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]

ACKNOWLEDGMENT

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[17] Several papers relevant to the work presented here were presented at the Proceedings of the International Conference on Nuclear Forces and the Few-Nucleon Problem, July, 1959 (to be published).

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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

* Supported by the Modern Physics Research Branch, Aeronautical Research Laboratory, Wright Air Development Center.
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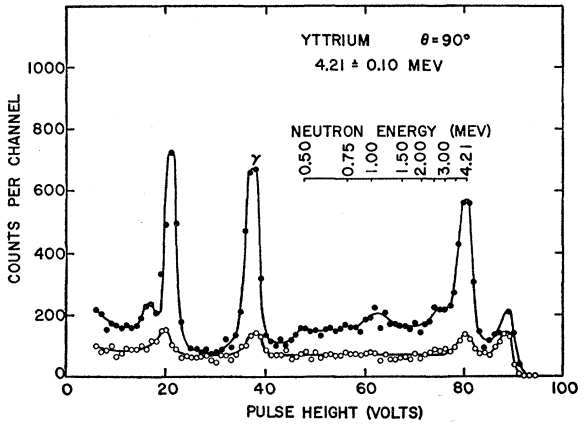

FIG. 1. Time-of-flight spectrum of 4.21-Mev neutrons scattered from yttrium. The open circles indicate the background. Time increases to the left.

2.2 Mev, the angular distribution of the neutrons that result from excitation of the 0.845-Mev level in iron is isotropic. Very recent experiments by Thomson et al.[10] on Bi^{209} and Mg^{24} indicate that for bombarding energies of 2.0, 3.0, 4.0, and 5.0 Mev no direct interaction occurs.

In the present work, we have measured the distributions of the neutrons inelastically scattered from iron, yttrium, zirconium, lead, bismuth, and radiogenic lead (88% Pb^{206}) at a neutron energy of 4.2 Mev, and the angular distributions of the neutrons inelastically scattered from iron, yttrium, zirconium, and lead at an incident neutron energy of 15.2 Mev. Angular distributions for lead were also measured at 3.67 and 4.7 Mev. In all these measurements, the incident neutron energy spread was large enough to insure that a large number of levels were excited in the compound nucleus.

II. EXPERIMENTAL PROCEDURE

The measurements were made using a pulsed beam time-of-flight spectrometer of the type developed by Cranberg et al. at Los Alamos. The details of this type of spectrometer have been described elsewhere.[7] The experimental arrangement has been illustrated and described in a previous publication.[11] The experimental procedure consisted of bombarding cylindrical samples with monoenergetic neutrons and recording the time-of-flight spectrum in a 20-channel analyzer. A run with the scatterer removed yielded the background to be subtracted. Complete angular distributions were taken and then repeated from two to five times.

The scattering samples consisted of elemental metals in the form of cylinders 5.08 cm long by 2.54 cm in diameter. The purity of all samples, as stated by the manufacturers, was 99% or better. The radiogenic lead sample was obtained from the Atomic Energy of Canada Limited, and the spectrographic analysis given by them was Pb^{204}, 0.08%; Pb^{206}, 88.25%; Pb^{207}, 8.78%; and Pb^{208}, 2.92%.

Neutrons from the D-D reaction were obtained by bombarding deuterium in a gas cell with a mean deuteron current of 0.4 microampere. The deuterons entered the cell through a nickel foil 0.00025 cm thick. Gas cells ranging in length from one to three centimeters were used at pressures ranging from one to three atmospheres. The tritium target used to produce 15.2-Mev neutrons from the $T(d,n)He^4$ reaction consisted of tritium gas absorbed in zirconium metal. This target was approximately 160 kev thick for incident deuterons of 300 kev.

The neutron detector consisted of a plastic scintillator (Pilot *B*) optically coupled to an RCA 6342 photomultiplier tube. The detector was biased so that the threshold, i.e., the point at which the efficiency attained one-half of its maximum value, was 0.5 Mev. This was determined experimentally by calibrating the detector with $T(p,n)$ neutrons.

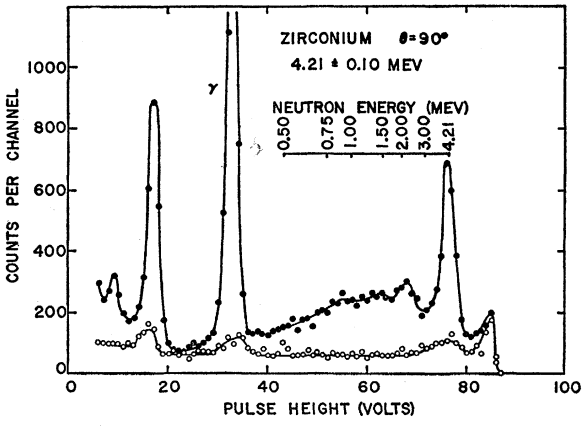

FIG. 2. Time-of-flight spectrum of 4.21-Mev neutrons scattered from zirconium.

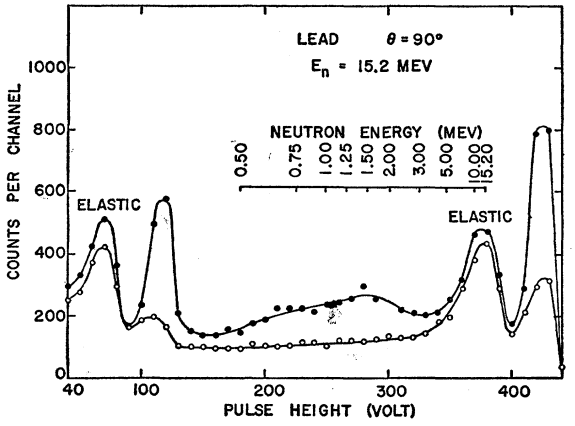

FIG. 3. Time-of-flight spectrum of 15.2-Mev neutrons scattered from lead.

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III. RESULTS

Figures 1 and 2 show time-of-flight spectra of 4.21-Mev neutrons scattered from yttrium and zirconium. These spectra were taken at 90° using a flight path of 1 meter. The resolution, width at half maximum, of the system for the elastic peak was between 5 mμsec and 7 mμsec. The only inelastic neutron group which was resolved in these spectra was that caused by excitation of the 2.18-Mev level in zirconium-90. The unresolved peak just to the left of the elastic peak in the yttrium spectrum was caused by neutrons which resulted from excitation of the first two levels in yttrium-90 (0.91 and 1.50 Mev).

Figure 3 shows a typical time-of-flight spectrum of 15.2-Mev neutrons scattered at 90° from lead. The

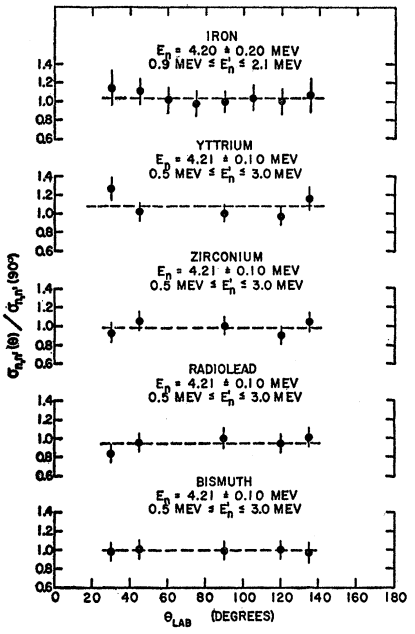

FIG. 4. Relative angular distributions of the neutrons inelastically scattered from iron, yttrium, zirconium, radiolead (88% lead-206), and bismuth. The bombarding energies and energy spreads are indicated, as well as the energy interval comprising the energies of the inelastically scattered neutrons for which the angular distributions were measured.

presence of the elastically scattered neutrons was obscured by the large background of neutrons from the target which penetrated the shielding. The resolution of the spectrometer was not sufficient to resolve inelastic neutrons of energies greater than about 4.0 Mev from the elastic neutrons. Consequently, the angular distributions given include only neutrons whose energies lie in the interval from 0.5 Mev to 4.0 Mev.

Relative angular distributions of the inelastically emitted neutrons were obtained from time-of-flight spectra taken at each angle. The analysis consisted of subtracting the background and integrating the number of counts between the two pulse heights corresponding

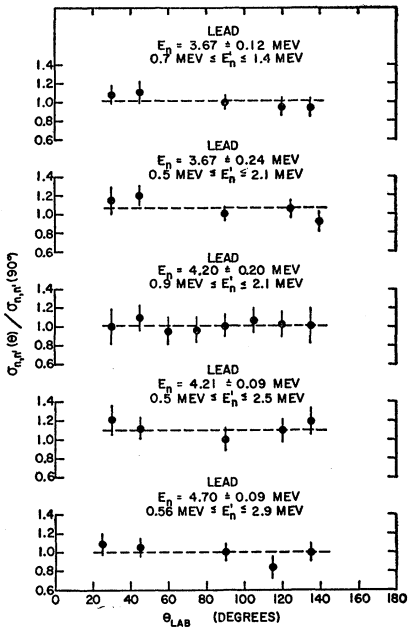

FIG. 5. Relative angular distributions of the neutrons inelastically scattered from common lead.

to the energy limits given for each of the angular distribution curves. From the number of counts obtained after subtraction of the background, the contribution due to the tail of the elastic peak was subtracted. This contribution was always less than 10% of the total number of counts. The number of counts obtained for each angle was normalized to the corresponding number of counts at 90°. Since our primary aim was to measure angular distributions of the inelastic neutrons, no attempt was made to determine cross-section values.

Angular distributions for neutrons inelastically scat-

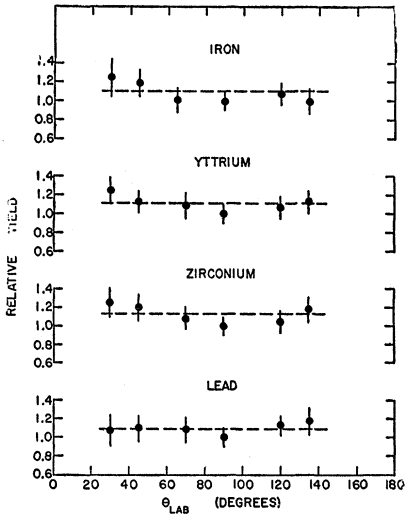

FIG. 6. Relative angular distributions of the neutrons emitted from iron, yttrium, zirconium, and lead in the energy interval from 0.5 to 4.0 Mev due to bombardment with 15.2-Mev neutrons.

tered from various elements at 4.2 Mev are shown in Fig. 4. The interval of inelastic neutron energies taken and the incident neutron energy spreads are indicated in the figures. Figure 5 shows angular distributions obtained with a lead scatterer for various incident energies and energy spreads. In all cases, the distributions are isotropic to within the experimental errors (±15%). These results are in agreement with the predictions of the statistical theory and with the recent results of Thomson et al.[10]

Figure 6 shows the angular distributions of neutrons of energies from 0.5 to 4.0 Mev nonelastically emitted from various elements for an incident neutron energy of 15.2 Mev. No significant deviations from isotropy were observed.

The angular distributions were not corrected for multiple scattering, but due to the fact that the amount of anisotropy was small, the distortions introduced in the distribution by multiple scattering were estimated to be less than about 5%. Cranberg and Levin,[7] as well as Landon et al.,[9] have made measurements to test this assumption, and they have found that the error introduced by multiple scattering was negligible.

IV. CONCLUSION

From the data in the energy region from 3.7 to 4.7 Mev we conclude that, for these energies and for the elements studied, the upper limit for any anisotropy due to direct interaction is 15%.

For incident neutrons of 15.2 Mev, our results also show that the low-energy neutrons (0.5 to 4 Mev) from nonelastic scattering result from compound nucleus formation, in agreement with the results of O'Neill[2] and of Rosen and Stewart.[3]

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Survey of (p,d) Reactions at 22 Mev

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Energy spectra of deuterons from (p,d) reactions on medium and heavy weight elements were surveyed. The experimental method of particle identification is described. The spectra show gross structure indicative of strong selection rules. The gross structure can be correlated with nuclear shell structure, and the levels which are most strongly excited are those which have the same shell configurations as the target with one neutron missing. Angular distributions confirm the shell assignments. This leads to a picture of the reaction mechanism for (p,d) reactions in which the incoming proton interacts principally with a single neutron rather than with the nucleus as a whole.

INTRODUCTION

A PREVIOUS study of (p,d) reactions with 22-Mev protons showed striking similarities among the deuteron spectra from lead isotopes and bismuth.[1] A survey of (p,d) spectra from various elements showed that the shapes of the spectra could not be interpreted as being due to the product of a level density and a Coulomb-barrier penetration function; the intensity of deuterons falls off with decreasing energy well above the Coulomb barrier.[2] In the survey, however, the resolution was not sufficient to show detailed structure.

The present work was undertaken to explore the structure of deutron spectra from (p,d) reactions and to look for element-to-element regularities in the structure of the kind suggested in reference 1.

APPARATUS

The proton source is the external beam of the Oak Ridge National Laboratory 86-inch cyclotron which provides 22.2-Mev protons magnetically analyzed by a 15-deg bending magnet. The protons strike a target in the center of a 24-in. diam scattering chamber and stop on a carbon block in a Faraday cup attached to a direct-current integrator. A proportional-counter-scintillation-counter telescope similar to one previously described[3] is mounted on the continuously rotatable upper part of the scattering chamber. The proportional counter is cylindrical with the particle path on the axis and a 0.001-in. tungsten anode wire displaced from and parallel to the axis. The windows are 2.8 mg/cm² full hard aluminum foils sealed against neoprene O rings. The window-to-window distance is approximately 10 cm.

* Operated for the U. S. Atomic Energy Commission by Union Carbide Corporation.

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