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Interaction of 24.0- and 27.2-MeV Neutrons with Deuterons*

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The angular distributions of 24.0- and 27.2-MeV neutrons scattered elastically by deuterons through angles between 90 and 166° (c.m.) were measured. Proton-emission energy spectra were studied at 11 and 22° (lab) and angular distributions were measured between 11 and 46° (lab). The spectra and angular distributions were normalized to the n-p differential cross section at 158° (c.m.). The minimum cross sections of neutrons elastically scattered by deuterons were found to be less than the minimum cross sections of elastically scattered protons.

[NUCLEAR REACTIONS ^{2}H(n,d), (n,p), E=24.0, 27.2 MeV; measured $\sigma(\theta_n)$, θ_n=90–166° (c.m.), $\Delta\theta_n$=5.6–10.0°; measured $\sigma(\Theta_p)$, Θ_p=11–45° (lab), $E_p \geq 10$ MeV, $\Delta\Theta_p$=5–6° (lab); measured $\sigma(E_p, \Theta)$, Θ=11, 22° (lab), $E_p \geq 10$ MeV, $\Delta\Theta$ = 5°.]

INTRODUCTION

The present experiment was undertaken to provide additional information on the three-nucleon interaction and the neutron-neutron interaction.

Previous measurements of the N-d differential cross sections in the region between 14 and 30 MeV include p-d cross-section measurements at 22- and 20.57-MeV incident energies[1,2] and n-d differential cross sections between 45 and 155° for neutron energies of 18.55, 20.5, and 23.0 MeV (part of a set of seven distributions extending down to 5.5 MeV),[3] and between 10 and 180° for 28-MeV neutrons.[4]

Seagrave *et al.*[3] have compared their data, those of Gouanère *et al.*,[4] and the data of Romero *et al.*[5] at 36 and 46.3 MeV to p-d data at 22, 35, and 46.3 MeV,[1] 18.52 and 19.55 MeV,[6] 25.7 MeV,[7] and 31 MeV.[8] They note that the neutron cross section at the minimum becomes more pronounced relative to the p-d minimum as the incident energy increases. Additional measurements of the n-d differential cross sections should shed more light on this trend.

Ludin *et al.*[9] have fitted the n-d data evaluated by Horsley[10] for neutron energies below 14 MeV with the following semiempirical expression based on the Gammel treatment of n-d scattering[11,12]:

$$\sigma(\theta) = N \left| e^{\alpha \cos\theta} - \eta e^{i\phi} e^{-\beta \cos\theta} \right|^2 , \tag{1}$$

where the parameters are smoothly varying functions of the incident energy. A comparison with the data of Romero *et al.*[5] showed that the extrapolation of Eq. (1) to 36 MeV is about 35% low, but the angular distribution has the same shape and same angle for the position of the minimum. Extension of this formula to higher energies would be useful for interpolations and to clarify whether some modified form of Gammel's treatment of n-d scattering is correct.

Many experiments have been performed to study the final-state interactions which leave two neutrons in the final state.[13-30] At low and medium energies the ^{2}H(n,p)2n reaction is the simplest process in which the neutron-neutron interaction can be studied. The measurements tend to group around two values for the neutron-neutron scattering length, −24 and −17 fm.

With the exception of the ^{2}H(n,p) measurements of Debertin, Hofmann, and Rössle[13] there has been no recent study of the proton angular distribution to emission angles greater than 20°. Additional precise measurements of the zero-degree spectra of the ^{2}H(n,p)2n reaction combined with a study of the emission-proton and recoil-deuteron angular distributions should therefore be useful.

EXPERIMENTAL METHOD

The neutron source, counter telescope, and associated equipment have been described previously.[31] In addition to the radiators described in Ref. 31, the counter telescope contained a deuterated polyethylene radiator 50 mg/cm^2 thick, obtained from the Lawrence Livermore Laboratory. The carbon content of the radiator was $(74.8 \pm 0.1)\%$ by weight.[32] Mass spectroscopic analysis yielded 82.86 at.% of deuterium.[33]

Initially a particle-identification program based on the Bethe-Livingston expression[34] for the stopping power provided on-line analysis. This program was subsequently replaced by a particle-identification program based on the method suggested by Hird and Ollerhead.[35] The latter program was more versatile. Both programs have been described previously.[31] Figure 1 shows typical particle-identification spectra obtained with these programs.

Spectra were taken with the deuteron radiator and background-subtraction sample at several angles, both left and right of 0°, up to 45° (lab). These measurements included spectra taken near the minimum in the elastic *n-d* angular distributions. The contributions from chance coincidences and neutron-induced reactions in the platinum were negligible. To provide normalization for the data, recoil-proton spectra from a polyethylene foil at 0° (lab) were collected between each measurement with the deuteron radiator. The spectra were normalized to the *n-p* differential cross section[31] at 158° (c.m.). The spectra for a given target and angle, both left and right of 0°, were summed.

Additional recoil-proton spectra between 0° and 53.5° (lab) provided a proton-energy calibration curve for each data-taking period. By means of these curves the proton spectra for a given incident energy, target, and angle taken in different periods could be summed. With the aid of range-energy tables, the mean energy losses of protons in the targets were calculated and the proton spectra were corrected for these losses. The ratio of carbon atoms in the deuterated polyethylene to carbon atoms in the background-subtraction sample was 0.53. After correction of the background proton spectra for the ratio of carbon atoms, the background proton spectra were subtracted from the foreground spectra point by point.

The background recoil-deuteron spectra were also adjusted for the ratio of carbon atoms. Background subtraction then took place in two steps. First, the background and foreground deuteron spectra were compared to determine the channels at which foreground and background merged. The deuteron peaks in the background-corrected energy and mass spectra were integrated between these channels. The two values obtained were compared and the limits of integration adjusted until there was good agreement. In addition the background-corrected emission-proton spectra were integrated above 10 MeV for 24.0-MeV neutrons and above 13.2 MeV for 27.2-MeV neutrons. Typical uncorrected foreground energy spectra are shown in Fig. 2.

Dead-time effects were less than 0.1% at all angles and were neglected. Corrections for attenuation of the neutron flux by inelastic processes in the platinum backing and windows have been discussed previously.[31] Corrections for Coulomb and inelastic scattering of the recoil deuterons and emission protons were less than 1 and 0.5%, respectively, at all angles[36] and were neglected.

Mean recoil-deuteron angle. The mean laboratory recoil angle Θ_M, differs from the geometrical angle, Θ_0. The deuterons recoil not only at Θ_0, but at angles near Θ_0. To calculate the mean recoil angles it was first necessary to calculate $\sigma_{lab}(\Theta_0)$, using Eq. (1) for $\sigma_{c.m.}(\theta)$.[37] The mean laboratory recoil angle may then be found from the relationship

$$4\cos\Theta_M \sigma_{c.m.}(\theta) = \sigma_{lab}(\Theta_0). \qquad (2)$$

The c.m. neutron angle is related, nonrelativistically, to the mean recoil angle by the expression $\theta = \pi - 2\Theta_M$. The mean angles and c.m. neutron angles are summarized in Table I.

The method of calculating the angular resolution of the counter telescope for recoil deuterons has

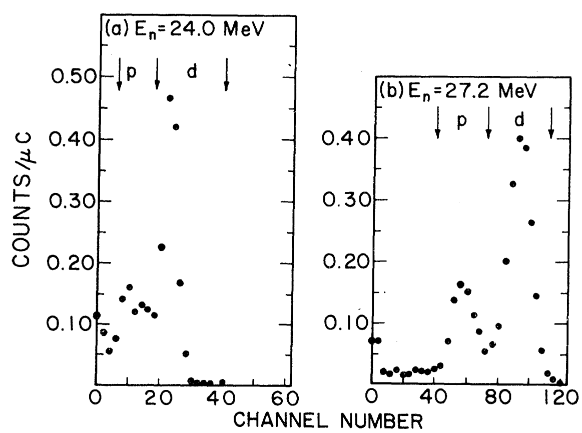

FIG. 1. (a) Typical mass spectrum using the first particle-identification program. $E_n = 24.0$ MeV. (b) Typical mass spectrum using the second particle-identification program. $E_n = 27.2$ MeV. The arrows indicate the cutoff points for protons and deuterons. $\Theta_0 = 0°$. 50-mg/cm^2 deuterated polyethylene radiator.

been described previously in Ref. 37. The c.m. angular resolution for the scattered neutrons is equal to twice the angular resolution of the counter telescope. The c.m. angular resolutions ranged from 5.6 to 12.2°.

Mean proton-emission angle. The mean laboratory emission angle, Θ_M, also differs from the setting angle, Θ_0. The mean laboratory emission angle was calculated using the following expression:

$$\langle \cos\Theta \rangle = C(\Theta_0)\cos\Theta_0 , \qquad (3)$$

where $C(\Theta_0)$ is the Nakamura correction factor.[38] It was assumed that $\cos\Theta_M = \langle \cos\Theta \rangle$. The angular resolution of the counter telescope for emitted protons was calculated employing the method described in Ref. 37. The angular resolution for emitted protons was 5–6°. Note that these calculations include only the dependence on finite geometry and not the dependence on the cross section.

Uncertainties in the mean angles. There is an uncertainty in the mean angle, Θ_M, due to an uncertainty of 0.5° in the detector angle. The uncertainty in the c.m. scattering angle is twice the uncertainty in the mean angle and ranged from 0 to 1°. The uncertainty in the mean emission angle ranged from 0.0 to 0.5°.

RESULTS

Elastic Scattering of Neutrons by Deuterons

The elastic n-d data are summarized in Table I. At 24.0 MeV two methods were employed to obtain the data. In the first method a 67.8-mg/cm^2 proton radiator was used for normalization and the particle-identification program was based on the Bethe-Livingston expression[34] for stopping power. The ratio of deuterons to protons in the radiators was 0.558 ± 0.002. In the second method a 22.6-mg/cm^2 proton radiator provided normalization, while analysis was by a particle-identification program suggested by Hird and Ollerhead.[35] The ratio of deuterons to protons in the radiators was 1.674 ± 0.006. Only the second method was employed at 27.2 MeV. The n-p differential cross sections employed in the normalization were obtained from Table II of Ref. 31. No attempt was made to unfold the angular resolution of the counter telescope.

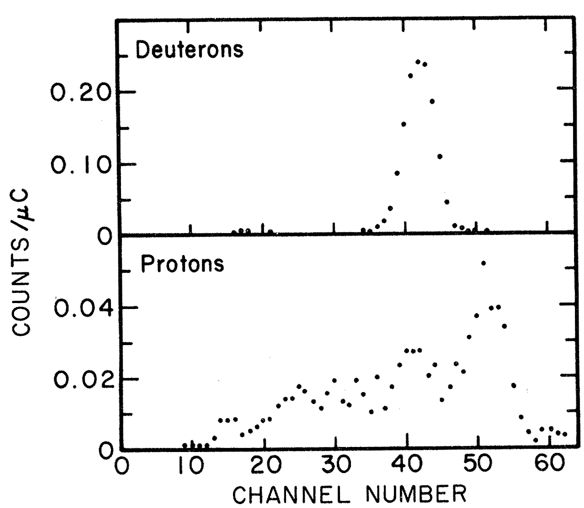

FIG. 2. Typical uncorrected foreground energy spectra. $E_n = 27.2$ MeV. $\Theta_0 = 0°$. 50-mg/cm^2 deuterated polyethylene radiator.

The present data along with the data of Refs. 1, 3, 4, 7, and 8 are shown in Fig. 3. In the interest of clarity and in view of the higher precision of the proton data,[1,7,8] the latter are shown as smooth curves. The solid curve represents the extrapolation of the semiempirical formula for n-d scattering developed by Ludin *et al.*[9] All the n-d data have been adjusted to the present energies of 24.0 and 27.2 MeV by assuming a $1/E$ energy dependence of the differential cross section. This is a reasonable assumption whenever the phase shifts are slowly varying, since the dominant variation in the cross section is the factor $k^2 \propto 1/E$. The large triangles represent the angular resolution of the present data. The arrows represent Wick's limit.[3,39]

The mean deviations of the extrapolated values of the semiempirical formula from the present data are -1 and -2% at 24.0 and 27.2 MeV, respectively. The root-mean-square deviation between the present 24.0-MeV data and the 23-MeV

TABLE I. Summary of elastic n-d data.

Neutron energy (MeV)	Θ_0 (deg)	Θ_M (deg)	$\theta_{c.m.}$ (deg)	$\left\langle \frac{\sigma_d(\theta_{c.m.})}{\sigma_p(158°)} \right\rangle_{av}$	$\sigma_d(\theta_{c.m.})$ (mb/sr)
24.0	0.0	6.8	166	0.81 ± 0.04	27.6 ± 1.6
	10.0	11.0	158	0.55 ± 0.06	18.9 ± 2.8
	20.0	18.3	143	0.27 ± 0.02	9.3 ± 0.8
	27.5	28.1	128	0.036 ± 0.006	1.4 ± 0.2
	30.0	31.5	117	0.078 ± 0.006	2.7 ± 0.2
	37.5	37.6	105	0.092 ± 0.004	7.1 ± 1.9
	45.0	44.9	90	0.146 ± 0.009	12.5 ± 1.0
		$\sigma_p(158°) = 34.4 \pm 0.7$ mb/sr [a]			
27.2	0.0	6.9	166	1.03 ± 0.02	31.2 ± 0.8
	10.0	11.0	158	0.39 ± 0.03	12.1 ± 0.9
	20.0	18.2	144	0.13 ± 0.01	4.2 ± 0.4
	25.0	20.9	138	0.049 ± 0.004	1.5 ± 0.1
	30.0	26.5	127	0.030 ± 0.008	1.0 ± 0.2
	33.0	33.6	113	0.072 ± 0.012	2.6 ± 0.4
	39.0	39.1	102	0.14 ± 0.01	5.6 ± 0.5
	45.0	45.1	90	0.22 ± 0.01	9.6 ± 0.5
		$\sigma_p(158°) = 30.8 \pm 0.5$ mb/sr [a]			

[a] The n-p differential cross sections are from Table II of Ref. 15.

data obtained by Seagrave *et al.*[3] is 3%. There is an rms deviation between the present 27.2-MeV data and the 28-MeV data of 4.9%. These deviations are within the mean uncertainties of 7 and 5% for the present data at 24.0 and 27.2 MeV, respectively.

Figure 3 shows that the minimum *n-d* cross sections are less than the minimum *p-d* cross sections. However, the difference between the *p-d* minimum and the *n-d* minimum cross sections at 27.2 MeV is relatively larger than the difference at 36 MeV.[1,5]

An attempt was made to extend Ludin's semiempirical formula to 36 MeV by finding the best fit to all the available *n-d* data,[3-5,10] including the present data. The parameters given by Ludin *et al.*[9] still gave the best fit to the data.

^{2}H$(n,p)2n$ Reaction

Figure 4 compares the present proton emission spectra at 11° with the 7.5° spectrum reported by Debertin, Hofmann, and Rössle,[13] at 22 MeV and with the 5° spectra given by Bond[14] at 23 and 28 MeV. The 22° emission spectra are compared with the 15°, 22-MeV spectrum found by Debertin, Hofmann, and Rössle and with the 20°, 28-MeV

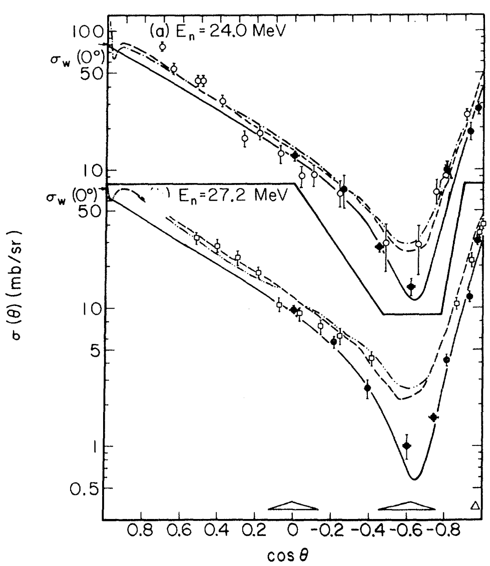

FIG. 3. (a) N-d angular distributions at 24.0 MeV. (b) N-d angular distributions at 27.2 MeV. n-d elastic scattering data: ●, present work; ○, Ref. 3×23/24; □, Ref. 4×28/27.2. p-d elastic scattering data: ——, Ref. 7×25.7/E_n; —·—, Ref. 1×22/24; and —··—, Ref. 8×31/27.2. The solid lines represent the extrapolation of the semiempirical formula of Ref. 9 to 24.0 and 27.2 MeV. The large triangles indicate the angular resolution of the present experiment. The arrows indicate Wick's limits.

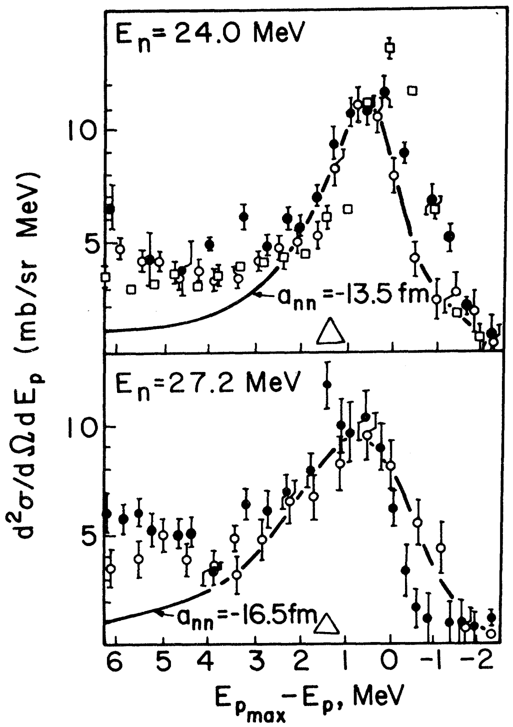

FIG. 4. Emission-proton spectra at $\Theta_M = 11°$: ●, present data; ○, $E_n = 23, 28$ MeV, $\Theta_M = 5°$, Ref. 14; □, $E_n = 22$ MeV, $\Theta_M = 7.5°$, Ref. 13. The solid lines are from Ref. 14 and represent an impulse-approximation fit. The large triangle represents the energy uncertainty of the present experiment.

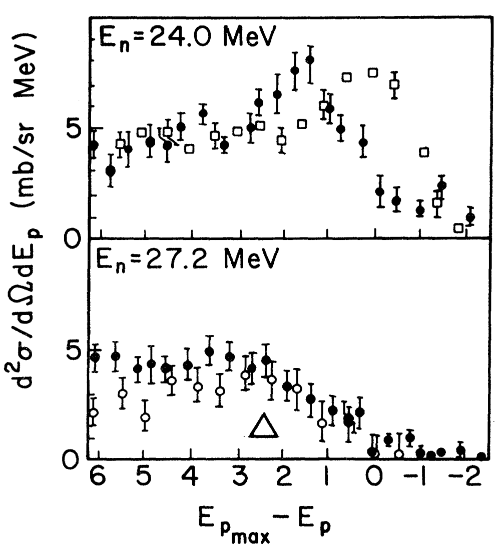

FIG. 5. Emission-proton spectra at $\Theta_M = 22°$: ●, present data; ○, $E_n = 28$ MeV, $\Theta_M = 20°$, Ref. 14; □, $E_n = 22$ MeV, $\Theta_M = 15°$, Ref. 13. The large triangle represents the energy uncertainty of the present experiment.

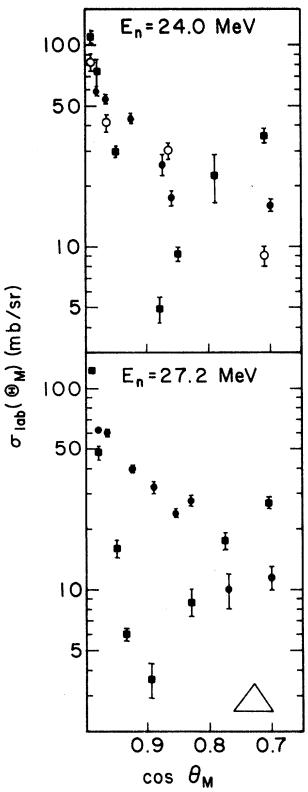

FIG. 6. Angular distribution of the laboratory differential cross sections for recoil deuterons and emission protons at E_n =24.0 and 27.2 MeV: ●, present emission-proton data; ■, present recoil-deuteron data; ○, emission-proton data from Ref. 13, E_n =22 MeV.

spectrum measured by Bond in Fig. 5.

The maximum proton energy, $E_{p_{max}}$, was calculated by assuming that the two neutrons were emitted as a single entity in the direction opposite to that of the proton. At 11° the maximum proton energies were 21.4 ± 0.5 and 24.5 ± 0.5 MeV and at 22° the maximum energies were 20.2 ± 0.6 and 23.1 ± 0.7 MeV for incident energies of 24.0 and 27.2 MeV, respectively.

The large triangles in Figs. 4 and 5 represent the energy uncertainty in the present experiment. Also, Fig. 4 includes the fits made by Bond to the 5° data. Bond used the impulse approximation to find the neutron-neutron scattering length, a_{nn}, which best fitted the shape of his spectra and then normalized the fit to the measured absolute value.

The present data agree with the work of Debertin, Hofmann, and Rössle[13] at 22 MeV and Bond[14] at 23 and 28 MeV. The largest discrepancy in the position of the high-energy peaks occurs between the 22°, 24.0-MeV spectrum and the 15°, 22-MeV spectrum. This is partially due to the large difference in mean emission angle between the two data sets.

Figure 6 compares the present recoil-deuteron and emission-proton angular distribution with the angular distribution obtained from the spectra of Debertin, Hofmann, and Rössle.[13] No attempt has been made in the present work to extract the neutron-neutron scattering length or any three-nucleon parameters.

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