This event is then interpreted as the collision of a primary alpha-particle of several Bev energy with a nucleus in the emulsion, which leads to the emission of several charged nucleons of energies estimated to be from 4 to 200 Mev and the production of a low energy π-meson. Since the alpha-particle lost an energy or more than 1 Bev in this encounter and then continued on with an angular deviation of 2.5°, its energy was greater than the cut-off energy for alpha-particles at 50° magnetic latitude.

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* Assisted by the joint program of the ONR and the AEC.

[1] Brown, Camerini, Fowler, Murihead, Powell, and Ritson, Nature **163**, 47 (1949).

Angular Distribution of Neutrons from (*d*,*n*) Reactions*

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May 25, 1949

THIS letter gives further results of preliminary experiments on the angular distributions of neutrons from (*d*,*n*) reactions.[1] The theory explaining the phenomena of (*d*,*n*) reactions at high deuteron energies (approximately 200 Mev) is well known[2–4] and has been satisfactorily verified by experiments.[5] However, from the work of Roberts and Abelson[6] there is evidence that (*d*,*n*) reactions at comparatively low energies (about 13 Mev) cannot be explained by the present day theories.

Deuterons of approximately 16 Mev, produced by the University of Pittsburgh cyclotron which was made available to us through the courtesy of Dr. A. Allen, were used to bombard thick targets of various elements. The relative resulting neutron fluxes were then measured at different angles by means of threshold detectors. Different elements were used as targets in order to study distributions as functions of the atomic weight of the target and the Q value of the reactions as shown in Table I.

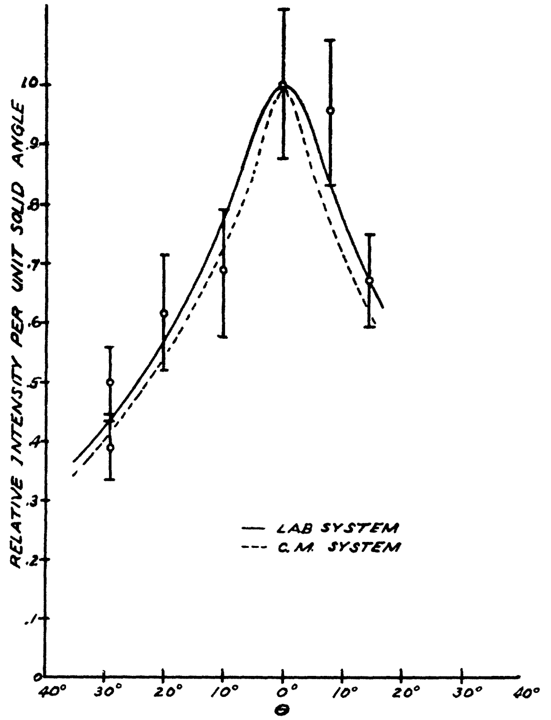

FIG. 1. Angular distribution of neutrons from $Au^{197}(d,n)Hg^{198}$ reaction. θ is angle between direction of maximum neutron intensity and other measured intensities.

TABLE I. Targets used.

Target	A	Q	
$LiBO_2$	Li-6, 7 B-10, 11	+15 Mev +13.8 Mev −1.6 Mev	for Li for B for O
Be	9	+4.3 Mev	
Cu	63.64	∼+8 Mev	
Au	197	∼+8 Mev	

Table II gives a list of the elements used for detection and the respective thresholds of the reaction.

Figures 1 and 2 show the resulting angular distributions for two typical cases, and Table III shows a summary of the experiments. It is immediately apparent that the distribution in all cases is sharply peaked in the forward direction. As there was a considerable amount of scattering of neutrons from the coils, poles, and the yoke of the cyclotron, small corrections had to be made for this effect. This was accomplished by a graphical integration of the effect over the complete area of the magnet pole pieces. Columns 4 and 5 in Table III show the corrected experimental half-widths (full width at half-maximum) of the angular distributions. The estimated experimental error in the listed half-width is ±10°. The magnitude of this experiment, however, makes it impossible as yet to determine the variation of the half-width of the distributions with A and Q.

TABLE II. Elements used for detection and threshold values.

Detector	Reaction	Half-life of product nucleus	Threshold energy	Reference
C^{12}	$C^{12}(n,2n)C^{11}$	20.5 min.	20.4 Mev	R. Sherr, Phys. Rev. **68**, 240 (1945).
Cu^{63}	$Cu^{63}(n,2n)Cu^{62}$	10.5 min.	12–13 Mev	R. Sagane, Phys. Rev. **53**, 492 (1938); E. O. Salant and N. F. Ramsay, Phys. Rev. **57**, 1075A (1940).
Ag^{107}	$Ag^{107}(n,2n)Ag^{106}$	24.5 min.	5–7 Mev	R. Sagane, Phys. Rev. **53**, 492 (1938); D. C. Graham and G. T. Seaborg, Phys. Rev. **53**, 795 (1938).
Al^{27}	$Al^{27}(n,p)Mg^{27}$	10.2 min.	∼4.5	D. C. Graham and G. T. Seaborg, Phys. Rev. **53**, 795 (1938); Feld, Scalettar, and Szilard, Phys. Rev. **71**, 464 (1947).

Nevertheless, the results are of interest. In particular, the data for the gold is hard to reconcile with Serber's stripping theory.[3] Furthermore, the distinct directionality of the distribution is difficult to explain by a simple isotropic evaporation theory of a liquid drop compound nucleus.

TABLE III. Summary of experimental results.

Target	Detector	Reaction	Half-width of neutron distribution (lab. system)	(c.m. system)
$LiBO_2$	C	$Li^{6,7}(d,n)Be^{7,8}$	26°	23°
$LiBO_2$	Cu	$B^{10,11}(d,n)C^{11,12}$	30°	22°
$LiBO_2$	Ag		34°	27°
Be	Ag	$Be^{9}(d,n)B^{10}$	26°	18°
B_4C	C	$B^{10,11}(d,n)C^{11,12}$	34°	26°
Co	Cu	$Co^{59}(d,n)Ni^{60}$	26°	25°
Cu	Cu	$Cu^{63,65}(d,n)Zn^{64,66}$	26°	24°
Cu	Ag	$Cu^{63,65}(d,n)Zn^{64,66}$	48°	42°
Au	Ag	$Au^{197}(d,n)Hg^{198}$	49°	44°

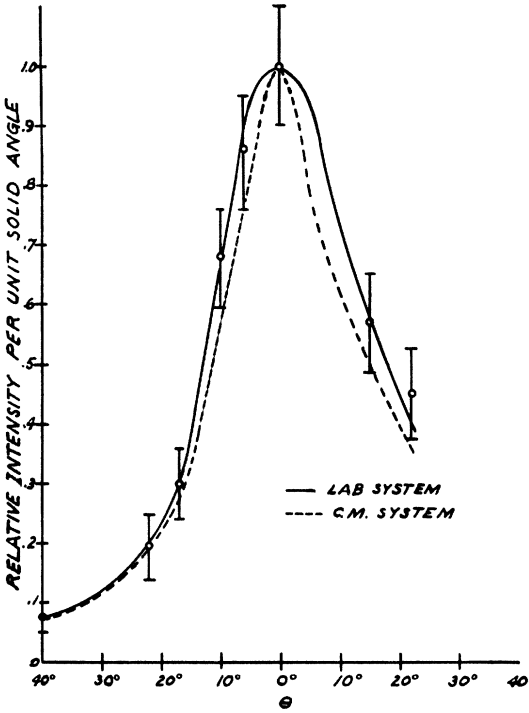

FIG. 2. Angular distribution of neutrons from a $LiBO_2$ target bombarded by 15-Mev deuterons. θ is angle between the direction of maximum neutron intensity and other measured intensities.

To obtain a better understanding of the above described phenomena, experiments are now in progress to improve this data. A four-proportional counter telescope has been built. Better experimental accuracy is expected since the error due to room scattered neutrons is eliminated. Furthermore, it will be possible to measure the neutron spectrum at different angles.

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* Assisted by the ONR under Contract N7onr-30304.
** AEC Fellow.
[1] Falk, Creutz, and Seitz, Phys. Rev. **74**, 1226 (1948).
[2] J. R. Oppenheimer, Phys. Rev. **47**, 845 (1935).
[3] R. Serber, Phys. Rev. **72**, 1008 (1947).
[4] S. Dancoff, Phys. Rev. **72**, 1017 (1947).
[5] Helmholz, McMillan, and Sewell, Phys. Rev. **72**, 1003 (1947).
[6] R. B. Roberts and P. H. Abelson, Phys. Rev. **72**, 76 (1947).

Proton Stopping Power of Gold

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THE previously reported measurements of the proton stopping power of beryllium[1] have been extended to gold, using the proton resonances F-339 and Al-986 as energy indicators.

A foil thickness of about $\frac{1}{2}$ mg/cm^2 was chosen for the experiment in order to obtain a shift of the resonance peaks of approximately three times the half-width calculated from the theory of straggling.

The results found are given in Table I for three different foils, each consisting of three layers of commercial gold-leaf (content of copper less than 1 percent). An example of the measurements on the line F-339 is reproduced in Fig. 1. The broadening of the peak is only slightly greater than should be expected because of the straggling, indicating that the foils are only slightly inhomogeneous.

TABLE I. Proton stopping power for three different foils.

Resonance	Total thickness mg/cm^2	Shift kev	Mean energy kev	Stopping power kev per mg/cm^2
F-339	0.46	39	364	85
F-339	0.52	42	366	81
Al-986	0.46	27	1001	59
Al-986	0.51	30	1002	59
Al-986	0.52	31	1003	60

Wilcox[2] reports a value of 67 kev per mg/cm^2 for the stopping power of gold at a proton energy of 365 kev. This value is about 20 percent smaller than ours, but in the experiment of Wilcox, the energy shift is only of the same order of magnitude as the half-width, and the results are, for this reason, probably less accurate. The reported difference of 10 percent between the values for protons and deuterons of the same velocity may, therefore, also be expected to be within the experimental uncertainty. This explanation is in agreement with later experiments by Hall and Warshaw.[3]

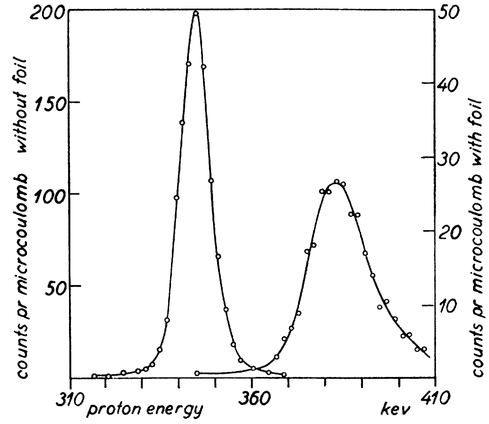

FIG. 1. The F-339 resonance measured without foil and with a 0.46 mg/cm^2 gold-foil inserted in the proton beam.

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[1] C. B. Madsen and P. Venkateswarlu, Phys. Rev. **74**, 648 (1948).
[2] H. Wilcox, Phys. Rev. **74**, 1743 (1948).
[3] T. A. Hall and S. D. Warshaw, Phys. Rev. **75**, 891 (1949).

The Density Field in Mach Reflection of Shock Waves

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June 6, 1949

WHEN two shock waves interact with one another the result is not always a simple crossing of the two waves as would be expected from a linear theory. The nature of the more complicated phenomenon was observed by Mach.[1] Von Neumann[2] has pointed out that the interaction is equivalent to the oblique reflection of a single shock from a rigid wall and he proposed a theory by which the strengths and angles of the other discontinuities could be predicted at the point of intersection from the direction of the incoming flow and the strength of the incident shock. His theory of Mach reflection assumed that the three shocks and a slip stream were the only discontinuities present and that the pressure was constant in each of the three angular domains bounded by the three shocks at least in the neighborhood of the intersection. The experimental results of Smith[3] who determined