.0, with an uncertainty of ±0.5, which was carried along in subsequent estimates of error. A typical distribution obtained in this manner is shown in the lower part of Fig. 6(e). Some confidence that there is no gross error in thus proceeding is to be had from the numerous cases in the original data, one of which is illustrated in Fig. 6(b), where the discriminators for accepting dE/dx pulses were deliberately set so as to exclude protons but not deuterons above a certain pulse height. In no case was the net number of counts above such a point in excess of the correction subsequently applied for deuterons, and in general the correction was less than the statistical uncertainty of the net data. Also, in a number of cases it was possible to compare a set of data corrected in this manner with another in which no correction was made in certain channels because the deuterons were biased out. Good agreement was noted, i.e., the order of magnitude of the correction was correct, and agreement of such sets was within statistical uncertainties only if the correction was made. It may be remarked that deliberate "cutoffs" produced by manipulation of dE/dx limits were rather more sharp than would be inferred from the widths of the combined dE/dx distributions and the theory of energy loss.[26] Experimentally, however, the shape of the cutoff for one kind of particle could generally be inferred from the data for the other type.

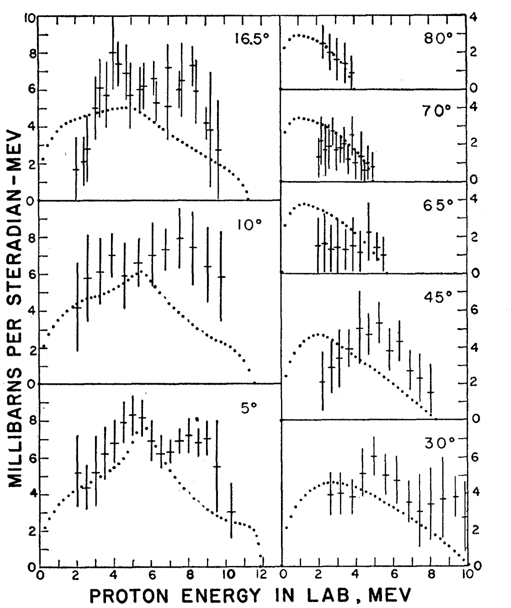

FIG. 9. Distribution in energy of the disintegration protons from the n-d interaction at $E_n = 14.1$ Mev. The predictions of the theory of Frank and Gammel are shown as dotted curves.

TABLE I. Elastic scattering of deuterons by 14.1-Mev neutrons.

Lab. angle θ_d	3.5	5.5	10	13.5	16.5	30	45	55
degrees[a]	± 2.0	3.5	3	3	3	2.5	2.5	2.0
Lab. $d\sigma/d\Omega$	468	404	339	219	161	30.4	75	121
mb/sterad	±14	6	9	10	8	3	5	9
Cm angle ϕ_n	174	169	160	153	147	120	90	70
degrees[a]	± 4	7	6	6	6	5	5	4
Cm $d\sigma/d\Omega$	117.5	101.5	86	56.4	43	8.8	26.5	52.7
mb/sterad	± 3.5	1.5	2.3	2.6	3	0.9	1.8	4

[a] Angles given are mean angles of observation, and the associated uncertainties indicate the corresponding half-widths of the angular resolution functions.

RESULTS

The differential cross sections for elastic scattering of 14.1-Mev neutrons by deuterium are presented numerically in Table I, and the angular distribution in the center-of-mass system is shown in Fig. 8, where it is compared with the experimental results of Allred, Armstrong, and Rosen,[8] and with the theory of Christian and Gammel.[9] The close agreement between the results of two very different experimental techniques is gratify-

[26] See B. Rossi, *High Energy Particles* (Prentice-Hall, New York, 1952) for a summary of relevant parts of Symon's theory of energy loss by ionization (unpublished).

ing and indeed the small differences can readily be accounted for by the broader angular resolution and statistical uncertainties of the previous experiment. In comparing these two experiments, a possible source of error affecting both experiments equally should be discounted: both experiments were performed with the same neutron source whose absolute strength is uncertain to 4 percent. It is hard to draw a much better curve through the data than that provided by the theory, but it may be noted that most of the data falls slightly above the theoretical curve, and an integral of the present results, granting the extrapolation provided by the theory, is 0.61 ± 0.03 barn. The theoretical value is 0.60 barn.[27]

The distribution in energy of the protons from the disintegration of deuterium by 14.1-Mev neutrons is shown in Fig. 9, where the results of this experiment

TABLE II. Protons from disintegration of deuterons by 14.1-Mev neutrons.

Lab. angle θ_p degrees	5	10	16.5	30	45	55	65	70	80
Lab. $d\sigma/d\Omega$ mb/sterad	60.2 $\pm$4.5	60.8 6.1	49.5 4.6	35.9 4.7	23.2 4.1	15 5	7.5 3.3	8.1 2.6	7.3 5
Deuteron bgnd.[a] percent	12	14	17	20	26	35	47	39	0

[a] See text. The average figure given is the percent correction applied to the data to obtain the proton distribution, although the channel-by-channel correction varied considerably, and in some instances was zero due to the bias setting. At 80 degrees all deuterons were degraded below the threshold of detection.

are compared with the prediction of the theory of Frank and Gammel.[13] Qualitatively it would appear that the experimental distributions lie well above the theoretical curves in the upper third of the energy range, while the theory predicts peaking at from half to one-third of the maximum. More quantitative comparison is probably not warranted since the theory contains a number of convenient assumptions permitting a result in closed form, while on the other hand the experimental probable errors, though believed conservative, are sufficiently large that no smooth curves through the data were drawn.

The data extend over a sufficiently large portion of the allowed range of energy, however, that extrapolation to the end points can be made without appreciably increasing the aggregate probable error of the integral. The distribution must vanish at both end points,[28] so the extrapolation for purposes of integration was made

[27] The value of 0.62 barn quoted on p. 119 of reference 9 is an error.

[28] Reference 13 and J. L. Gammel (private communication).

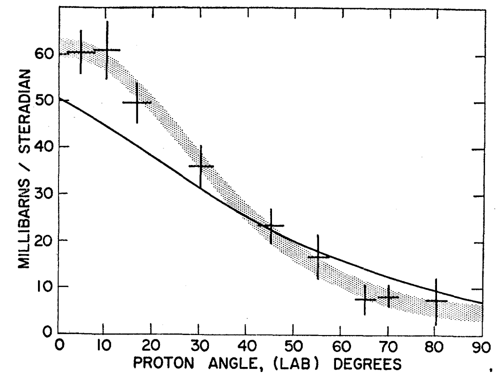

FIG. 10. Comparison of the angular distribution of disintegration protons from the n-d interaction at $E_n=14.1$ Mev as given by this experiment and by the theory of Frank and Gammel.

by drawing straight lines from the last data points to the end points (i.e., constructing triangular areas) and including these areas with probable errors equal to their values in the integral. The resulting differential cross sections are tabulated in Table II, and shown in Fig. 10 in comparison with the theoretical angular distribution. The difference in this case is less marked, with experiment indicating a somewhat more strongly forward-peaked distribution. The integral over the forward hemisphere is slightly greater, namely 117 mb for the theoretical curve than for the experimental curve which gives the value 112 ± 15 mb.

There remains, however, a difference of nearly 200 mb between the total cross section measured by transmission[21] of 803 ± 14 mb and the elastic cross section of 0.61 ± 0.03 barn as determined in this experiment. The cross section for disintegration protons in the rear hemisphere must then be about 90 mb, whereas the theory predicts only 27 mb. It is regrettable that it was not possible to obtain data in the rear hemisphere, since the neglect of the n-n interaction in the theory[13] should have proportionately a larger effect in the rear hemisphere and a direct comparison of distributions would be more enlightening than the grosser comparison just made, namely, that the theory neglecting the n-n interaction accounts for only about one-third of the interactions producing protons in the rear hemisphere.

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