obtained from six separate sets of runs, using

$$\frac{N_1}{N_2}=\frac{\sum[(N_1/N_2)_i/e_i]}{\sum(1/e_i)}\pm\frac{\sqrt{n}}{\sum(1/e_i)}=6.5\pm1.0,$$

where e_i is the probable error in the ith ratio, $(N_1/N_2)_i$, and n is the number of sets.

From the relation $d\Omega'_{\text{cm}}=4\cos\theta d\Omega_{\text{lab}}$ between an element of solid angle in the laboratory system and an element of solid angle in the center-of-mass system, we have $d\Omega_2'/d\Omega_1'=0.547$.

The ratio of the "effective" volume of scattering foil for a proton scattering angle of 15 degrees to the "effective" volume of scattering foil for a proton scattering angle of 44 degrees 24 minutes is equivalent to the ratio of the areas under the neutron-spectrum weighted curves shown in Fig. 8. This ratio has a value of 0.298±0.10.

Hence, the product of these three factors is

$$R=1.06\pm0.16.$$

The results of this experiment seem to be consistent with the existing data, provided that the results of Amaldi are discounted in favor of the predominance of corresponding data presented by numerous other investigators. That is, there does not appear to be any high degree of anisotropy in the neutron-proton scattering at this energy range.

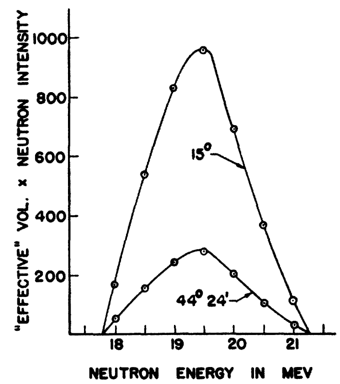

FIG. 8. Spectrum-weighted neutron energy intervals.

The author wishes to express his appreciation for the guidance and help given him by Professors R. B. Sutton, E. C. Creutz, H. C. Corben, and L. Wolfenstein, and is indebted to Dr. M. Foss for his active interest in the problem. He also wishes to express his thanks to Dr. A. J. Allen and the cyclotron staff of the University of Pittsburgh for their cooperation, to Dr. B. Cohen for his helpful suggestions, and to Dr. C. E. Falk and Dr. A. Lasday for their help in construction of equipment and operation of the cyclotron.

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(d,n) Reactions with 15-Mev Deuterons. Part I. Angular Distributions*†

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Nine elements are bombarded with 15-Mev deuterons from a cyclotron. The resulting angular distributions of 9.25- to 13.1-Mev neutrons are measured by means of a four-proportional counter telescope and also by threshold detectors. It is observed that all the measured angular distributions are peaked in the forward direction, some showing a peak at 0° and others peaks at 10°–15° with respect to the deuteron beam. Different methods of production of neutrons from (d,n) reactions are discussed, and it is shown that most of the observed neutrons are produced by a stripping process.

INTRODUCTION

ALTHOUGH the interaction between high energy deuterons (~200 Mev) and nuclei has been thoroughly investigated and explained,[1-3] the nature of the interaction at medium deuteron energies is not clear. Several investigations[4-7] have not produced sufficient evidence to determine whether stripping,[2] which explained the high energy reaction, can account for the nature of the yields in d,n and d,p reactions.

The deuteron beam of the University of Pittsburgh cyclotron was used to investigate the characteristics of the yields of (d,n) reactions. These experiments can be divided into two groups: the investigation of the angular distributions of neutrons produced by 15-Mev deuterons, which is reported here, and the study of neutron energy spectra and neutron yields from d,n reactions, which will be reported in Part II. The integrated interpretation of all the data will be pre-

* Assisted by the ONR.
† This work was carried out in partial fulfillment of the requirements for the degree of Doctor of Science at the Carnegie Institute of Technology.
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[1] A. C. Helmholtz, Phys. Rev. **72**, 1003 (1947).
[2] R. Serber, Phys. Rev. **72**, 1008 (1947).
[3] S. Dancoff, Phys. Rev. **72**, 1017 (1947).
[4] R. B. Roberts and P. H. Abelson, Phys. Rev. **72**, 76 (1947).
[5] Falk, Creutz, and Seitz, Phys. Rev. **76**, 322 (1948).
[6] P. Ammiraju, Phys. Rev. **76**, 1421 (1949).
[7] R. Gove, Phys. Rev. **78**, 344 (1950).

sented at the end of Part II after all the experimental evidence has been reported.

The angular neutron distributions were measured with threshold detectors and also with a proportional counter telescope[8] which detected proton recoils from a polyethylene foil. The apparatus, which consisted of four counters, was able to detect neutrons within any arbitrary energy interval through the use of absorbers in front of the first and last counter. The telescope was then operated with the counters in a coincidence-anticoincidence arrangement. By placing the telescope or the detectors at various angles with respect to the incident deuteron beam it was possible to obtain the neutron angular distributions.

APPARATUS

Thick internal cyclotron targets were used in all experiments. These targets were of the rotating cup type with most metals machined directly as cups. In the case of a gold a heavy layer was sprayed onto a copper cup.

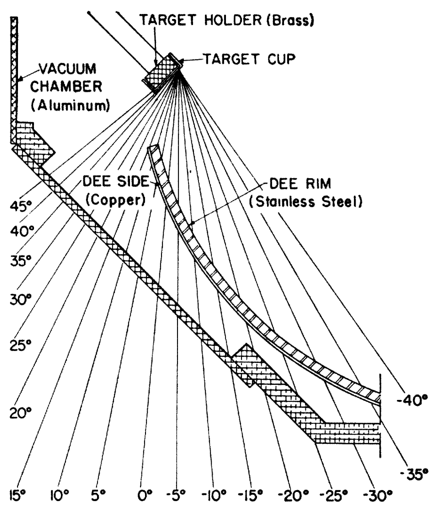

FIG. 1. Horizontal cross section of cyclotron dee and vacuum chamber showing attenuating materials encountered by neutrons coming from the target.

Silver was used as the threshold detector, since the $Ag^{107}(n,2n)Ag^{106}$ reaction had a sufficiently high threshold[9] of ~11 Mev and the 24.5-minute half-life of Ag^{106} was convenient for counting. The detectors were 2″ long cylinders with an o.d. of 1″ and a thickness of 0.020″. The cylindrical form made it convenient to slip the detectors over the G-M tubes.

The counter telescope construction is described by E. Baldwin.[8] The geometry of the detected beam is defined by circular apertures cut into the walls of the counters which have their axes at right angles to the direction of detection. This system of circular apertures permitted only protons within a 10° circular cone to pass from the polyethylene foil through all the counters.

As the experiments were performed inside the cyclotron room it was necessary to discriminate against γ-ray pulses. However, it was important that the electronic discriminators were set low enough to make detection of the high energy proton pulses possible. For this reason the size of pulses produced by polonium α-particles were measured. From range-energy relationships it was possible to calculate how much energy the α-particles would lose in the counter and also how much energy would be lost by the fastest protons. Subsequently, it was possible to determine the minimum discriminator voltage by direct proportionality. Actually, it was possible to set the discriminators at $\frac{1}{3}$ of the height of the smallest proton pulse and still prevent γ-ray pulses from being counted.

As the accidental counting rate is proportional to the cube of the individual counting rate, it was important to keep the latter as low as possible. For this reason a shield consisting of 20 to 30 cement blocks (4″×8″ ×16″) was placed between the counter telescope and the cyclotron. However, it was found that when the telescope was placed in such a position that it pointed along the direction of the opening of the shield, the single-counter counting rate was still much too high. This can be understood if one considers that the neutron flux coming through the opening of the shield would not only irradiate the polyethylene foil but also the aluminum absorbers and the center portion of the brass counters in the telescope. It was found that when the telescope was placed at an angle of 15° with respect to the neutron beam, most neutrons would miss the bulk of the telescope. (The experimental arrangement was similar to the one shown in Fig. 2 of the preceding paper[8] except that the telescope is oriented at 15° away from the cyclotron yoke.) After these precautions had been taken, the deuteron beam was kept at such an intensity that the counting rate of the single counters was small enough to make the number of accidentals negligible.

EXPERIMENTAL PROCEDURE

All experiments on angular distributions were run with the absorbers of the telescope set to detect neutrons from 9.25 Mev to 13.1 Mev. Before and after every run the equipment underwent tests to check the consistency of the gain of the amplifiers and the counting ability of the scalers. The telescope and shield were moved to different angles and the relative neutron intensity per unit monitor count was measured. A thorium fission chamber of the Rossi-Staub type[10] was used as a monitor. It was assumed that the number of fissions would be proportional to the number of deuterons striking the target. The threshold for thorium

[8] For details of telescope construction see E. Baldwin, Phys. Rev. **83**, 495 (1951).

[9] G. C. Baldwin and H. W. Koch, Phys. Rev. **67**, 1 (1945).

[10] B. Rossi and H. Staub, *Ionization Chambers and Counters* (McGraw-Hill Book Company, Inc., New York, 1949), p. 207.

fission being 1.1 Mev,[11] this would be true only if the neutron spectrum remained constant during the run. Neutron spectra measurement showed this to be the case. The monitor was cross checked by measuring the actual deuteron current striking the target.

At each angle, measurements were taken without the polyethylene foil in place in order to determine the background. This measured the number of protons produced by (*n*,*p*) reactions in the aluminum foil, absorbers, and the gas mixture. However, it did not measure those protons produced by (*n*,*p*) reactions in the carbon of the polyethylene. In order to measure these a carbon layer corresponding to the carbon in the polyethylene was placed in front of the counters. It was found that the number of protons produced in the carbon was so small that it could not be measured within the experimental error. By making measurements at different angles the angular distributions in the laboratory system were obtained. However, attenuation corrections have to be made. As can be seen from Fig. 1, the neutrons produced in the target have to traverse the cyclotron vacuum chamber to reach the neutron detectors. Thus, the detected neutrons have to traverse various thicknesses of aluminum, copper, and stainless steel and are consequently attenuated to varying extents before they are actually observed.

The attenuation was calculated by using the total scattering cross section σ_T, which can be broken up into two parts, $\sigma_T=\sigma_{CN}+\sigma_E$. σ_{CN} is the cross section for the formation of the compound nucleus and σ_E the elastic scattering cross section. It has been shown[12,13] that at energies used in this experiment one obtains $\sigma_{CN}=\sigma_E$. Thus, both of these processes had to be considered.

The neutrons produced by the compound nucleus are emitted almost isotropically and usually at lower energies. However, the elastically scattered neutrons are diffracted and are thus scattered predominantly in the forward direction. Their angular distribution is given by[12]

$$B=d\sigma_E/d\omega=R^2[J_1(R\theta/\lambda\!\!\!^{-})/\theta]^2,$$

where R is the radius of the scattering nucleus, θ is the angle of scattering, $\lambda\!\!\!^{-}$ is the De Broglie wavelength of the incoming neutron, and J_1 is a bessel function of the first order. The angular distribution of the elastically scattered neutrons is thus very dependent on the energy of the incident neutron and the radius of the scattering nucleus. Using 11-Mev neutrons the distribution falls to half-intensity at $\theta=0.375$ radian for copper and $\theta=0.490$ radian for aluminum. Because of this anisotropic distribution some of the elastically scattered neutrons will be scattered into the detector. The magnitude of this effect has been calculated for one case, the angular distribution of neutrons produced by deuterons impinging on a copper target, by graphically integrating the following expression:

$$K=\int_0^{\varphi}Bd\theta\Big/\int_0^{2\pi}Bd\theta,$$

where K is the fraction of the elastically scattered neutrons which are scattered into the detectors and φ is the angle subtended by the detector as seen from the scatterer. Results of this calculation showed that the error introduced by neglecting this effect is small enough not to alter the shape of the curves to any noticeable extent.

The above discussion is valid for the measurements which were made with the counter telescope, as in that case where the cement shield prevents elastically scattered neutrons from all parts of the cyclotron from being radiated into the telescope. When threshold detectors are used, there is, of course, no shield in front of them, and then only a fraction of the total cross section should be used for the attenuation calculations, as an appreciable fraction of the elastically scattered neutrons are essentially scattered back into some detectors.

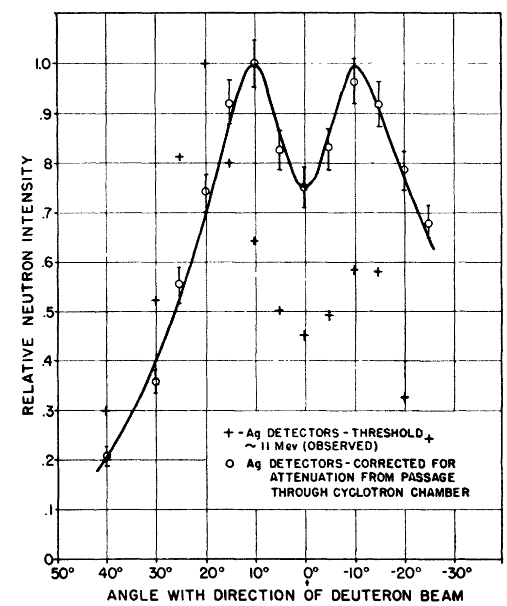

FIG. 2. Angular distribution of neutrons from 15-Mev deuterons or beryllium.

However, the fact that the data obtained with the counter telescope (which does not count scattered-in neutrons) is in good agreement with the threshold detector data (using the same attenuation corrections as those used for the telescope data) shows that the effect of the scattered-in neutrons is very small.

It should be kept in mind, however, that either attenuation calculation procedure is only an approxi-

[11] W. E. Shoupp and L. E. Hill, Phys. Rev. **75**, 785 (1949).
[12] E. Amaldi *et al.*, International Conference on Fundamental Particles and Low Temperatures, Phys. Soc. (London) 1, 97 (1947).
[13] H. Bethe, Phys. Rev. **57**, 352, 1125 (1940).

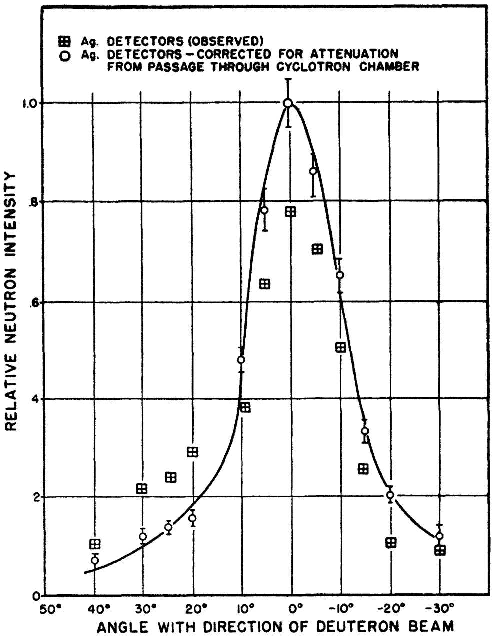

FIG. 3. Angular distribution of neutrons from 15-Mev deuterons on magnesium.

mation and that the accuracy of the results will depend upon this approximation. The proof for "double" and single-peak existence, however, is not affected by this approximation, as in most cases "double" and single peaks are already evident in the data before correction. Figures 2–10 show both the measured distributions and the ones corrected for this attenuation effect.

After the angular distributions of Al and Co (the first being single-peaked and the second double-peaked)

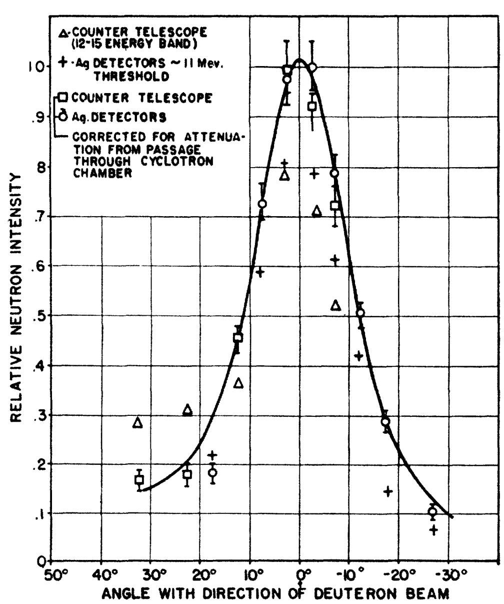

FIG. 4. Angular distribution of neutrons from 15-Mev deuterons on aluminum.

had been measured with the counter telescope, the measurements were repeated with Ag threshold detectors. As can be seen from Figs. 4 and 6, the agreement between the results of the two methods is good. Consequently, the remaining angular distributions were measured only with Ag detectors, as this was the least time consuming method.

Attention is called to the fact that the direction of the deuteron beam was not exactly known within 5°. Thus, it was assumed to be at the center of symmetry of the angular distribution. The orientation of the center of symmetry with respect to the cyclotron varied slightly from run to run; and, consequently, the attenuation corrections are not always identical at the same angle with respect to the deuteron beam.

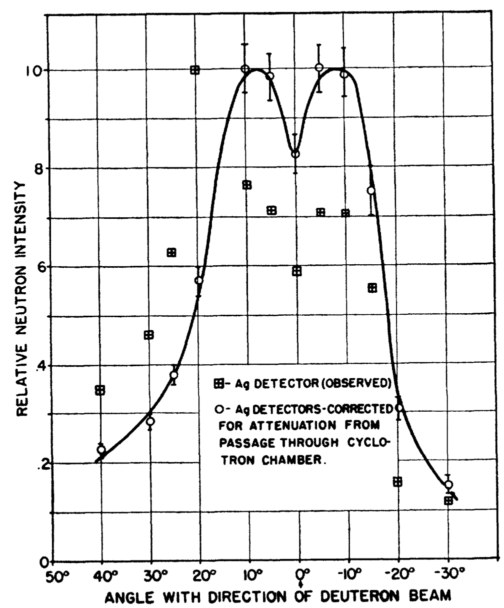

FIG. 5. Angular distribution of neutrons from 15-Mev deuterons on titanium.

As the changes due to the transformation into the center-of-mass system are so slight that no change of the distributions is apparent, all distributions are plotted in laboratory system coordinates.

RESULTS—DISCUSSION

As can be seen from Figs. 2–10 all angular distributions show definite preferred directions. For some elements this preferred direction is that of the deuteron beam. Thus, Mg, Al, Mo, and Ag produce "single" peaks in the neutron distribution. Other targets, such as Be, Ti, Co, Cu, and Au show preferred directions at some angle (usually about 12°–15°) with respect to the deuteron beam. The neutron angular distributions resulting from this appear to be "double" peaked. These experimental results for Be and Al are in good agreement with the recent work by Holt.[14] His neutron angular distributions produced by 8.2-Mev deuterons show also a "double" peak in Be and a "single" peak in Al.

When deuterons interact with nuclei, deuterons can be produced by three different processes: neutron ejection from a compound nucleus formed by the deuteron, stripping, and electric disintegration of the deuteron in flight. Considering neutron production from compound nuclei, the statistical theory of the compound nucleus predicts that, at the energies used in this experiment, the angular distribution of the neutrons should be isotropic,[15] or show a very wide and small peak in the forward direction.[16] As the measured peaks have a maximum to minimum intensity ratio of at least

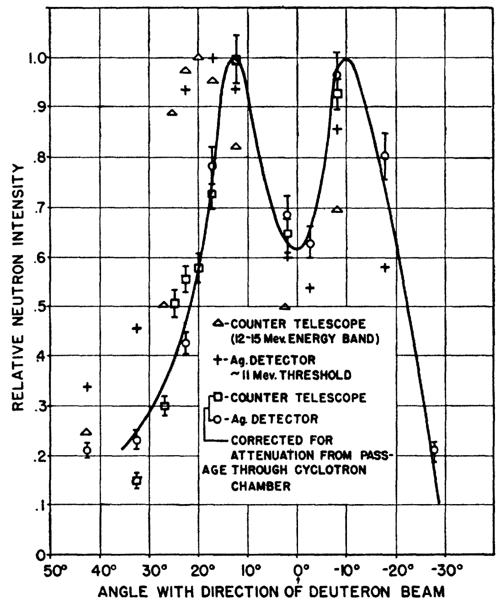

FIG. 6. Angular distribution of neutrons from 15-Mev deuterons on cobalt.

4, it is difficult to see how a compound nucleus can account for the majority of the observed neutrons.

Another method of neutron production through deuteron-induced reactions is stripping. This process has been demonstrated experimentally,[1] and a satisfactory model has been given by Serber.[2] However, this model, which explained the process with 190-Mev deuterons, has to be modified if it is applied to 15-Mev deuterons. While the coulomb effect of the target nucleus on the incoming deuteron becomes much more important at these low energies, the Serber model simply modified for coulomb effect still predicts "single" peaks in the angular distribution of neutrons. Stripping at relatively low energies ($\sim$10 Mev) has been recently

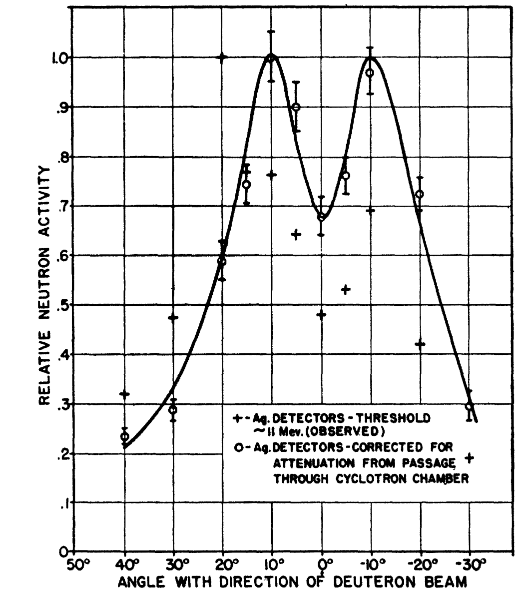

FIG. 7. Angular distribution of neutrons from 15-Mev deuterons on copper.

worked out theoretically. It was shown by Butler[17] that the shape of the angular distributions of the neutrons or protons are determined by the spins and parities of the target and residual nuclei. Thus, an angular momentum change of 0 in the production of the residual nucleus will produce a "single" peaked neutron distribution, a change of $\Delta l = 1$ will produce a slight "double" peak, and a change of $\Delta l = 2$ a very pronounced "double" peak. This explains why the shape of the observed

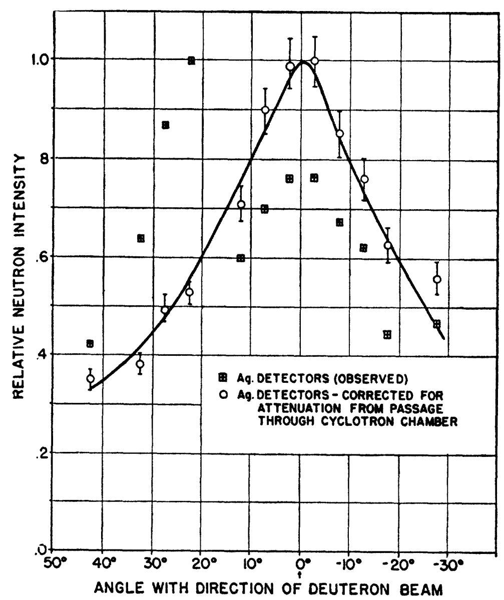

FIG. 8. Angular distribution of neutrons from 15-Mev deuterons on molybdenum.

[14] J. H. Holt, Proceedings of the Harwell Nuclear Physics Conference (September, 1950), p. 52.
[15] V. Weisskopf, Phys. Rev. **52**, 295 (1937).
[16] L. Wolfenstein, Phys. Rev. **78**, 322 (1950).

[17] S. T. Butler, Phys. Rev. **80**, 1095 (1950).

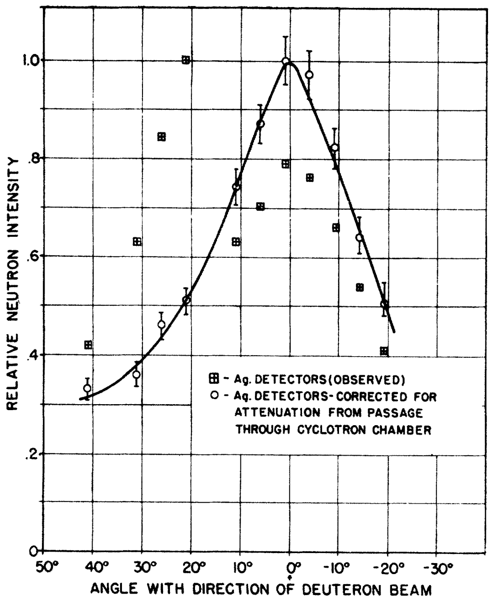

FIG. 9. Angular distribution of neutrons from 15-Mev deuterons on silver.

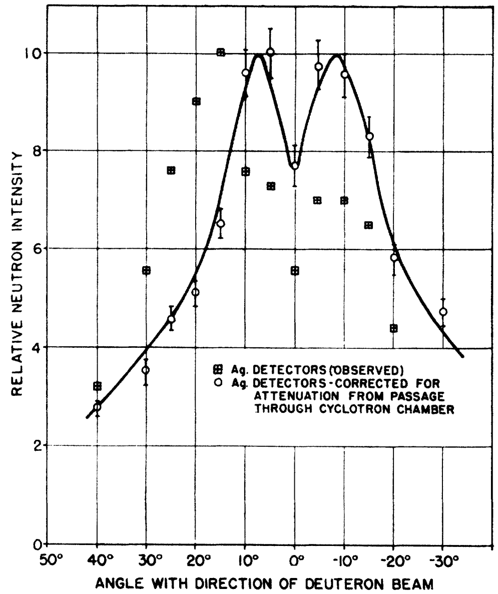

FIG. 10. Angular distribution of neutrons from 15-Mev deuterons on gold.

angular distributions seems to vary irregularly with Z. As the deuteron energies in this experiment (15.0 ± 1Mev) are great enough to have the absorbed proton produce many excited states in the residual nucleus, one would expect all the angular distributions to be a mixture of the $\Delta l=0$, 1, and 2 distributions and thus be "single" peaked and rather wide. The fact that some of the distributions show sharp "single" peaks while others are even "double" peaked seems to indicate that the cross section for the production of some particular excited level must be very large as compared with the cross sections for the formation of the other levels.

The theory for electric disintegration at deuteron energies of about 15 Mev has been worked out in detail for relatively low energy neutrons. Guth[18] has shown that if one considers neutrons of all energies, the angular distributions resulting from electric break-up do show wide "double" peaks and that the cross section for electric disintegration might be comparable to that for stripping. As the assumptions in the theory are not valid for high energy neutrons, it is difficult to apply these theoretical results to this data. However, in the light of the good qualitative agreement between the stripping theory and the experimental results reported in this paper, the work on proton angular distributions and spectra resulting from d,p reactions,[19] and the neutron spectra resulting from d,n reactions,[20] it seems very likely that the stripping process accounts for the majority of the neutrons produced through the bombardment of targets by 15-Mev deuterons.

The author wishes to thank Dr. A. J. Allen, Mr. J. Nechaj, and the crew of the University of Pittsburgh cyclotron for their cooperation and the use of the cyclotron, Drs. E. Creutz, L. Wolfenstein, and F. Seitz for their experimental and theoretical guidance, Drs. E. Baldwin and A. Lasday for their help throughout the experiment, and Dr. B. Cohen for many helpful discussions.

[18] E. Guth (private communication).

[19] H. Gove, Phys. Rev. **78**, 344 (1950).

[20] C. Falk and B. Cohen (to be published).