n-d Scattering at 2.45 and 3.27 Mev*

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Complete angular distributions for the elastic scattering of neutrons by deuterons have been obtained at 2.45 and 3.27 Mev by direct observation of the scattered neutrons using a time-of-flight technique, and results are given with a probable error of less than 3%. No support is found for the strong forward scattering indicated by a previous cloud-chamber experiment. The theoretical predictions of Buckingham, Hubbard, and Massey are in closer agreement with this experiment than are those of Christian and Gammel. *n-d* scattering is found to be very similar to *p-d* scattering at the same incident energy.

INTRODUCTION

DIFFERENTIAL cross sections for *p-d* and *n-d* elastic scattering have been measured at a number of different energies over quite a wide range, and extensive theoretical effort has been devoted to interpreting the data. But theoretical ambiguities together with large experimental uncertainties have led to rather inconclusive results. A comprehensive review of the general problem of nucleon-deuteron interactions together with a bibliography up to 1953 will be found in a survey article by Massey.[1] Experimentally, information about *n-d* scattering is very much less satisfactory than that for *p-d* scattering. Almost all *n-d* measurements to date have been based on observation of recoil deuterons and most of them have been seriously deficient in not giving information corresponding to small-angle neutron scattering. This is the region of highest interest since the several theoretical approaches appear to diverge in that region. The bulk of *n-d* distributions have also been relative and sufficiently incomplete to make normalization to the total cross section unsatisfactory. The theoretical ambiguities are so serious that it is practically essential to have absolute cross sections for meaningful comparison.

Absolute experimental data at 4.5 and 5.5 Mev[2] have been independently analyzed by introducing special theoretical assumptions,[3] and by conjoint analysis with *p-d* cross sections invoking the charge-independence hypothesis.[4] In the latter case *n-d* cross sections were compared with *p-d* cross sections for about 0.5 Mev higher bombarding energy, corresponding roughly to the *p-d* Coulomb barrier. Disagreement was found in both cases with the phases suggested by Buckingham and Massey,[5] but no very clear suggestions for improvement resulted. The limitations of the experimental data precluded significant improvements in the theory.

At $E_n = 14$ Mev the counter telescope measurements of Seagrave[6] very closely confirm the nuclear-plate measurements of Allred, Armstrong, and Rosen.[7] The counter measurements also provided spectra of the protons from the neutron disintegration of the deuteron. The theory of Christian and Gammel[8] is in excellent agreement with the comparatively precise experimental data at 14 Mev for elastic scattering, and predicts scattering reasonably compatible with the less satisfactory experimental results at lower energies. The major physical process determining the phase shifts in this theory[8] is the pickup by one of the particles in the deuteron of the incident particle to form a new deuteron, and the scattering is apparently insensitive to the *n-n* and *p-p* forces. The theory predicts considerably too low a cross section, however, for the 2–10 Mev energy range, and plausible normalization of the incomplete relative data at intermediate energies indicates that the differential cross sections are probably appreciably higher at the small forward angles than predicted. deBorde and Massey[9] have extended their earlier calculations to include higher order phase shifts with Serber exchange forces and their results are also in reasonable agreement with the data at 14 Mev.

A careful *p-d* experiment at $E_p = 20.6$ Mev has recently been performed.[10] It reveals very marked Coulomb-nuclear interference near 20° which awaits theoretical interpretation. Unfortunately no directly comparable neutron measurements are yet available.

An isolated measurement of small-angle *n-d* scattering at $E_n = 3.1$ Mev has been reported from Japan.[11] Ring scattering from D_2O gave absolute cross sections for center-of-mass scattering angles of 25 and 35 degrees with a probable error of about 16%. A Swiss cloud-chamber small-angle recoil experiment[12] in 1952,

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supplementary to an earlier measurement[13] at large angles at the same energy, 3.27 Mev, extended measurements down to a center-of-mass angle of 18° and indicated extremely strong forward scattering. This is a result which, if normalized to the large-angle data at the same energy and to the total cross section, is irreconcilable with charge-independence of nuclear forces.[1] It should be noted that much improved measurements of the total cross section for the n-d interaction up to 22 Mev are now available,[14] but to date no theoretical attempt to fit the data has been published.

The angular distributions measured in the experiment to be described were obtained at 3.27 Mev for direct comparison with previous small-angle data[11,12] at that energy, and at 2.5 Mev where comparison could be made with the Wisconsin recoil-counter results at 2.5 Mev[15] and with the p-d results at 2.53 and 3.0 Mev.[16] The actual neutron experiment was conducted at 2.45 Mev for practical reasons. Neutron energy spread for both cases was ± 50 kev for the full width at half-maximum.

EXPERIMENTAL ARRANGEMENT

A pulsed-beam time-of-flight technique and a shielded scintillation detector were used to detect fast neutrons elastically scattered by deuterons. The time-of-flight installation at the large Los Alamos Van de Graaff accelerator has been described in detail previously.[17–20] Briefly, the dc beam from the accelerator is swept across slits at a repetition rate of 7.4 megacycles per second and the chopped beam is focused on the target to give bursts of about 3 millimicroseconds duration with an average current of about $\frac{1}{2}$ microampere. The target is a 3-cm long cell filled with tritium gas to a pressure of 120 cm of mercury. The neutrons are produced by the $T(p,n)He^3$ reaction. Forward neutrons from the source are scattered by a cylindrical sample whose axis is 10.1 cm from the center of the target. A set of scattering samples is supported on a fine vertical wire so that comparison samples can be moved into position by remote control. The mean flight path from scattering sample to shielded hydrogeneous scintillation detector is 115 cm. The detector and its collimator are mounted on a cart so that the entire detection system can be rotated about the axis of the scatterer to obtain angular distributions. Figure 1 shows the time-of-flight neutron spectrum

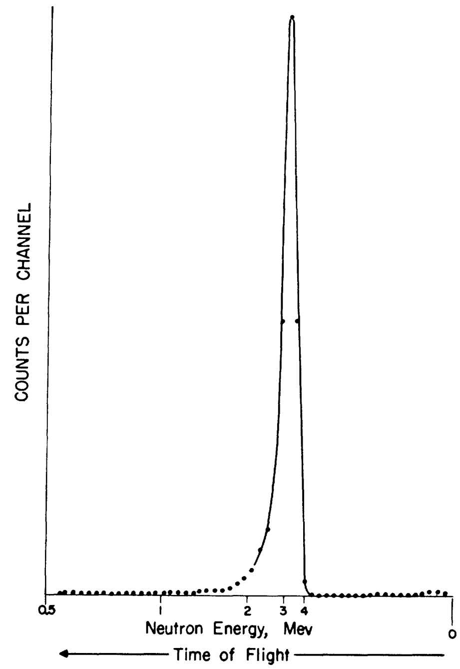

FIG. 1. Time-of-flight spectrum of the 3.27-Mev neutrons incident on the scattering sample.

incident on the scatterer as observed by the detector system at zero degrees with no scattering sample present.

The relative sensitivity of the detector was determined by measuring the number of counts per microcoulomb on the target for some 18 energies over the range of interest, and dividing these numbers by the known forward yield of the $T(p,n)$ reaction.[21] The resulting relative sensitivity as a function of neutron energy is similar to Fig. 2 in reference 20. The effective electronic bias for the pulses to be recorded was about 200 kev.

The scattering samples were cylinders disposed symmetrically with axis normal to the plane of symmetry in which the detector moved. The deuterium sample was prepared in the form of deuterated polyethylene (CD_2) made by Dr. A. Ronzio of this laboratory. The cylinder was 0.5 inch in diameter with 0.031-inch central hole for the supporting wire and its length was 1.5 inches. Its mass was 5.3666 grams. A carbon sample for a difference measurement of the deuteron cross section was prepared with the same mass of carbon as was calculated to be present in the CD_2 sample, namely 4.0515 grams. Its diameter was 0.375 inch with a 0.067-inch central hole, and its length was 1.375 inches. A normal polyethylene sample (CH_2) was also used to obtain a cross section scale by comparison with the n-p cross section. To minimize multiple-scattering uncertainties, this was prepared as a thin-walled cylinder 0.375 in. o.d. by 0.250 in. i.d., of

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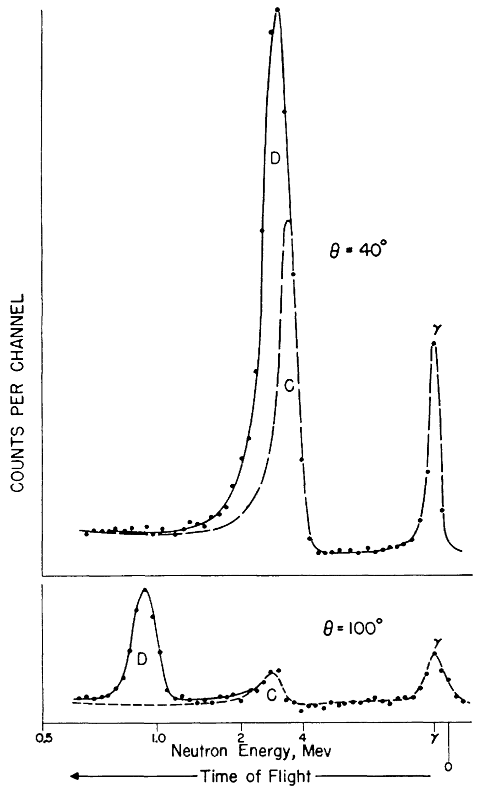

FIG. 2. Time-of-flight spectra of neutrons scattered by CD_2 (points and solid curves) and by C (dashed curves) for lab angles of 40° and 100° at an incident neutron energy of 3.27 Mev.

length 2 in., and mass 2.0168 grams. Typical time-of-flight spectra are shown in Fig. 2, for 100°, where the neutrons scattered by deuterons and by carbon are completely resolved, and at 40° where it is possible to resolve the proton and carbon groups from CH_2 but not the deuteron and carbon groups from CD_2. At progressively smaller angles the carbon "group" contains a progressively larger contribution in excess of the carbon scattering arising from direct penetration of the shield and scattering-in by the collimator.

TREATMENT OF THE DATA

Owing to the difficulty of obtaining precisely symmetrical geometrical alignment, the time spectra from the two halves of the rf cycle were not identical in appearance. A 100-channel analyzer was used to record both halves of the full cycle and the two parts of the data were handled separately until certain of the preliminary corrections had been made. Although the mass of the carbon sample was made identical to the mass of carbon contained in the CD_2 sample so that the yield due to deuteron scattering would be just the difference between CD_2 and C data, several corrections were necessary before this could be done quantitatively to obtain differential cross sections. The relative sensitivity of the detector as a function of energy was determined as discussed above and the value appropriate to the neutron energy for the angle and scattering material in question read from a smoothed curve. The standard error assigned to this correction was 2.5%, except for the most backward angle at the lower bombarding energy, where the neutron group from the deuterons fell on the steeply descending part of the sensitivity curve. Here it was necessary to treat the data channel-by-channel to obtain an effective sensitivity with a larger uncertainty. A mean flux correction factor was also computed to take into account the variation of flux over the dimensions of the samples and the self-absorption or attenuation of the flux by scattering in the sample itself. The geometrical factors were about 2% for all samples and the self-absorption factors about 12% for CD_2 and 5 to 6% for C and CH_2. The product of both factors was assigned the standard error of 1% for CD_2 and C, and $\frac{1}{2}$% for CH_2.

The angular distributions for carbon and deuteron scattering vary rapidly with energy, and the energy of neutrons scattered by protons and deuterons varies rapidly with angle. Hence a fairly detailed calculation of the multiple scattering to be expected had to be carried out. This was done on the Los Alamos MANIAC computer in such a manner that the uncertainties in the cross section input data supplied to the computer appeared only in second order in the corrections applied to the experimental data. These uncertainties were in general much smaller than statistical uncertainties of the calculation arrising from the Monte Carlo method of computation employed. The carbon[22–24] and *n-p* cross sections are adequately known for this purpose. The *n-d* cross sections, being the subject of the experiment, were somewhat less well known in advance. For purposes of the correction, the data supplied to the computer were the predictions of Christian and Gammel[8] with the differential cross sections for forward angles increased progressively in such a manner as to make up the difference between the theoretical value and the well-known total cross section.[14] The preliminary data indicated that this would be an excellent approximation at 2.45 and 3.27 Mev, and should be satisfactory at lower energies.

Because of the inefficiency of the Monte Carlo process of computation, which must of necessity follow individual particles through their several interactions in a scattering sample, an exact mock-up of the experimental geometry would lead to very poor results, if any, due to the small solid angle of the detector. It was accordingly necessary to modify the description of the problem for the machine calculation in such a manner that a statistically meaningful result could be

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obtained in a finite time. In the actual physical problem the finite size of source, scatterer, and detector led to a range of several degrees through which the individual scattering events might have taken place for a particular nominal angle of the detector. This finite angular resolution was taken advantage of in describing the artificial problem for the machine calculation. The machine could be directed to accept as relevant many scattering events which departed considerably from the nominal plane of detection. For a spread in scattering angle of about 3° corresponding to the experimental angular resolution, the computer was permitted to accept trajectories falling within 10° of the plane of symmetry at a projected scattering angle of 15°, and progressively larger sector half-widths up to 30° near a scattering angle of 90°. A further simplification was then possible without further error in the computation —namely, to treat the neutrons as incident on the scatterer in a parallel beam. The machine was directed to distinguish between, and keep track of separately, those particles which were scattered singly and those that were scattered more than once. It was also permitted to drop from further consideration those particles whose energy had fallen below tabulated thresholds of interest determined from inspection of the experimental time-of-flight graphs. For each of the 6 MANIAC runs (3 samples at each of 2 energies) a total of 50 000 neutrons which had made at least one interaction were followed. If we designate by S the number of neutrons scattered singly for a particular situation and by M the number of neutrons scattered more than once for the same situation, which meet the energy-band requirements imposed by the experimental analysis, then the fraction of experimentally acceptable events detected which were singly scattered is $(1+M/S)^{-1}$. The magnitude of the multiple scattering correction so calculated ranged from $(3\pm1)\%$ to $(11\pm2)\%$, being smallest, fortunately, at the forward angles where the input data were the least certain. The indicated uncertainties in the correction are statistical, arising from the Monte Carlo calculations.

For forward angles, there was a significant contribution of background indistinguishable from the neutrons scattered by the sample. Although this background subtracts out in first order, an additional error would be generated if effective-flux and multiple-scattering corrections were applied to the forward-angle data without taking account of this background. The proportion of this type of background was not measured directly by an additional "background" run, since it could be estimated from the known carbon cross sections with a residual uncertainty from this effect of about 1%.

The hydrogeneous content of the deuterated polyethylene is 96 atomic percent deuterium and 4% hydrogen, based on mass spectrometer measurements of the ethylene gas before polymerization and confirmatory nuclear measurements using thin foils of the same

TABLE I. Absolute differential cross sections for n-d scattering at $E_n=2.45$ and 3.27 Mev.

θ (lab)	θ'(c.m.)		$E_n=2.45$ Mev			$E_n=3.27$ Mev		
degrees		$\cos\theta'$	$\sigma(\theta)$ mb/sterad	$\sigma(\theta')$ mb/sterad	P.E. %	$\sigma(\theta)$ mb/sterad	$\sigma(\theta')$ mb/sterad	P.E. %
16.5	24.7	0.908	652	296	2.5	...	...	...
19.0	28.4	0.880	621	286	2.5	...	...	...
21.0	31.3	0.855	598	278	2.4	569	265	2.6
26.0	38.6	0.781	...	...	...	517	248	2.6
30.6	45.4	0.702	470	232	2.3	460	227	2.4
40.5	59.5	0.507	343	184	2.4	329	176	2.4
70.1	98.2	−0.142	139	111	2.5	114	91.0	2.6
100.0	130.4	−0.637	133	190	2.2	95.7	136	2.8
130.4	152.8	−0.889	129	328	2.6	116	297	2.7
150.7	164.9	−0.965	118	407	5.8	99.8	344	4.6

material.[6] The effect of assuming that the hydrogen content was $(4\pm1)\%$ was investigated and the corresponding uncertainty in the n-d cross section was carried along as a random error. It never exceeded one fifth of the compound uncertainty from all causes. The standard errors from the several sources discussed above were then combined to obtain an rms standard error. The numerical values for 30° at 2.45 Mev are typical: counting statistics, 1.7%; multiple scattering, 1.4%; background, 0.7%; sample composition, 0.3%; detector sensitivity, 2.5%. These together lead to an rms value of 3.4%.

Absolute cross sections were obtained from comparison with the known n-p differential cross section at 40°, where the groups scattered by protons and by carbon could be completely resolved. It was found possible in the course of the experiment to obtain essentially complete angular distributions at both energies, and the integrals of the data obtained with the n-p normalization differed by $(1\pm4)\%$ and $(-4\pm4)\%$ from the accepted values[14] of the total cross sections at 2.45 and 3.27 Mev, respectively. The final results reported below have been renormalized to the total cross sections. Table I summarizes the results of this experiment. Though data were obtained with a detector at convenient laboratory angles, the values of the angles given in the table are mean angles of detection based on analysis of the finite angular resolution. The cross section uncertainties quoted in the table are to be regarded as absolute *probable* errors. In Fig. 3 the results of the present experiment are plotted as a function of the cosine of the center-of-mass neutron angle and compared with other experimental data. The relative results of previous experiments have been normalized to the present absolute results on the basis of the integrals over the region of overlap. Very satisfactory agreement is noted with the Wisconsin recoil-counter experiment[15] at 2.5 Mev, in which the angular distribution of the scattered neutrons was inferred from the energy distribution of the recoil deuterons in a proportional counter. Less satisfactory, though still reasonable agreement is found with the 1951 Swiss cloud-chamber experiment[13] in which deuterons recoiling in the forward hemisphere were

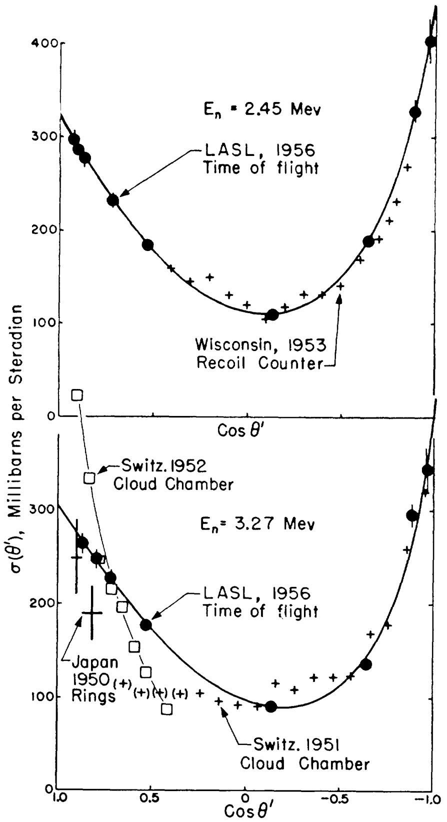

FIG. 3. Time-of-flight results for *n-d* scattering compared with previous experiments.

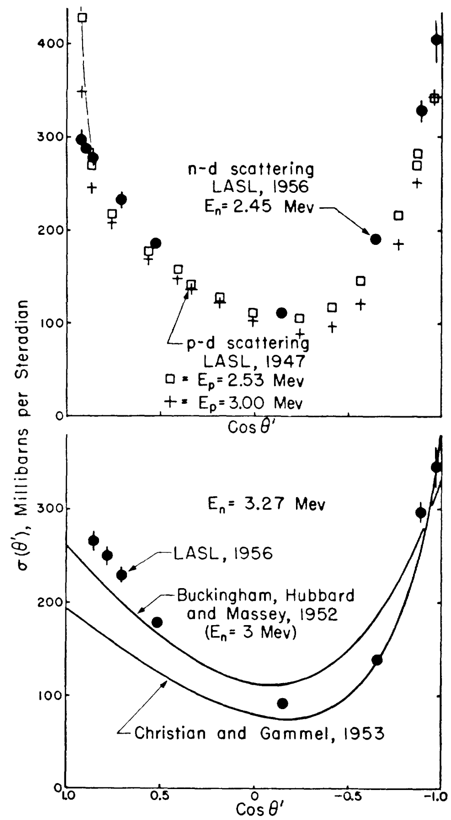

FIG. 4. (Above) *n-d* scattering at 2.45 Mev compared with *p-d* scattering at 2.53 and 3.00 Mev. (Below) *n-d* scattering at 3.27 Mev compared with theoretical predictions.

observed. However, substantially no agreement is found with the 1952 Swiss cloud-chamber experiment[12] in which the very low-energy, large-angle deuteron recoils were observed. We are unable to account for the discrepancy. The Australian cloud-chamber measurements[25] at 3 Mev (not shown), are also in fair agreement with the present results if due allowance is made for the large statistical uncertainties in that work.

A detailed comparison with the theoretical possibilities will not be attempted in this paper, but in Fig. 4 the experimental results for 3.27 Mev are compared with the predictions of Christian and Gammel for that energy, and with the 1952 predictions of Buckingham, Hubbard, and Massey[26] for 3 Mev. It will be noted that the former gives very good agreement with the rear hemisphere and falls progressively below the experiment for more forward angles. The latter interlaces the data better but predicts somewhat too "shallow" a distribution with about the right total cross section.

A final comparison, also shown in Fig. 4, is of the present *n-d* scattering at $E_n = 2.45$ Mev with the results obtained at this laboratory[16] in 1947 for *p-d* scattering at $E_p = 2.53$ Mev, and $E_p = 3.00$ Mev. The situation is qualitatively the same at $E_n = 3.27$ Mev. These comparisons are relevant for the charge-symmetry hypothesis. The *n-d* cross section resembles the *p-d* cross section at approximately the same energy more than that for 0.5 Mev higher. It appears that at this energy the Coulomb interaction leads only to a small interference effect other than the usual very-small-angle peak. Although the difference between *p-d* and *n-d* scattering is comparatively small, it is hoped that the present refinement in the precision of *n-d* measurements is sufficient to permit resolving existing theoretical ambiguities by analysis of the nucleon-Coulomb interference.

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