Proton Polarization in *p-d* Scattering*

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The proton polarization resulting from proton-deuteron elastic scattering has been measured in a double-scattering experiment. The first scattering took place in helium, which served as a polarizer, and the left-right asymmetry observed in a second scattering in deuterium. Spurious asymmetries were checked by substituting xenon and, separately, helium for deuterium as the second scatterer. Measurements taken at a proton-deuteron scattering energy of $E_p=3.4$ Mev, $\theta=45°$ and 90°, and $E_p=3.74$ Mev, $\theta=45°$ all yielded results consistent with no polarization. From these data it is concluded that the proton polarization in *p-d* elastic scattering is $<\sim 10\%$ in this energy region.

INTRODUCTION

THE presence of a large spin-orbit term in nuclear forces renders large polarization effects possible in nuclear reactions. Significant polarizations have been found in the elastic scattering of nucleons by heavy nuclei,[1] and these polarizations can be explained by the inclusion of a spin-orbit term of reasonable magnitude in an optical model potential. In the lighter nuclei high ($\sim 100\%$) polarizations have been observed in reactions proceeding through a well-defined resonance[1–4] and in reactions which appear to proceed via a stripping mechanism.[5–7]

The situation in the very light ($\leq He^4$) nuclei is somewhat different. An optical model potential cannot be considered as applicable to nuclei containing only two or three nucleons and few well-defined resonances are encountered in reactions involving only the very light nuclei. However, since only a few nucleons are involved, there is hope that with the aid of machine computing techniques the observable properties of reactions among the very light nuclei can be calculated directly from nucleon-nucleon forces. Such calculations are already underway for the case of nucleon-deuteron scattering.[8]

The polarization of neutrons elastically scattered by deuterons at energies in the Mev range has been measured by White, Chisholm, and Brown[9] who find polarizations $\sim 50\%$, by Gerber, Brüllmann, Meier and Scherrer,[10] and also by Cranberg,[11] both of whom find polarizations $\leq \sim 10\%$, with zero polarization being consistent with all of the points in the latter two experiments. As no sharp resonances are seen in *n-d* or *p-d* scattering, the phase shifts and therefore the polarization is expected to vary only slowly with energy and hence the results of White et al. must be considered in disagreement with those of Gerber et al. and Cranberg. From the symmetry between *p-d* and *n-d* scattering, one can expect the polarization in *p-d* scattering to be qualitatively similar to that present in *n-d* scattering.

EXPERIMENTAL RESULTS

The polarization of the protons scattered from deuterium was measured in the present experiment by observing the left-right asymmetry when the scattered protons were again scattered by helium. The polarization in the deuterium scattering P_1 is related to the observed asymmetry by the formula

$$P_1=\frac{1}{P_2}\frac{1-A}{1+A}, \tag{1}$$

where P_2 is the polarization in the proton-helium scattering and A is the ratio of the number of protons scattered first left and then right or vice versa to the number scattered twice to the left or twice to the right. P_2 can be calculated from the known phase shifts in p-α scattering using, of course, the set of phase shifts which corresponds to an inverted doublet in Li^5. The correctness of the polarization as calculated from these

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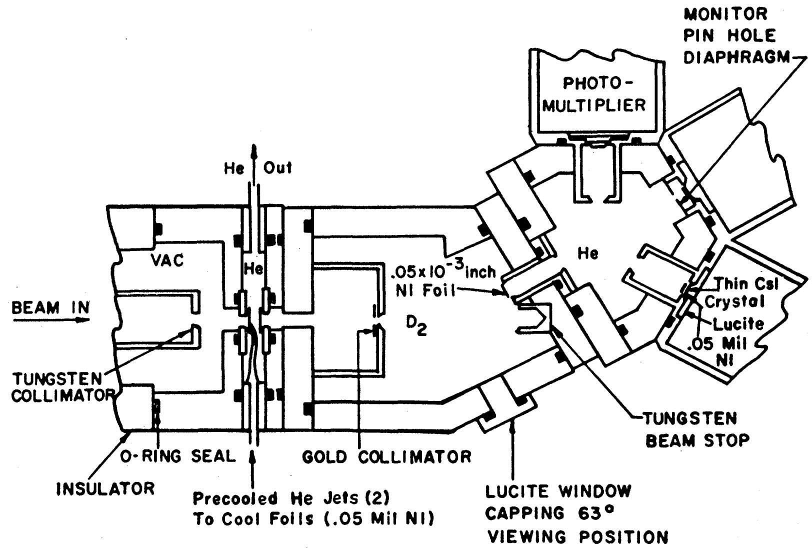

FIG. 1. The first and second scattering chambers. The second chamber (in the 30.5° viewing position) contains the monitor counter and the two side counters.

phase shifts has been experimentally verified in the range of energies of interest in this experiment.[2]

A drawing of the target chamber is given in Fig. 1. Protons from the Northwestern electrostatic accelerator entered the first scattering chamber through thin (0.05×10^{-3} in.) nickel foils. The foils were cooled by a helium jet.[12] The scattered protons passed through a foil into a second scattering chamber, which could be placed at either 30.5° (45° c.m. for p-d scattering) or 63° (90° c.m.) to the incident beam. An angular spread of $\pm7.5°$ was accepted at the 30.5° position, and $\pm10.5°$ at the 63° position. The energy at the second scattering was adjusted by varying the thickness of the foil between the chambers, and/or the gas pressure in the second chamber. The energy and angle of the second scattering were such as to have a high (80–100%) polarization in the helium scattering. An angular spread of $\pm14°$ was accepted in the second scattering, the mean scattering angle being 59.5° to the axis of the second chamber. The doubly scattered protons were detected by thin CsI(Tl) crystals. The pulse-height spectra from the crystals, after amplification, were displayed on two halves of a split 256-channel analyzer.

The poor geometry (i.e., large solid angles) necessitated by the low yield inherent in double scattering experiments renders it essential to try to minimize the possibility that the left-right asymmetry measured is influenced by spurious effects. In the present experiment it was possible to use an analyzer of close to 100% efficiency [i.e., $P_2=1$ in Eq. (1)] and therefore, if spurious asymmetries were present, their effect was minimized. The actual values of A measured turned out to be close to unity and therefore a small error of a certain magnitude in A would be reflected as an error of one-half that magnitude in P_1.

Spurious asymmetries were investigated by substituting xenon for helium as the gas in the second chamber. The proton energy at the second scattering was about 2 Mev which is far below the Coulomb barrier for xenon. An absence of spurious asymmetries would lead to a measured left-right ratio of unity for xenon, independent of the polarization of the singly scattered protons since Coulomb scattering is known to show no polarization effects for nonrelativistic protons.[13] In fact, asymmetries of $\sim10\%$ were measured with xenon as the second scatterer. As explained below, these spurious asymmetries could largely be accounted for by a difference in detection efficiency between the two CsI(Tl) crystals, and this effect was therefore suitably allowed for.

The yield of doubly scattered protons was about 1 count into each crystal per 50 microcoulombs into the first chamber. This low yield made it necessary to have the counters as insensitive as possible to the neutron and gamma-ray background from the accelerator. The crystals were therefore polished down until they were about 10^{-3} inch thick. It can be seen in Figs. 2–4 that with crystals of this thickness the proton peaks were well out of the background. The protons entered the crystal with energies of 1.0–1.3 Mev, and therefore their range was comparable to the crystal thickness. It was not feasible to polish the crystals very uniformly and therefore parts of the crystals were so thin that some of the protons passed through without losing all of their energy; hence the low-energy tail in the pulse-height spectra in Figs. 2–4. A larger portion of the counts fell in the low-energy tail as the energy of the protons entering the crystals was raised.

Since different crystals were used at various times, and since they differed somewhat in quality, particularly as regards to uniformity, the doubly scattered proton spectra are of variable quality. The pulse-height spectra

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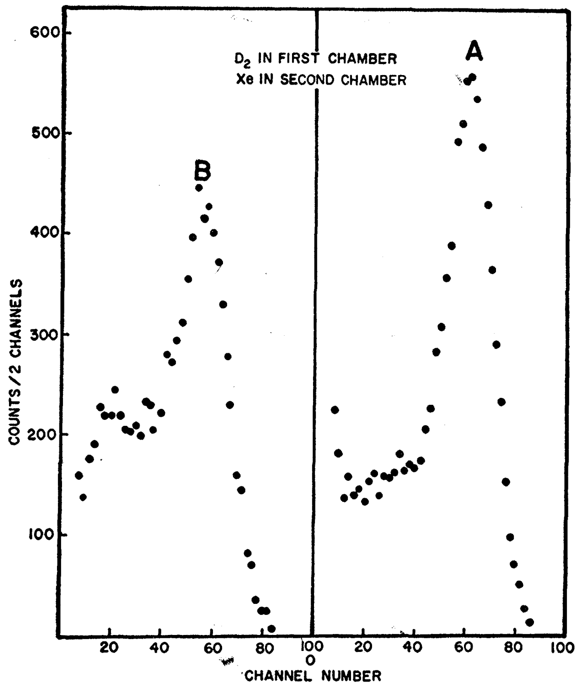

FIG. 2. Typical pulse-height spectra in the side counters with one atmosphere of deuterium in the first chamber and $\frac{1}{10}$ atmosphere of xenon in the second chamber. The second chamber is in the 30.5° position. The low pulses are due to protons which traverse thin parts of the crystal. These spectra allow one to compensate for mechanical asymmetries and differences in efficiencies of the counters.

from both crystals with the second chamber in the 30° position and containing $\frac{1}{10}$ atmosphere xenon are shown in Fig. 2, and the corresponding spectra with 1 atmosphere helium in the second chamber are shown in Fig. 3. In the D_2-Xe case, the above-mentioned low-energy tails are particularly evident, and they introduce some uncertainty in the measurement of the number of protons entering the crystal. However, because the background decreased so rapidly with increasing pulse height, it was possible to count all pulses $>\frac{1}{3}$ the pulse height of the proton peak and thus the detection efficiency of the crystals was close to unity and therefore the uncertainty in detection efficiency was small. Pulse-height spectra similar to those of Figs. 2 and 3 are shown in Figs. 5 and 6. The only difference is that the side crystals were changed and the second chamber was in the 63° position. In the latter two figures the low-energy tail effect is negligible. The high-energy peak is due to doubly scattered protons and the sharp rise on the low-energy end of the spectrum is due to gamma and neutron background. For spectra such as those the proton pulses were considered to be all those greater than the pulse height corresponding to the minimum in the spectrum after background subtraction.

The background was measured by running with the second chamber evacuated. The runs were monitored by a CsI(Tl) crystal which counted the singly scattered protons coming straight through the second chamber. When the second chamber was filled with helium, a correction of about 10% had to be applied to the monitor in order to account for the protons scattered out by the helium. The background was $\sim$20% of the total counting rate in the channels used in counting the doubly scattered protons when helium was the second scatterer. When xenon was used as the second scatterer, the background was $<$1% and was neglected.

The gas pressure in the second scattering chamber was adjusted so that the protons entered the CsI(Tl) crystals with the same energy when they were scattered by xenon as when they were scattered by helium. The asymmetry with helium in the second chamber was compared to that with xenon as the second scatterer, with the same channels counted in both cases. Thus, differences in detector efficiencies tended to cancel out. The left-right asymmetries used to calculate the polarizations in this work were corrected for the asymmetries with xenon as the second scatterer.

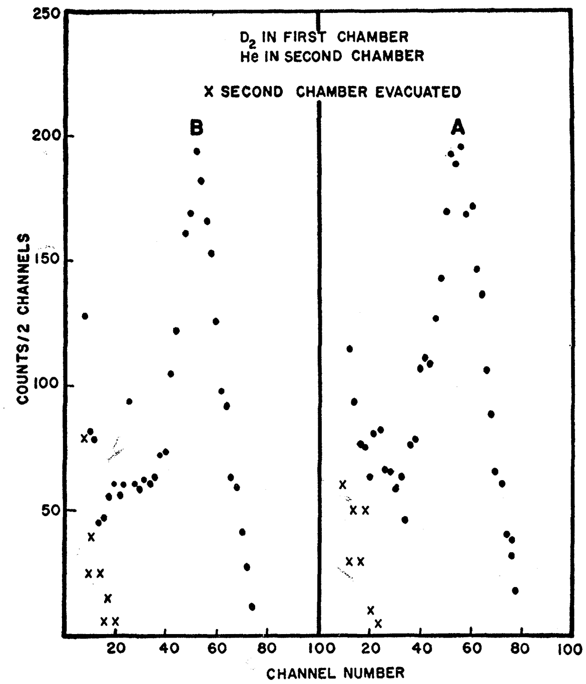

FIG. 3. Typical pulse-height spectra in the side counters with one atmosphere of deuterium in the first chamber and one atmosphere of helium in the second chamber. The second chamber is in the 30.5° position. The points indicated by X were obtained with the second chamber evacuated. They are a direct measure of the background.

The above procedure still leaves room for some small error as the wide (±14°) angle accepted in the scattering lead to a 20% spread in proton energy due to the helium recoil, while this spread is negligible for the case of a xenon scatterer. Thus, even though the average energy of the protons entering the crystals was the same in both cases, the energy spectrum was somewhat different.

Furthermore, the angular distribution of the scattered protons differs between the two cases and therefore the relative importance of the different areas of the crystals might have been different. Finally, we note that the average energy of the protons entering the crystals was matched to no better than 10%.

From the above considerations it is estimated that a systematic error of as much as 5% could be present in the measured left-right helium asymmetry. This estimate is based on noting the sensitivity of the result to the choice of which channels to count. A spurious asymmetry of 5% would lead to a $2\frac{1}{2}$% error in the polarization.

As a check on the above procedure runs were taken with helium as the first scatterer, at an energy at which a large polarization was to be expected. One of several pairs of spectra obtained are shown in Fig. 4, where it can be seen that there were about twice as many counts in the backward counter. After correcting for the xenon

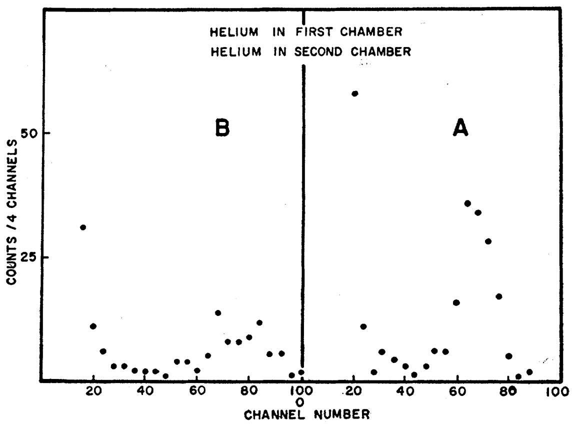

FIG. 4. Pulse-height spectra obtained with one atmosphere of helium in both chambers. The second chamber is in the 63° position. These were run as a further check on the apparatus. The angles and energies were chosen so as to produce about twice as many counts in the backward counter.

asymmetry (10%) a value for the polarization product $P_1P_2=0.32\pm0.04$ was obtained to be compared with the calculated[2] value of 0.29. The error quoted includes only counting statistics.

Data were taken for the proton-deuteron scattering at three different points and these data are summarized in Table I, which also includes the n-d results reported by other workers. At each point data were taken with the second chamber in the "normal" position, and then with the second chamber inverted. In each case the results obtained in the two positions agreed within the accuracy of the counting statistics ($\sim\pm0.03$ for P_1) and therefore the values quoted in Table I are the average for the two positions. The results of the present experiment are all consistent with zero polarization which agrees with the n-d results of Cranberg[11] as well as those of Gerber et al.,[10] but is in disagreement with the work of White et al.[9]

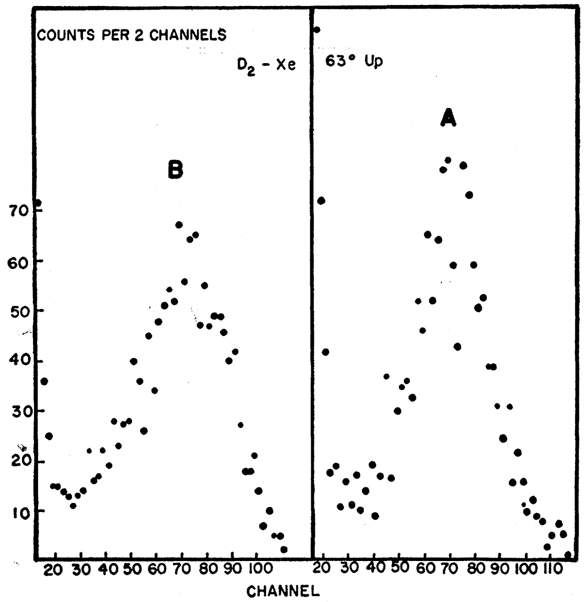

FIG. 5. Pulse-height spectra in the side counters with one atmosphere of deuterium in the first chamber and $\frac{1}{10}$ atmosphere of xenon in the second chamber. The second chamber is in the 63° position and the crystals in the side counters are different from those used to obtain the spectra shown in Fig. 2 and Fig. 3. Practically all of the protons lose their full energy in the crystal.

The polarization intensity can be expressed[13]

$$P\frac{d\sigma}{d\omega}=\sum_{n=0}^{2l_{\max}-1} a_n \cos^n\theta \sin\theta, \qquad (2)$$

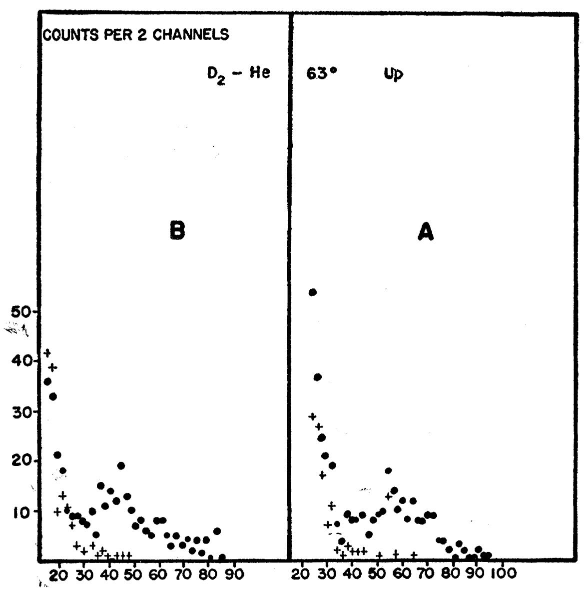

FIG. 6. Pulse-height spectra in the side counters with one atmosphere of deuterium in the first chamber and one atmosphere of helium in the second chamber. The points indicated by ✕ were obtained with the second chamber evacuated. The experimental conditions are the same as for Fig. 5 except that helium has been substituted for xenon.

TABLE I. Summary of polarization measurements in nucleon-deuteron scattering.

Reference	*Polarizer*	*Analyzer*	$E_{n\text{ or }p,\text{ lab}}$	$\theta_{\text{c.m.}}$ for scattering of n or p by d	Pol.[a]
Present work	$H^2(p,p)H^2$	$He^4(p,p)He^4$	3.74	45°	$+0.04\pm0.05$
Present work	$H^2(p,p)H^2$	$He^4(p,p)He^4$	3.34	45°	$+0.06\pm0.05$
Present work	$H^2(p,p)H^2$	$He^4(p,p)He^4$	3.45	90°	-0.02 ± 0.05
White et al.[b]	$H^2(d,n)He^3$	$H^2(n,n)H^2$	2.26	90°	$+0.48\pm0.05$
White et al.[b]	$H^2(d,n)He^3$	$H^2(n,n)H^2$	3.1	90°	$+0.40\pm0.20$
Cranberg[c]	$Li^7(p,n)Be^7$	$H^2(n,n)H^2$	2.1	several	<0.07
Gerber et al.[d]	$H^2(d,n)He^3$	$H^2(n,n)H^2$	3.27	several	$-0.02+0.08$

[a] Polarization measured along the direction $\mathbf{k}_{\text{inc}}\times\mathbf{k}_{\text{out}}$.
[b] See reference 4.
[c] See reference 11.
[d] See reference 10.

where $l_{\max}$= maximum value of orbital angular momentum taking part in the reaction, and $d\sigma/d\omega$= differential cross section.

The work of Christian and Gammel[14] indicates that the d-wave contribution should still be small at $E_p=3.5$ Mev. The sum in Eq. (2) therefore consists of two terms:

$$P(d\sigma/d\omega)\simeq a_0 \sin\theta + a_1 \sin\theta \cos\theta. \tag{3}$$

The angular distributions are known[15] to vary only slowly with energy, and therefore the polarization should also be a slowly varying function of energy. We can therefore consider the measurements at 3.34 and 3.45 Mev as having been made at the same energy. The low polarization at 90° implies $a_0/(d\sigma/d\omega)$ small, while, taking into account the angular distribution data, the 45° measurement indicates that $a_1/(d\sigma/d\omega)$ is likewise small. Hence, the polarization at all angles at this energy should be small ($<\sim 10\%$).

The fact that the polarization does not vary rapidly with energy is experimentally verified by the agreement between the two measurements at $\theta_{\text{c.m.}}=45°$; taken at proton energies separated by 0.4 Mev. We therefore conclude that the polarization at all angles and energies in the region about $E_p=3.5$ Mev must be less than about 10% in absolute magnitude.

DISCUSSION

It has been realized for some time (for the case of proton-proton scattering) that it is necessary to perform several experiments, in addition to polarization and angular distribution measurements, before a complete set of scattering parameters can be determined. The situation in nucleon-deuteron scattering is even more complicated than that in proton-proton scattering as the deuteron has spin 1, and, furthermore, the simplifying circumstance that the system consists of two identical particles is no longer present. Hence, for any value of angular momentum >1 there are six phase shifts in the nucleon-deuteron case, as against only one or three phase shifts for each l value in p-p scattering. The data presently available in nucleon-deuteron scattering must therefore be considered as rudimentary when compared to what is required in order completely to determine the scattering. Hence, at the present time, the most reasonable approach to nucleon-deuteron scattering appears to be to compare measured or easily measurable quantities with theoretical calculations, recognizing that the various theories cannot be put to a full test until more complete data is available.

Christian and Gammel[14] have performed a phase shift analysis of the p-d and n-d scattering data in the 0–10 Mev range. Their approach was to use a central nuclear potential and adjust the strength of the various (eight in all) two-body potentials such that the calculated angular distributions best fit the experimental data. Since only central forces were used in calculating the phase shifts only one doublet and one quartet phase shift was obtained for each value of l (i.e., ^2S, ^4S, ^2P, ^4P, ^2D, $\cdots$). With their analysis Christian and Gammel were able satisfactorily (rms deviation$\sim$3%) to fit the experimental data (data accurate to $\sim\pm 3\%$).

It is not clear how much the phase shifts could be split, and still an equally good fit to the data obtained. One could certainly expect that there could be some splitting of the phase shifts, and consequently some polarization, without worsening the fit to the angular distribution data. However, the fact that the angular distribution can be fit using phase shifts derived using only central forces does indicate that small polarizations might be expected.

Delves and Brown[16] have calculated differential cross sections and polarizations for the neutrons in neutron-deuteron scattering also for the energy range 0–10 Mev. These authors included distortion of the deuteron and a tensor force in their nucleon-nucleon potential, but they also had to make various simplifying assumptions. The neutron polarizations predicted by this work range up to $\sim$10% which is just about the lower limit of detectibility in the present experiment. As Delves and Brown remark, all of the present p-d or n-d polarization

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data to date, with the exception of that of White et al.,[9] is consistent with their calculation.

A more exact, but as yet incomplete, calculation using high speed computers has been performed by Haas and Robertson.[8] These authors have calculated the ^2S and ^4S phase shifts which, of course, can give no insight into the polarization. However, it is hoped that the calculations will be extended to include the higher angular momenta, in which case the polarization data should prove a rather stringent check on the validity of the calculation.[17]

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Nonelastic Scattering of Fast Neutrons*

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The relative angular distributions of neutrons inelastically scattered from iron, yttrium, zirconium, radiogenic lead (88% Pb^{206}), lead, and bismuth were measured for neutrons in the region from 3.7 to 4.7 Mev. The relative angular distributions of the low energy (0.5 to 4 Mev) neutrons resulting from nonelastic scattering of 15.2-Mev neutrons were also measured. In each case the distributions were found to be isotropic within experimental error (±15%), therefore supporting earlier evidence of compound nucleus formation as the predominant interaction mechanism.

I. INTRODUCTION

ACCORDING to Hauser and Feshbach,[1] the angular distributions of the neutrons inelastically scattered by nuclei will be symmetrical about 90° provided a sufficient number of levels are excited in the compound nucleus. Moreover, the distributions are expected to be isotropic if enough levels are excited in both the compound and residual nuclei and if the density of levels of spin J in the residual nucleus is proportional to $(2J+1)$. If direct interactions occur, the angular distributions will, in general, be peaked in the forward direction.

The present work was undertaken with a view to the measurement of the angular distributions of inelastically scattered neutrons.

Until recently, there has been very little experimental data on the angular and energy distributions of inelastically scattered neutrons. Possibly the most promising method, at the present time, for studying inelastic neutron spectra is by time-of-flight techniques. The work by O'Neill[2] indicated that for a bombarding energy of 14.8 Mev the neutrons nonelastically emitted from carbon, aluminum, and lead in the range 0.5 to 4 Mev were isotropic to within about 15%. Similar results were obtained by Rosen and Stewart,[3] who found that the angular distributions of the low-energy neutrons (0.5 to 4 Mev) due to nonelastic scattering in tantalum and bismuth were isotropic. In addition, Rosen and Stewart found that the angular distributions of neutrons emitted with high energy (4 to 12 Mev) were highly peaked in the forward direction. The results of Rosen and Stewart, as well as those of O'Neill, indicate that most of the high-energy neutrons may be scattered by a direct interaction mechanism, while the low-energy neutrons may result from compound nucleus formation. Other recent experiments[4–6] at 14 Mev confirm these conclusions.

Cranberg and Levin[7] measured the angular distributions of neutrons inelastically scattered from iron, nickel, and titantium at incident neutron energies of 2.25, 2.35, and 2.45 Mev. Their results show that the angular distributions are, in general, nearly symmetric about 90°. The experiments of Muehlhause et al. at Brookhaven[8] show that for incident neutrons of 1.58 and 1.66 Mev the neutrons from the 0.845-Mev level in iron are asymmetric about 90°. They attribute this asymmetry to a direct interaction process. More recent experiments[9] indicate that for an incident energy of

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