d-D Reactions at 6- to 14-Mev Input Energy*

J. E. BROLLEY, JR., T. M. PUTNAM, AND LOUIS ROSEN
Los Alamos Scientific Laboratory, University of California, Los Alamos, New Mexico

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Differential cross sections for both branches of the d-D reaction have been obtained over the input energy interval 6 to 14 Mev by charged particle measurements utilizing a nuclear multiplate camera. Legendre expansions are given which permit interpolation of the data over both energy and angle.

INTRODUCTION

ALTHOUGH the d-D reactions have been known for a long time,[1] a satisfactory theoretical and experimental picture of the process does not exist. Calculations for low input energy have been carried out by Konopinski and Teller,[2] Nakano,[3] and Beiduk, Pruett, and Konopinski.[4] These considerations indicate that the principal features of the reaction can be accounted for by invoking centrifugal barriers and spin-orbit forces.

Applicability of stripping theory calculations to the hydrogen isotope reactions was indicated by Butler and Symonds.[5] They were able to fit the shapes of the experimental angular distribution for the mirror reactions[6] $He^3(d,p)He^4$ and[7] $T(d,n)He^4$ at 10.5-Mev deuteron energy. The agreement is not, however, such as to preclude a contribution from compound nucleus formation. Fairbairn[8] has symmetrized the stripping theory to apply to the d-D reaction. At 19-Mev deuteron energy (in the laboratory system) the general theoretical prediction of the differential cross section is consonant with experiment, but the agreement appears to deteriorate with diminishing input energy. The trend of the calculated 0° cross section in the center-of-mass system is opposite to that observed experimentally.

To amplify the experimental picture of this reaction, we have made observations on the differential cross sections of both branches over the range from 6- to 14-Mev laboratory input energy. The present study is confined to charged particle measurements and necessarily leaves some gaps in the differential cross sections. We also observed, but did not make quantitative measurements of, tertiary branching of the reactions.

TABLE I. Angular dependence of the $D(d,p)T$ reaction at $E_d=6.1\pm0.1$ Mev, based on 125 779 tracks. Angular error is $\pm0.1°$.

Proton c.m. angle (deg)	$\sigma(\theta)$[a] (mb/sterad)	Proton c.m. angle (deg)	$\sigma(\theta)$[a] (mb/sterad)
13.8	27.73	114.8	4.07
17.2	23.84	119.6	3.43
20.6	20.43	121.9	3.38
24.0	16.63	124.2	2.98
27.5	13.73	126.5	2.84
30.8	9.60	128.6	3.20
34.2	7.63	130.8	2.95
37.6	5.65	133.0	2.90
40.9	4.41	135.1	3.34
44.2	3.40	137.1	3.75
47.6	2.96	139.1	4.47
50.8	2.86	141.1	5.04
54.1	2.65	143.1	6.13
57.4	3.01	145.0	7.46
60.6	3.26	146.9	8.31
63.8	3.71	150.5	11.89
66.9	4.39	152.3	13.57
70.0	4.72	154.1	15.00
73.1	5.06	157.5	19.60
76.2	5.44	159.2	20.78
79.2	5.35	160.9	22.09
82.2	5.65	162.6	22.73
85.1	5.89	167.4	29.66
90.9	6.12	169.0	30.43
96.5	5.84	170.6	31.96
99.2	5.50	172.2	34.00
107.2	5.08	173.8	34.08
109.8	4.83	175.4	36.27
112.3	4.75		

[a] The rms errors for the cross sections are as follows: 13.8° through 114.8°, 3%; 119.6° through 143.1°, 4%; 145.0° through 175.4°, 3%.

TABLE II. Angular dependence of the $D(d,p)T$ reaction at $E_d=8.1\pm0.1$ Mev, based on 80 211 tracks. Angular error is $\pm0.1°$.

Proton c.m. angle (deg)	$\sigma(\theta)$[a] (mb/sterad)	Proton c.m. angle (deg)	$\sigma(\theta)$[a] (mb/sterad)
14.1	29.77	130.5	2.34
17.6	24.26	136.8	2.80
24.6	15.46	140.8	3.72
35.0	5.80	142.7	4.63
41.9	3.18	144.6	5.30
45.3	2.64	148.3	7.89
55.3	2.67	151.8	11.58
65.2	4.02	153.6	13.22
74.7	5.08	155.3	14.31
83.9	5.59	158.6	19.69
86.9	5.44	163.4	25.41
92.7	5.44	168.0	32.78
101.1	5.27	169.6	33.80
109.1	4.81	171.1	35.78
116.7	4.03	172.6	36.07
123.8	2.89	174.1	36.75
128.3	2.62	175.6	38.81

[a] The rms errors for the cross sections are as follows: 14.1° through 109.1°, 3%; 116.7° through 144.6°, 3.5%; 148.3° through 175.6°, 3%.

* This work was performed under the auspices of the U. S. Atomic Energy Commission.

[1] A comprehensive bibliography is contained in a paper by J. L. Fowler and John E. Brolley, Jr., Revs. Modern Phys. **28**, 103 (1956).
[2] E. J. Konopinski and E. Teller, Phys. Rev. **73**, 822 (1948).
[3] Y. Nakano, Phys. Rev. **76**, 981 (1949).
[4] Beiduk, Pruett, and Konopinski, Phys. Rev. **77**, 622 (1950).
[5] S. T. Butler and J. L. Symonds, Phys. Rev. **83**, 858 (1951).
[6] J. C. Allred, Phys. Rev. **84**, 695 (1951).
[7] Brolley, Fowler, and Stovall, Phys. Rev. **82**, 502 (1951).
[8] W. M. Fairbairn, Proc. Phys. Soc. (London) **A67**, 990 (1954).

APPARATUS AND METHODS

The Los Alamos variable-energy cyclotron was utilized to supply deuterons with energies from 6 to 14 Mev. The deuteron beam was conducted from the accelerator vault to the reaction area vault by an ion optical system having suitable focusing and steering properties. The deuteron beam traversed a nuclear multiplate camera filled with deuterium and then passed into a vacuum chamber housing a Faraday cup. The camera and charge measuring equipment have been described in detail elsewhere.[9,10]

A salient problem in this investigation was the identification of the various charged particles produced. Scattered deuterons from the elastic process are detected along with protons, tritons, and He^3 nuclei from the reactions. The present measurements require the unambiguous identification of protons and He^3 particles. Proton measurements were facilitated by imposing range restrictions and by interposing aluminum absorbers to remove the deuterons from the beam of particles incident upon the nuclear emulsions. The absorbers, which were mounted in frames near the emulsions, introduced particle losses from multiple scattering. Considerations based on the work of Dickinson and Dodder[11] established that, for thicknesses of absorbers used, no significant loss of particles would occur, i.e., inscatter essentially compensates for outscatter. Further justification for ignoring multiple scattering in this particular case will be adduced from an examination of the final data. Recognition of He^3 tracks, on the basis of ionization and range, was expedited by suitably developing the emulsions to accentuate the He^3 tracks over those of the hydrogen isotopes.

Protons were counted in Ilford C-2 emulsions; He^3 particles in Ilford E-1 emulsions. The emulsions contained extra plasticizer and were predesiccated in a separate high-vacuum system for several days prior to insertion in the camera. This procedure resulted in the liberation of a negligible amount of water vapor during the exposure.

The entire camera was filled with deuterium at pressures ranging from 5 to 20 cm Hg. Pressures were measured with precision Bourdon gauges which were frequently calibrated against a mercury manometer. The purity of the deuterium, as given by the manufacturer, was 99.91%.

The input deuteron energy required for a given run was obtained by setting the cyclotron energy according to semiempirical operation curves. A test run was then made using the camera. From the ranges of the reaction products observed, the input energy at the center of the camera was determined and the cyclotron frequency trimmed to give the desired energy value. Energy

TABLE III. Angular dependence of the $D(d,p)T$ reaction at $E_d=12.15\pm0.15$ Mev, based on 77 200 tracks. Angular error is $\pm0.1°$.

Proton c.m. angle (deg)	$\sigma(\theta)$[a] (mb/sterad)	Proton c.m. angle (deg)	$\sigma(\theta)$[a] (mb/sterad)
14.5	27.78	135.0	2.19
18.1	20.78	139.0	2.41
25.3	11.95	142.9	3.30
36.0	3.72	144.8	3.80
43.1	2.33	146.6	4.90
46.6	2.10	150.1	7.24
56.9	3.52	153.5	10.84
66.9	4.11	155.2	13.01
76.7	4.36	156.8	14.03
86.1	3.99	159.9	19.01
89.1	4.10	164.5	24.02
95.1	4.18	167.4	31.19
103.6	4.24	168.8	32.73
111.6	4.56	170.3	35.21
119.2	3.82	171.7	35.20
126.3	3.18	173.1	38.86
130.8	2.54	174.5	40.91
132.9	2.44	175.9	42.12

[a] The rms errors for the cross sections are as follows: 14.5° through 103.6°, 3%; 111.6° through 119.2°, 3.5%; 126.3° through 135.0°, 4%; 139.0° through 146.6°, 3.5%; 150.1° through 175.9°, 3%.

TABLE IV. Angular dependence of the $D(d,p)T$ reaction at $E_d=13.8\pm0.15$ Mev, based on 74 997 tracks. Angular error is $\pm0.1°$.

Proton c.m. angle (deg)	$\sigma(\theta)$[a] (mb/sterad)	Proton c.m. angle (deg)	$\sigma(\theta)$[a] (mb/sterad)
14.6	26.67	131.4	2.66
18.3	19.50	133.6	2.39
25.5	10.18	143.5	3.24
29.1	7.33[b]	145.4	3.84
36.3	3.12	147.2	4.52
43.4	2.23	150.7	7.11
46.9	2.32	154.0	9.75
57.3	3.59	155.6	11.20
67.5	4.03	157.2	14.13
77.3	4.16	160.3	18.71
86.7	3.57	164.8	25.82
89.8	3.78	169.1	32.15
95.7	3.93	170.5	33.72
104.3	3.97	171.8	37.05
112.4	4.36	173.2	37.92
120.0	3.79	174.6	38.80
127.0	3.17	176.0	40.12

[a] The rms errors for the cross sections are as follows: 14.6° through 104.3° 3%; 112.4° through 120.0°, 3.5%; 127.0° through 147.2°, 4%; 150.7° through 176.0°, 3%.
[b] Average of two different runs.

TABLE V. Angular dependence of the $D(d,n)He^3$ reaction at $E_d=5.8\pm0.1$ Mev, based on 27 922 tracks. Angular error is $\pm0.1°$.

He^3 c.m. angle (deg)	$\sigma(\theta)$[a] (mb/sterad)	He^3 c.m. angle (deg)	$\sigma(\theta)$[a] (mb/sterad)
22.0	21.37	61.0	3.33
27.4	15.09	66.8	4.41
33.0	10.22	72.4	4.83
38.5	5.72	78.2	5.65
44.1	3.79	84.1	6.04
49.6	2.73	90.6	5.86
55.5	2.76	97.3	5.79

[a] The rms error for the cross sections is 4%.

[9] Allred, Rosen, Tallmadge, and Williams, Rev. Sci. Instr. **22**, 191 (1951).
[10] Putnam, Brolley, and Rosen, Phys. Rev. **104**, 1303 (1956).
[11] W. C. Dickinson and D. C. Dodder, Rev. Sci. Instr. **24**, 428 (1953).

TABLE VI. Angular dependence of the $D(d,n)He^3$ reaction at $E_d=8.15\pm0.1$ Mev, based on 30 600 tracks. Angular error is $\pm0.1°$.

He^3 c.m. angle (deg)	$\sigma(\theta)$[a] (mb/sterad)	He^3 c.m. angle (deg)	$\sigma(\theta)$[a] (mb/sterad)
22.9	19.28	70.1	4.95
28.7	11.20	76.3	5.42
34.5	7.01	82.6	5.55
40.3	3.49	89.1	5.57
46.1	2.32	95.8	5.73
52.0	2.41	102.9	5.41
58.0	3.05	110.5	4.96
64.0	4.14		

[a] The rms error for the cross sections is 4%.

TABLE VIII. Angular dependence of the $D(d,n)He^3$ reaction at $E_d=12.2\pm0.15$ Mev, based on 25 965 tracks. Angular error s $\pm0.1°$.

He^3 c.m. angle (deg)	$\sigma(\theta)$[a] (mb/sterad)	He^3 c.m. angle (deg)	$\sigma(\theta)$[a] (mb/sterad)
24.0	13.67	67.6	4.24
30.1	6.96	74.2	4.34
36.2	3.64	81.0	3.85
42.3	2.17	88.1	4.16
48.5	2.36	95.6	4.17
54.8	3.15	103.6	4.35
61.1	3.67	112.8	4.30

[a] The rms error for the cross sections is 4%.

stability was maintained by a high degree of regulation of both the magnetic field and the frequency of the cyclotron. The energy spread of the beam was less than 1% full width at half-maximum at all energies. The current density in the beam was kept sufficiently low to negate beam heating effects in the reaction volume.

EXPERIMENTAL RESULTS

We have obtained angular distributions for the He^3 branch at laboratory deuteron energies of 5.8 ± 0.1, 8.15 ± 0.1, 10.4 ± 0.1, 12.2 ± 0.1, and 13.8 ± 0.2 Mev. Angular distributions for the proton branch were obtained at laboratory deuteron energies of 6.1 ± 0.1, 8.1 ± 0.1, 12.15 ± 0.1, and 13.8 ± 0.15 Mev. The latter sequence of measurements is supplemented by a previous measurement[12] at 10.3 Mev using the same camera and the old Los Alamos cyclotron. The 10.3-Mev data from 0° to 90° (c.m.) were deleted since the uncertainties in the multiple-scattering corrections applied in this interval are now thought to be somewhat high.

The experimental results are compiled in Tables I through IV for the proton branch and Tables V through IX for the neutron branch of the reactions. For the purpose of displaying the essential features of the reaction, we have presented all data in the center-of-mass system. The Legendre expansions, $\sigma=\sum a_iP_i$, provide convenient relations for the interpolation and extrapolation of the data. The Legendre coefficients are collected in Table X.

TABLE VII. Angular dependence of the $D(d,n)He^3$ reaction at $E_d=10.4\pm0.1$ Mev, based on 29 738 tracks. Angular error is $\pm0.1°$.

He^3 c.m. angle (deg)	$\sigma(\theta)$[a] (mb/sterad)	He^3 c.m. angle (deg)	$\sigma(\theta)$[a] (mb/sterad)
23.6	16.60	66.2	4.18
29.6	9.08	72.6	4.66
35.3	4.39	79.2	4.62
41.6	2.74	86.0	4.66
47.6	2.29	93.0	4.81
53.7	2.75	100.5	4.66
59.9	3.75	108.6	4.75

[a] The rms error for the cross sections is 4%.

[12] Allred, Phillips, and Rosen, Phys. Rev. 82, 782 (1951).

Also included are expansions for the Minnesota data,[13] based on charged particle measurements, where zero-degree values estimated from reference 1 have been utilized. The energy dependence of the Legendre coefficients is given in Fig. 1. Cross sections given by the Legendre expansions may be readily transformed into the laboratory system with the aid of suitable tables.[14] Figure 2 graphically displays the present data and Legendre fits. Integration of the Legendre expansions provides the total cross sections presented in Table X, where we have again included the Minnesota data. From the Legendre expansions we have also obtained the extrapolated 0° yields, plotted in Fig. 3 together with earlier data for the neutron branch.[1]

DISCUSSION OF RESULTS

The elucidation of errors given in reference 10 is germane to this paper. However, some additional factors prevailed in this experiment.

The purity of the deuterium was stated by the manufacturer to be 99.91%, and no significant indication of impurity scattering was noted in the range distributions. No impurity correction was therefore incorporated in the data. A mass spectrographic analysis performed on the gas indicated slightly less purity, but this could

TABLE IX. Angular dependence of the $D(d,n)He^3$ reaction at $E_d=13.8\pm0.15$ Mev, based on 43 402 tracks. Angular error is $\pm0.1°$.

He^3 c.m. angle (deg)	$\sigma(\theta)$[a] (mb/sterad)	He^3 c.m. angle (deg)	$\sigma(\theta)$[a] (mb/sterad)
24.3	13.07	68.6	4.09
30.5	6.18	75.4	4.01
36.6	3.24[b]	82.4	3.82
42.9	2.19	89.7	3.66
49.2	2.79[b]	97.5	3.81
55.5	3.31[b]	106.2	4.20
62.0	3.92	116.5	4.62

[a] The rms error for the cross sections is 4%.
[b] Average of two different runs.

[13] Blair, Freier, Lampi, Sleator, and Williams, Phys. Rev. 74, 1599 (1948).

[14] L. Blumberg and S. E. Schlesinger, Atomic Energy Commission Report AECU-3118, May, 1956 (unpublished).

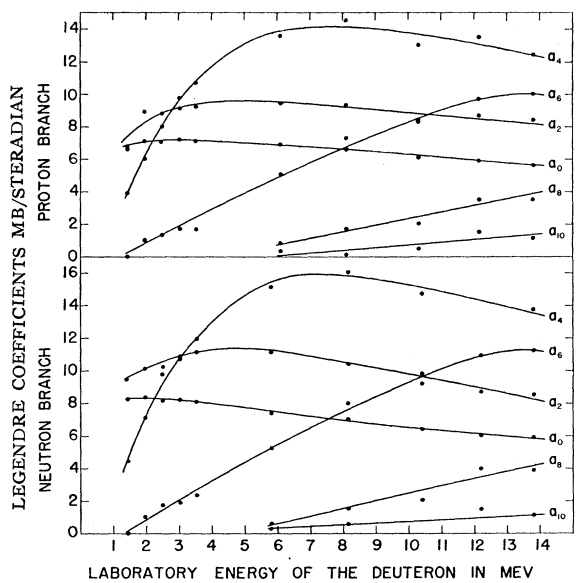

FIG. 1. Energy dependence of the Legendre coefficients for both branches of the d-D reaction.

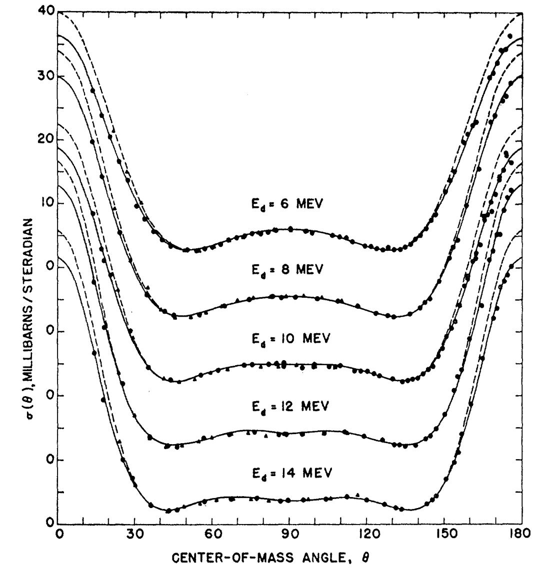

FIG. 2. Comparison of the experimental data with the Legendre expansions. The solid triangles and dashed curve are for the neutron branch; the solid circles and solid curves are for the proton branch.

have been occasioned by subsequent introduction of impurities during gas transfer from the reservoir to the mass spectrograph.

Multiple scattering requires consideration in several areas of the camera. The incident beam from the cyclotron experiences multiple scattering during its traversal of the camera and exit window. If, after leaving the reaction volume, the beam undergoes excessive multiple scattering in the gas and window, the Faraday cup will not collect all the charge. This would lead to an anomalously high cross section. It can be shown that even under the most extreme conditions of the present experiments, the combined scattering of the gas and window do not cause any significant loss to the Faraday cup. Multiple scattering in the gas could also depress the observed cross section by reducing the number of particles reaching the emulsion at any angle. Although a detailed calculation of this effect has not been made, it may be considered negligible on the basis of cross section measurements at different gas pressures. Lastly, scattering in the aluminum absorbers used at the most forward angles has been calculated and found to have a negligible effect on the observed cross sections. A perusal of Fig. 2 shows that the data are symmetric about 90° in the center-of-mass system within experi-

TABLE X. Legendre coefficients for both branches of the d-D reaction and total cross sections obtained from integrations of the Legendre expansions.

E_d (Mev)	a_0	a_2	a_4	a_6	a_8	a_{10}	a_{12}	σ_{total} (mb)
			Neutron branch					
1.43	8.30	9.48	4.48	0				104
1.96	8.40	10.16	7.16	1.06				105
2.49	8.19	10.25	8.80	1.80				102
3.02	8.24	10.91	10.73	1.92				103
3.52	8.12	11.17	11.97	2.39				102
5.80	7.40	11.14	15.16	5.28	0.64	0.34		93
8.15	7.03	10.45	16.06	8.02	1.59	0.61		88
10.4	6.43	9.85	14.77	9.22	2.11	0		81
12.2	6.04	9.71	14.55	10.94	4.02	1.48		76
13.8	5.93	9.56	13.77	11.26	3.97	1.13	0.26	75
			Proton branch					
1.43	6.63	6.80	3.94	0				83
1.96	7.14	8.95	6.02	1.07				90
2.49	7.12	8.87	7.05	1.38				89
3.02	7.23	9.15	9.79	1.74				90
3.52	7.11	9.25	10.71	1.73				88
6.10	6.96	9.45	13.58	5.14	0.85	0.39		87
8.10	6.64	9.36	14.53	7.32	1.73	0.18		84
10.30	6.12	8.46	13.03	8.32	2.09	0.52		77
12.15	5.92	8.70	13.50	9.72	3.53	1.55		74
13.80	5.65	8.42	12.44	10.03	3.58	1.17	0.39	72

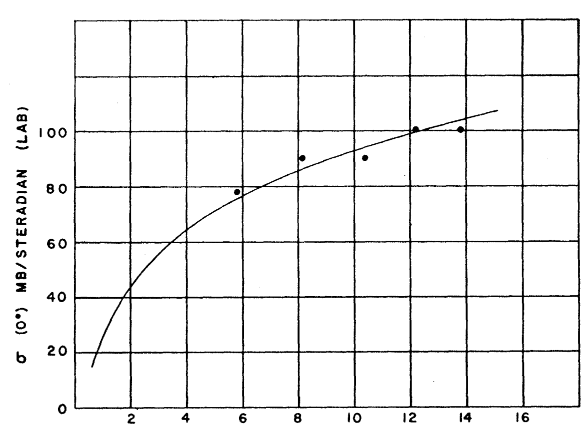

FIG. 3. 0° laboratory cross section of the neutron branch as estimated from the present work.

mental errors. This must, of course, be so for the interaction of two like particles at nonrelativistic energies and represents an excellent check on the internal consistency of the data.

The general behavior of the Legendre coefficients illustrates the importance of higher angular momenta with increasing energy. We have found it necessary to employ Legendre coefficients up to a_{12}, which does not imply an unreasonable value of angular momentum at 14 Mev.

Although the present work establishes the differential cross sections with respect to energy and angle with rather good precision over most of the angular region, additional information is required to complete the experimental picture. Thus, neutron measurements are required to extend the He^3 branch measurements to 0°. Moreover, the polarization of the reaction products should be determined. Theoretical calculations on the subject reactions are presently in progress at this laboratory.

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Neutron Emission Probabilities from the Interaction of 14-Mev Neutrons with Be, Ta, and Bi†

Louis Rosen and Leona Stewart
Los Alamos Scientific Laboratory, University of California, Los Alamos, New Mexico

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The spatial and spectral distributions of the neutrons from 14-Mev neutron interactions with Ta and Bi have been obtained by using nuclear emulsion detectors in conjunction with a neutron collimator. These results indicate that roughly 85 to 90% of the interactions proceed via compound-nucleus formation while approximately 10 to 15% proceed by "direct" interactions. The space-integrated neutron spectrum has been obtained for Be by means of a sphere experiment. Cross sections for neutron emission, nonelastic scattering, (n,n'), and $(n,2n)$ are derived for all three elements.

I. INTRODUCTION

THE spatial and spectral distributions of the neutrons emitted when heavy elements are irradiated by fast neutrons yield information concerning the basic mechanism of such interactions. Specifically, these data shed light on (a) the type of interaction processes involved: for example, the relative probability of compound-nucleus formation *versus* interactions involving a small number of nucleons, (b) level density of the residual nucleus, and (c) the applicability of various nuclear models.

Previous experiments have yielded data which are not in complete harmony with any one of the currently popular nuclear models. The low-energy neutron distribution has the shape expected from the statistical model of the nucleus, even at very high incident energies, but the high-energy tail contains too many neutrons. Though the "temperatures" and level densities are approximately those predicted by the statistical model, these quantities exhibit a disconcerting invariance with regard to mass number and excitation energy of the residual nucleus. It would almost appear as though the "temperature" of the residual nucleus cannot exceed several Mev regardless of the incident particle energy. Whether this be due to a "melting" effect,[1] to the emission of particles in times shorter than required for exchange of energy between the incident nucleus and the nucleons in the target nucleus, or to other effects, is at present far from clear. Recent results on (p,xn) reactions[2] for 12- to 85-Mev protons on Pb and Bi indicate that the compound-nucleus process is dominant at least up to 30 Mev. However, (p,xn) experiments[3] and (n,n') experiments[4] yield nuclear temperatures (τ) which appear to be a factor of 2 lower than those derived from (α,n) and $(\alpha,2n)$ experiments.[5]

Previous to the initiation of the present experiments on Ta and Bi, essentially all nonelastic neutron measurements had been concerned with the total cross sections for this process or with space-integrated neutron spectra. The present measurements give, in addition,

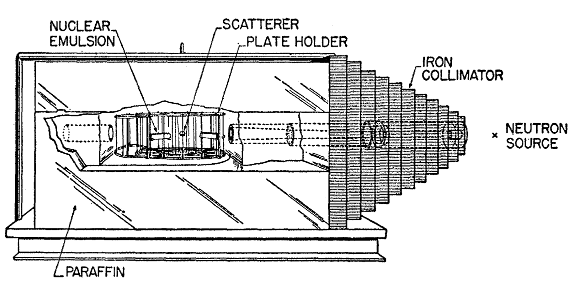

Fig. 1. Experimental arrangement for measuring angular distributions.

† This work was performed under the auspices of the U. S. Atomic Energy Commission.

[1] L. E. H. Trainor and W. R. Dixon, Can. J. Phys. 34, 229 (1956).
[2] R. E. Bell and H. M. Skarsgard, Can. J. Phys. 34, 745 (1956).
[3] P. C. Gugelot, Phys. Rev. 81, 51 (1951).
[4] E. R. Graves and L. Rosen, Phys. Rev. 89, 343 (1953).
[5] H. L. Bradt and D. J. Tendam, Phys. Rev. 72, 1117 (1947).