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Hydrogen-Helium Isotope Elastic Scattering Processes at Intermediate Energies*

J. E. Brolley, Jr., T. M. Putnam, L. Rosen,† and L. Stewart
Los Alamos Scientific Laboratory, University of California, Los Alamos, New Mexico
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Differential cross sections for the elastic scattering of various hydrogen and helium isotopes have been measured using accelerated particles from the Los Alamos 42-inch cyclotron. The scattering of protons and deuterons from deuterons, tritons, and helium-three particles has been studied over an energy range of 5 to 14 Mev. The elastic scattering of ~10-Mev polarized protons has also been studied. In all cases nuclear emulsions were used as detectors.

Proton-deuteron elastic scattering has been measured at 5.6 and 7.85 Mev. A comparison is made to results at nearby energies of both *p-D* and *n-D* scattering and to theoretical predictions. The scattering of 10-Mev polarized protons from deuterons has been measured and provides support for calculations using central force approximations.

Measurements of *p-T* and *p*-He^3 elastic scattering at 6.5 and 8.34 Mev give angular distributions which are quite similar to those for *p-D* and *p*-He^4. An encouraging agreement is found with resonating-group calculations with central-force approximations of the Serber type.

Deuteron-deuteron scattering has been measured at 6.0, 8.2, 12.1, and 13.8 Mev. A preliminary theoretical treatment indicates that the process is predominantly hard-sphere scattering with no strong level splitting.

Deuteron-triton and deuteron-helium three scattering has been measured over the energy range of 5 to 14 Mev. The results for the two processes are almost indistinguishable at the present level of accuracy.

INTRODUCTION

During the last few years a remarkable expansion of theoretical and experimental knowledge of the interactions amongst light nuclei has transpired. More specifically, scattering and reaction processes amongst the various hydrogen and helium isotopes have been receiving quite detailed experimental study at intermediate energies. One might hope that some of these processes involving few nucleons would be susceptible to "first principles" theoretical calculations which would bridge the gap between two-nucleon interaction theory and methods dealing with bulk nuclear matter such as the optical model and the statistical theory, etc. Indeed, resonating group calculations have produced rather encouraging results and a detailed comparison with recent experimental results will be made. It is possible that suitably refined calculations of this sort may further illuminate the question of the many-body force.

EXPERIMENTAL APPARATUS

The Los Alamos 42-inch cyclotron was used as a source of several kinds of bombarding particles at various energies. The accelerated particles were directed to and focused at the experimental station by an ion-optical system consisting of steering, bending, and strong-focusing magnets. The cyclotron and experimental stations are in separate shielded vaults.

Scattering processes were studied with an unpolarized incident beam and in some cases a polarized beam. In the unpolarized case, the cyclotron beam entered inside a multiplate nuclear camera that has been described previously in considerable detail.[1–3]

The elastic scattering of 10-Mev polarized protons was studied using another type of nuclear-plate camera that has been sketched in a previous note.[4] The fully polarized proton beam was obtained by bombarding hydrogen with 25-Mev alpha particles and selecting protons recoiling at a laboratory angle of 25°. The experimental results will receive further attention in a future publication.

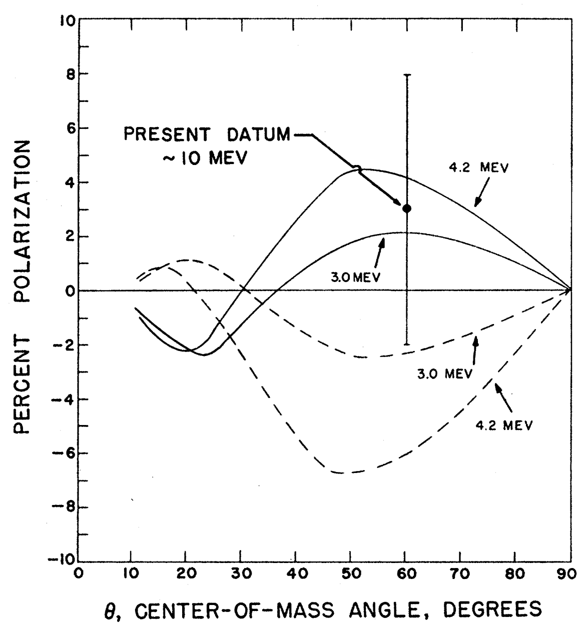

Fig. 1. Percent polarization as predicted from *p-P* phase shift analyses at 3.0 and 4.2 Mev. (See references 6 and 7.) The 10-Mev experimental value is indicated by the solid circle.

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† Now a Guggenheim Fellow at le Centre d'Études Nucléaires de Saclay, France.

[1] Allred, Rosen, Tallmadge, and Williams, Rev. Sci. Instr. 22, 191 (1951).

[2] Putnam, Brolley, and Rosen, Phys. Rev. 104, 1303 (1956).

[3] Brolley, Putnam, and Rosen, Phys. Rev. 107, 820 (1957).

[4] L. Rosen and J. E. Brolley, Jr., Phys. Rev. 107, 1454 (1957).

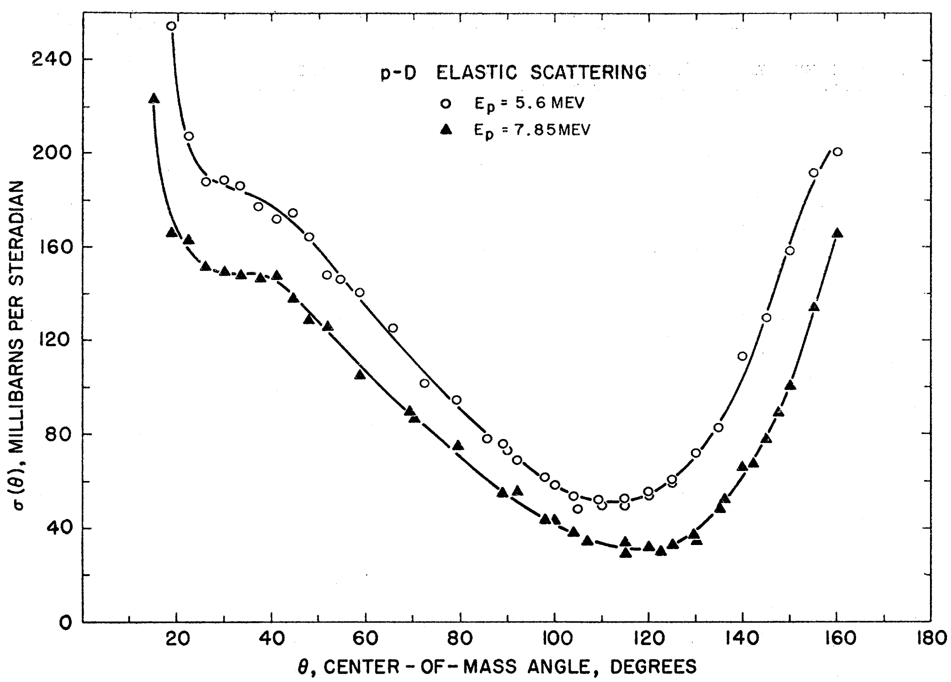

FIG. 2. Differential cross sections in the center-of-mass system for p-D elastic scattering at proton laboratory energies of 5.6 and 7.85 Mev.

PROTON-PROTON SCATTERING

The differential scattering cross sections for proton-proton scattering are experimentally well-known at intermediate energies. However, there is a paucity of experimental data relating to the spin interactions. In the region of ten million volts very little polarization is to be expected in proton-proton scattering if one assumes that contemporary potentials describe this process. Breit, Fischer, Hull, Pyatt, and Shapiro have performed calculations[5] employing the Gartenhaus-Chew-Case-Pais-Signell-Marshak potential and found the polarizations to be less than one percent. On the other hand, the differential scattering data do not afford an unambiguous answer to this problem.

Thus Hull and Shapiro[6] have performed a phase-shift analysis of the proton-proton scattering data of Worthington, McGruer, and Findley[7] and found that a split p-wave is consistent with the data. In fact, two solutions were found analogous to the early history of proton-alpha scattering.

Figure 1 shows the datum of the elastic scattering of ~10-Mev polarized protons and the lower-energy calculations of Hull and Shapiro.[6] Manifestly, this singular point does not have sufficient precision or proximity in energy to suggest the validity of one solution or the other. It should, however, be useful in setting limits on the p-wave splitting at 10 Mev. The advent of polarized ion sources for accelerators should facilitate the performance of definitive experiments on this interesting problem.

TABLE I. Differential cross sections in the center-of-mass system in millibarns/steradian for p-D elastic scattering at proton energies of 5.6 and 7.85 Mev. The rms errors for the cross sections are ~3% except for those denoted by an asterisk, at which angles recoil deuterons were counted. The recoil deuteron data have an rms error of approximately 3.5% with the exception of the region 115° to 130° at 7.85 Mev where the errors vary from 4.0 to 5.5%.

c.m. angle (degrees)	E_d (Mev) 5.6±0.1	E_d (Mev) 7.85±0.08	c.m. angle (degrees)	E_d (Mev) 5.6±0.1	E_d (Mev) 7.85±0.08
15.0	361	223	105.0	48.6*	
18.7	254	166	106.8		34.5
22.5	208	163	109.6	52.3	
26.2	188	152	110.0	49.9*	
29.9	189	150	115.0	49.5	29.5
33.6	186	148	115.0	53.1*	34.4*
37.2	177	147	120.0	55.4*	32.3*
40.9	172	148	120.1	53.9	
44.5	175	138	122.6		30.0
48.2	164	129	125.0	60.0	
51.7	148	126	125.0	60.7*	33.7*
54.6	146		129.6		37.4
58.8	140	115	130.0	72.1*	34.9*
65.8	125		135.0	82.4*	48.5*
69.2		90.0	136.1		52.4
70.0		86.9*	140.0	113*	66.3*
72.6	101		142.0		67.5
79.3	94.5	75.2	145.0	130*	77.9*
85.8	78.2		147.5		89.3
88.9	75.8	55.0	150.0	158*	100*
90.0	73.2*		155.0	191*	134*
92.0	69.2	55.4	160.0	201*	166*
98.1	61.6	43.9			
100.0	58.5*	43.5*			
104.0	53.6	38.7			

[5] Breit, Fischer, Hull, Pyatt, and Shapiro (private communications).

[6] M. H. Hull, Jr., and J. Shapiro, Phys. Rev. **109**, 846 (1958).

[7] Worthington, McGruer, and Findley, Phys. Rev. **90**, 899 (1953).

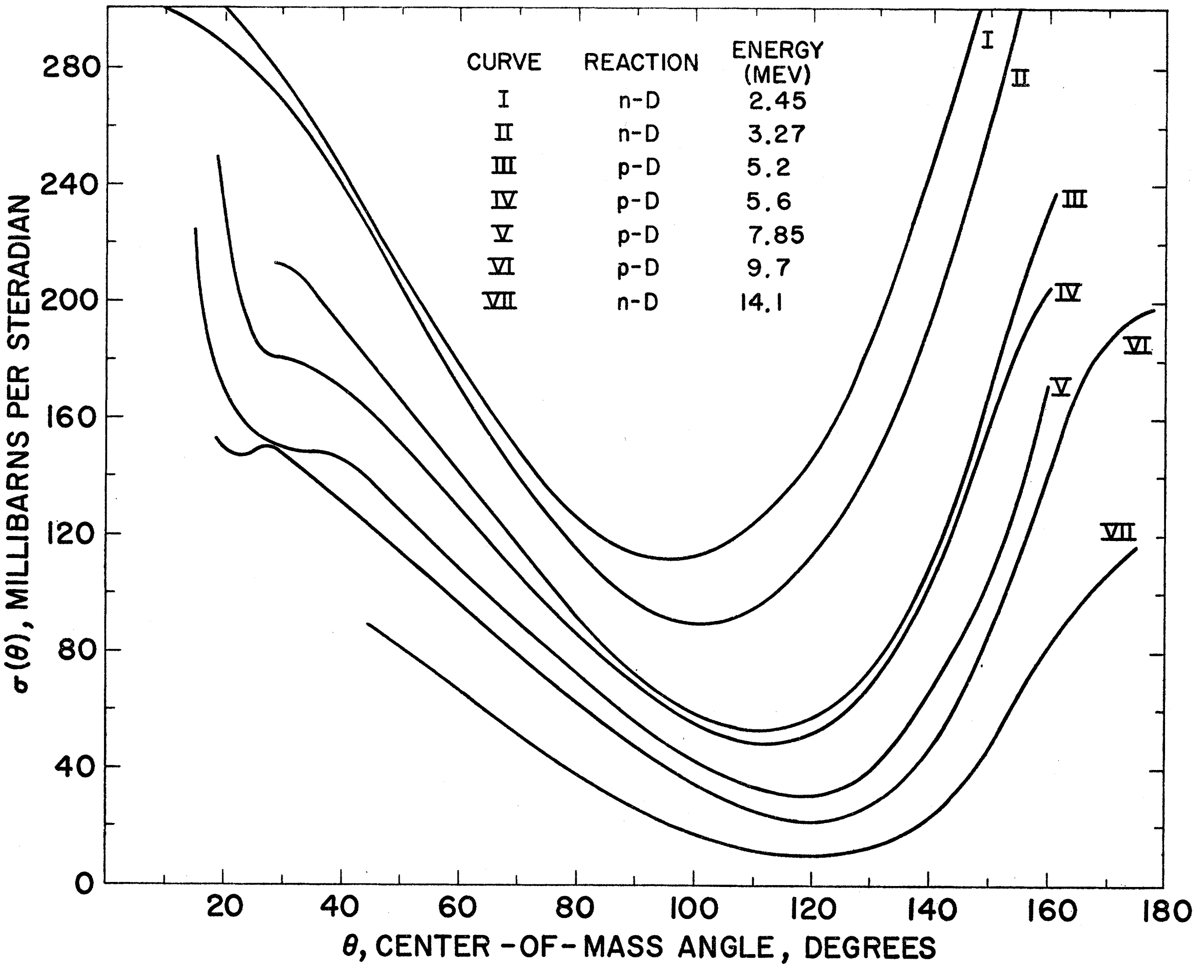

FIG. 3. Angular distributions at various energies for *p-D* and *n-D* elastic scattering. Curves I and II, reference 19; curve III, reference 16; curves IV and V, present data; curve VI, reference 17; curve VII, references 18 and 20.

PROTON-DEUTERON SCATTERING

The three-body scattering problem in nuclear physics has been the subject of considerable theoretical and experimental study. Initial theoretical work was done by Buckingham and Massey[8] employing the resonating group method of Wheeler.[9] Some of the more recent work is that of Christian and Gammel[10] and DeBorde and Massey[11] and Burke and Robertson[12] using central force approximations. In an experimental paper on neutron-deuteron scattering, White, Chisholm, and Brown[13] cite calculations of Delves and Brown on neutron-deuteron scattering which invoke tensor forces as well as the usual central forces. Bransden, Smith, and Tate[14] currently have a nucleon-deuteron calculation in progress which also employs tensor forces and takes into account the distortion[15] of the deuteron occasioned by the interaction. For the energies investigated in this report the work of Christian and Gammel[10] suggests that the distortion will not play an important role.

We have experimentally studied the scattering of 5.6- and 7.85-Mev (laboratory energy) protons by deuterium in the multiplate camera. In these experiments the entire camera was filled with deuterium and the plates were predesiccated to minimize the liberation of water vapor into the deuterium atmosphere. Water vapor was also removed by condensation in a liquid air trap markedly removed from the camera.

The results of these measurements are displayed in Fig. 2 and in Table I. These elastic scattering processes

[8] R. A. Buckingham and H. S. W. Massey, Proc. Roy. Soc. (London) **A179**, 123 (1941).
[9] J. A. Wheeler, Phys. Rev. **52**, 1083 (1937).
[10] R. S. Christian and J. L. Gammel, Phys. Rev. **91**, 100 (1953).
[11] A. H. DeBorde and H. S. W. Massey, Proc. Phys. Soc. (London) **A68**, 769 (1955).
[12] P. G. Burke and H. H. Robertson, Proc. Phys. Soc. (London) **A70**, 777 (1957).
[13] White, Chisholm, and Brown, Nuclear Phys. **7**, 233 (1958).
[14] Bransden, Smith, and Tate, Proc. Roy. Soc. (London) **A247**, 73 (1958).
[15] The term "polarization" is often used; the term "polarization" in this paper is reserved for spin expectation values.

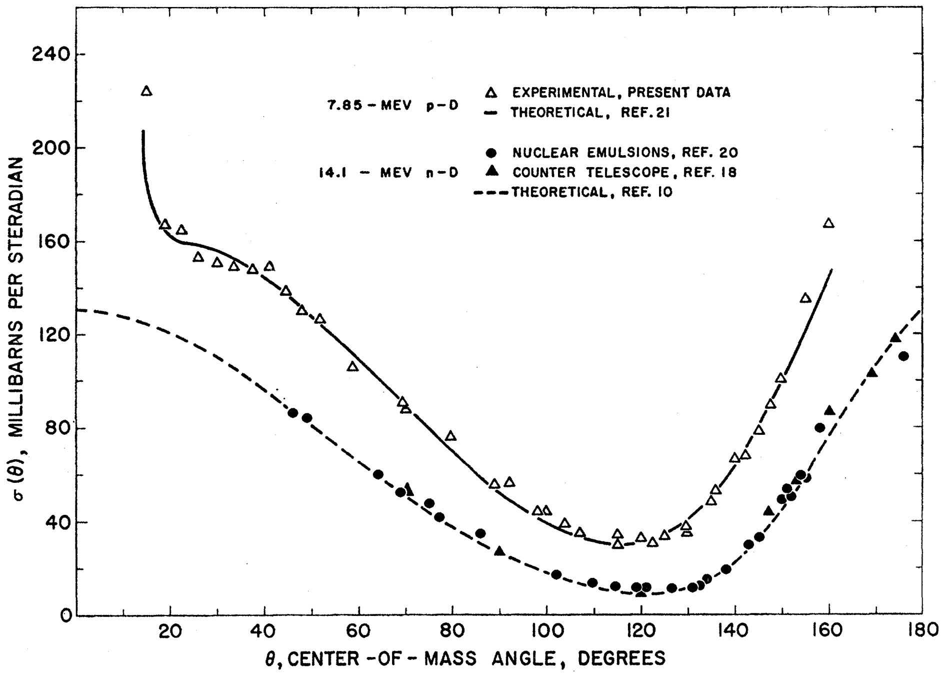

FIG. 4. Comparison of the 7.85-Mev p-D and the 14.1-Mev n-D elastic scattering data with the theoretical calculations of Christian and Gammel (references 10 and 21).

exhibit single well-defined minima and destructive Coulomb-nuclear interferences in the forward direction. In Fig. 3 the present data are collected with results at nearby energies of proton-deuteron[16,17] and neutron-deuteron[18–20] scattering. In Fig. 4 a comparison is made between the 7.85-Mev p-D data and the 14.1-Mev n-D data and the theoretical calculations of Christian and Gammel.[10,21] The data are consistent with these calculations.

The sundry published calculations on this problem have not invoked any non-central forces. On this basis, if these calculations provide a reasonable description of the experimental facts, no polarization could be expected.

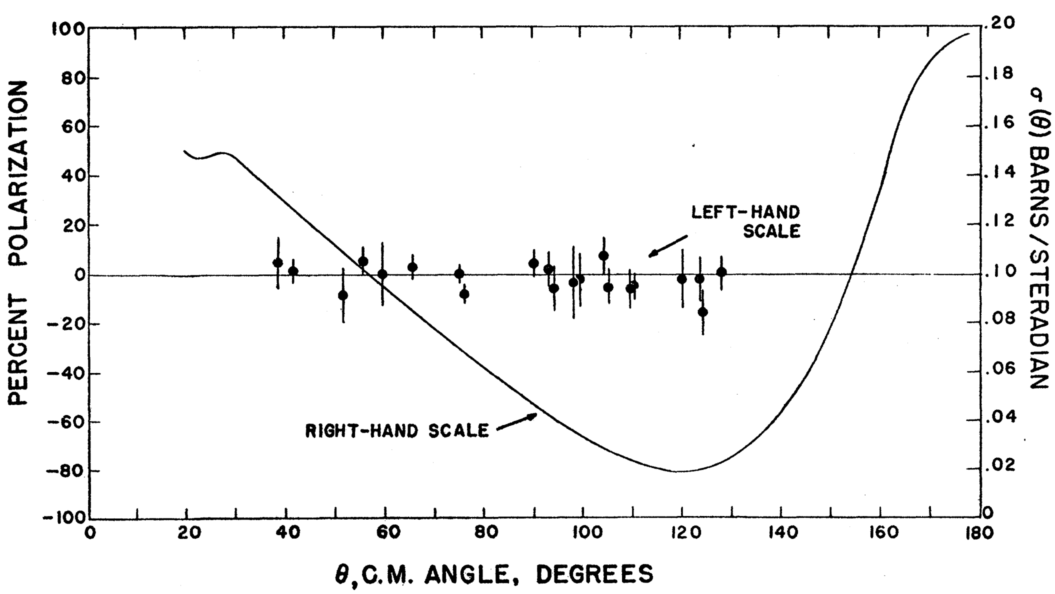

FIG. 5. Differential p-D scattering cross sections (reference 17) and associated polarization for a proton laboratory energy of approximately 10 Mev.

[16] L. Rosen and J. C. Allred, Phys. Rev. **82**, 777 (1951).
[17] Allred, Armstrong, Bondelid, and Rosen, Phys. Rev. **88**, 433 (1952).
[18] John D. Seagrave, Phys. Rev. **97**, 757 (1955).
[19] J. D. Seagrave and L. Cranberg, Phys. Rev. **105**, 1816 (1957).
[20] Allred, Armstrong, and Rosen, Phys. Rev. **91**, 90 (1953).
[21] We are indebted to J. L. Gammel for performing the 7.85-Mev calculation.

TABLE II. Differential cross sections in the center-of-mass system in millibarns/steradian for p-T and p-He^3 elastic scattering at 6.5 and 8.3_4 Mev. The rms errors for the cross sections obtained by counting protons is ±3%. The cross sections obtained by counting the recoil particles (denoted by an asterisk) have rms errors of approximately ±4%.

c.m. angle (degrees)	6.5 Mev p-T	6.5 Mev p-He^3	8.3_4 Mev p-T	8.3_4 Mev p-He^3	c.m. angle (degrees)	6.5 Mev p-T	6.5 Mev p-He^3	8.3_4 Mev p-T	8.3_4 Mev p-He^3
13.3	584	1141	456	612	109.6	21.4	44.1	12.8	26.4
16.7	430	470	364	318	110.0	22.5*		13.4*	
20.0	416	337	361	270	114.5	23.0	48.9	12.1	27.6
23.3	382	269	358	250	115.0	23.2*		14.6*	
26.6	375	272	343	263	119.3	27.1	50.1	15.9	32.6
29.9	354	264	324	260	120.0	28.5*		17.2*	34.4*
33.2	346	258	307	256	123.9	32.1	63.3	20.3	40.3
36.4	320	246	287	241	125.0	34.6*		20.4*	
39.7	305	245	277	245	128.4	43.9	74.7	29.5	48.6
42.9	281	237	252	236	130.0	48.7*		30.9*	53.5*
46.1	272	221	240	217	132.7	53.2	83.7	36.2	58.4
49.3	243	210	230		135.0	58.0*		37.4*	
52.5	231	204	197	187	136.9	63.8	102	44.5	70.7
58.7	196	174	170	167	140.0	71.1*	114*	51.8*	84.4*
64.9	153	148	133	138	140.9	75.1	115	51.3	80.3
71.0	126	124	104	109	144.9	84.0	126	63.6	88.8
76.9	96.3	96.8	81.2	89.0	145.0	86.5*	147*	64.1*	109*
82.7	75.9	76.3	60.8	72.0	148.7			76.8	105
88.4	52.8	64.2	41.8	54.5	150.0	103*	168*	78.6*	124*
90.0	53.0*				155.0	111*		83.9*	140*
93.9	38.6	49.1	30.2	43.2	160.0	127*	246*	102*	160*
99.3	29.5	45.1	21.1	35.0					
100.0	30.6*								
104.5	22.2	40.7	13.6	30.2					
105.0	23.6*		14.9*						

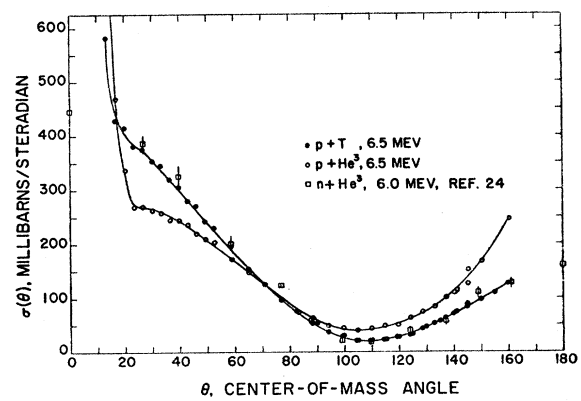

FIG. 6. Comparison of the angular distributions in the center-of-mass system for p-T, p-He^3, and n-He^3 elastic scattering at the indicated incident particle energies.

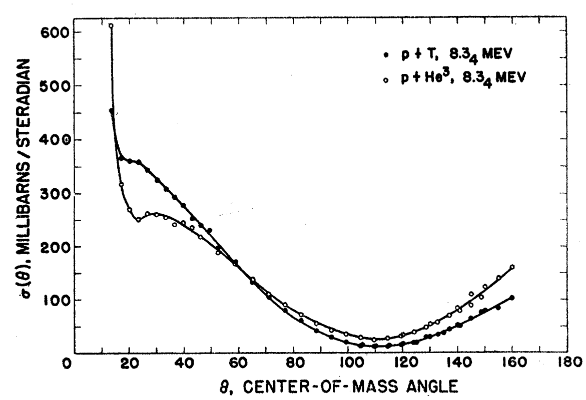

FIG. 7. Differential cross sections for p-T and p-He^3 elastic scattering in the center-of-mass system at 8.3_4-Mev proton laboratory energy.

To test this assumption we have scattered 100% polarized 10-Mev protons by deuterium. The polarizations measured in the scattering process are plotted along with the differential scattering cross sections[17] in

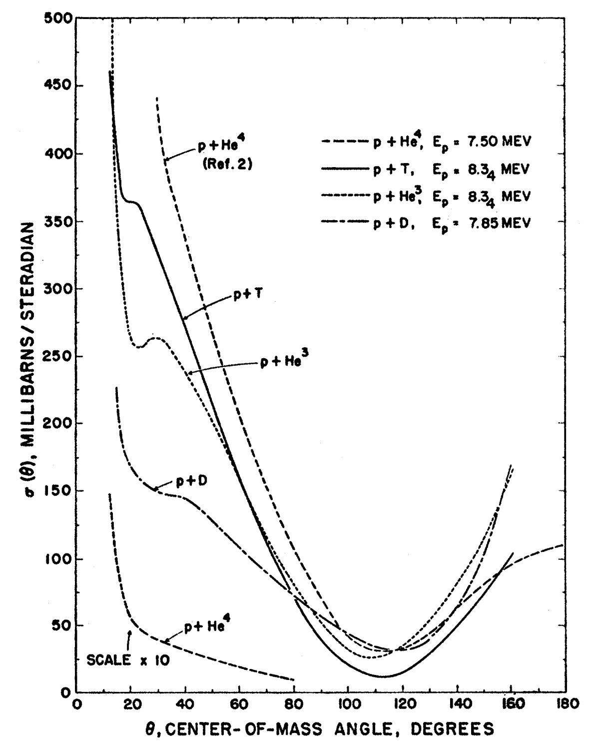

FIG. 8. Comparison of the center-of-mass angular distributions for the elastic scattering of protons by deuterons, tritons, helium three and helium four. The helium four data were taken from reference 2.

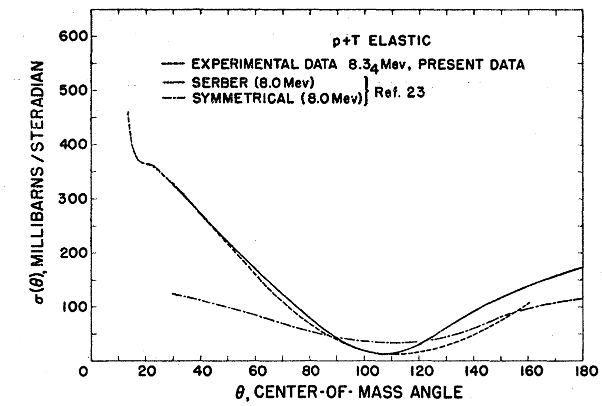

FIG. 9. Comparison of the 8.3_4-Mev p-T elastic scattering with the theoretical calculations of Bransden and Robertson, reference 23.

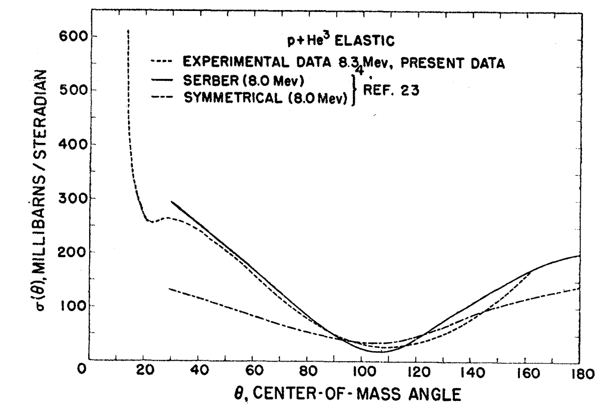

FIG. 10. Comparison of the 8.3_4-Mev p-He^3 elastic scattering with the theoretical calculations of Bransden and Robertson, reference 23.

Fig. 5. There appears to be no significant polarization over the angular range investigated. Polarization effects smaller than about 4% could not be established by our work. This experimental result would thus seem to provide support for calculational procedures that use central force approximations. Measurements of large polarizations of neutrons in the 2- to 3-Mev range scattered by deuterium have been reported by White, Chisholm, and Brown,[13] who also cite substantial polarizations calculated by Delves and Brown. Cran-

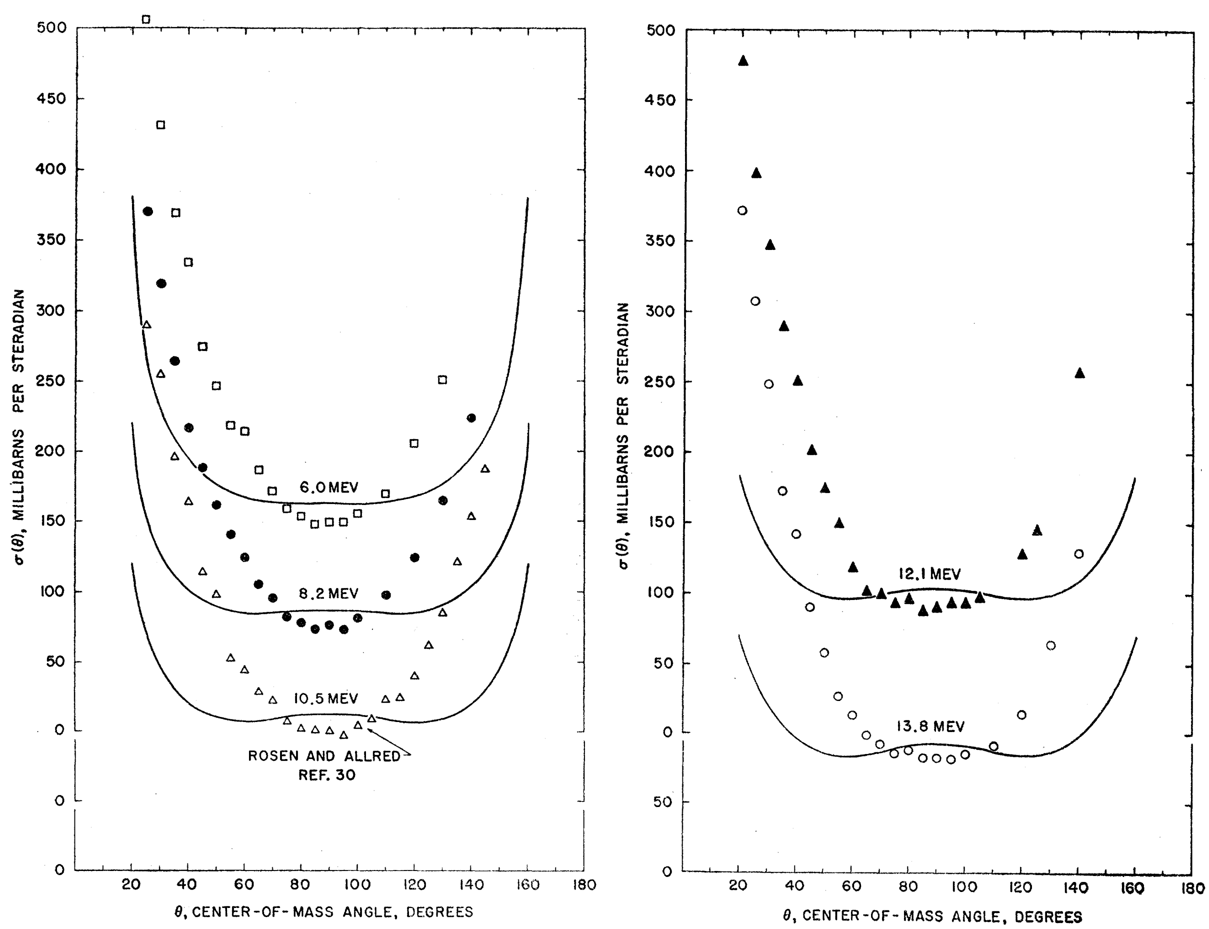

FIG. 11. Differential cross sections in the center-of-mass system for d-D elastic scattering at various deuteron laboratory energies. The smooth curves represent the theoretical calculations of Laskar and Burke, reference 28.

berg[22] has repeated their measurements and found no significant polarization. On the basis of Cranberg's results and the present data it seems unlikely that large polarizations are produced in nucleon-deuteron scattering in the energy range 0 to 10 Mev. These results support the use of the Serber force approximation for the present level of precision of experimental data.

PROTON-TRITON AND PROTON-HELIUM THREE SCATTERING

The scattering of mass-one particles by mass-three systems is still tractable to resonating group type calculations and has received the attention of several investigators. The most recent work is that of Bransden and Robertson[23] on the scattering of protons by tritium and helium three. Their calculation utilizes a two-body potential adjusted to provide reasonable deuteron and alpha-particle binding energies.

There is a large and growing body of mass-one mass-three experimental scattering data. We have measured the differential scattering cross sections for the scattering of 6.5- and 8.3_4-Mev protons by tritium and helium three. The tritium, or helium three as the case may be, was confined in a vessel with sufficiently thin dural walls to permit ingress and egress of the charged particles of interest. The data are displayed in Figs. 6 and 7 and enumerated in Table II. The general form of these differential scattering cross sections is similar to those of proton-deuteron scattering. There is a distinctive Coulomb-nuclear interference in the forward direction and a single pronounced minimum. This minimum is displaced towards larger scattering angles with increasing energy and in fact is quite close to the minimum in proton-helium four scattering. Figure 8 collates the scattering of protons by masses one, two, three and four at approximately similar energies.

At 6 Mev, n-He^3 scattering has been performed by Seagrave, Simmons, and Cranberg.[24] In Fig. 6 their data are also shown as a comparison with the 6.5-Mev p-T scattering. These results are experimentally indistinguishable except in the forward region where the Coulomb scattering is manifest. This is a measure of support for charge symmetry of nuclear forces.

Bransden and Robertson have calculated scattering cross sections at energies quite close to the 8.3_4-Mev p-T and p-He^3 results. The data are compared in Figs. 9 and 10. Of the several force mixtures they have used, only the symmetric and Serber are presented, as they most closely resemble the physical results. Of the two, the Serber mixture is somewhat favored. The Serber force also gave the best fit to recent neutron-tritium and neutron-helium three data of Seagrave, Simmons, and Cranberg.[24] The general agreement of the reso-

TABLE III. Differential cross sections in the center-of-mass system in millibarns/steradian for d-D elastic scattering at various deuteron laboratory energies. The rms errors for the cross sections are ±3%.

c.m. angle (degrees) \ E_d (Mev)	6.0±0.07	8.2±0.1	12.1±0.15	13.8±0.15
20.0	696	545	478	472
25.0	506	420	398	408
30.0	431	369	347	349
35.0	369	314	289[a]	273[a]
40.0	334	266	250[a]	242[a]
45.0	274	238	201[a]	190[a]
50.0	246	211	174[a]	158[a]
55.0	218	190	149[a]	127[a]
60.0	213	174	118[a]	113[a]
65.0	186	155[a]	101[a]	98.4[a]
70.0	171	145[a]	98.9[a]	92.8[a]
75.0	158	132[a]	92.2[a]	85.7[a]
80.0	153	128[a]	95.8[a]	88.1[a]
85.0	147	124[a]	87.3[a]	82.8[a]
90.0	149	126[a]	89.5[a]	83.1[a]
95.0	149	123[a]		82.1[a]
100.0	155	131[a]	93.1[a]	85.7[a]
105.0			96.8[a]	
110.0	169	148[a]		91.5[a]
120.0	205	174	128[a]	114[a]
125.0			145[a]	
130.0	250	215		164[a]
140.0		274	257[a]	229[a]

[a] Add 0.1° to the c.m. angle.

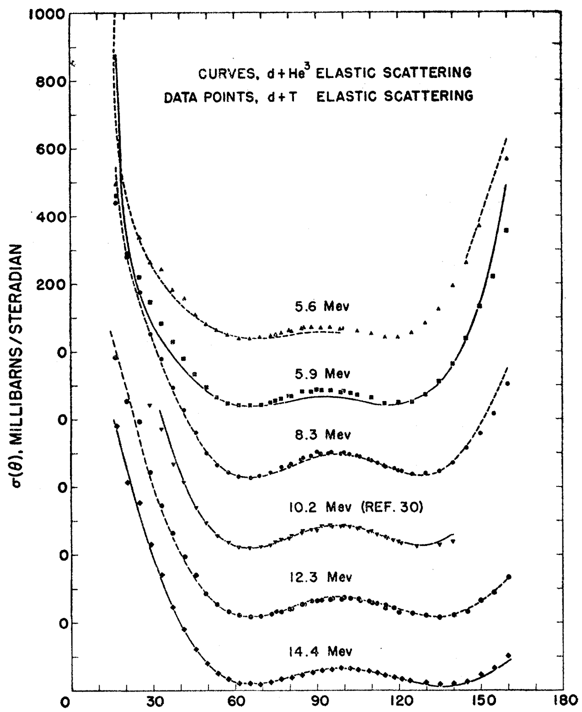

FIG. 12. Differential cross sections at various energies for d-T and d-He^3 elastic scattering in the center-of-mass system. The 10.2-Mev data were taken from reference 30.

[22] L. P. Cranberg, Los Alamos Scientific Laboratory (private communication).

[23] B. H. Bransden and H. H. Robertson, Proc. Phys. Soc. (London) A72, 770 (1958).

[24] Seagrave, Simmons, and Cranberg, Los Alamos Scientific Laboratory (private communication).

TABLE IV. Differential cross sections in the center-of-mass system in millibarns/steradian for d-T and d-He^3 elastic scattering for various deuteron laboratory energies. The rms errors for the cross sections obtained by counting deuterons is ±3%. The cross sections obtained by counting the recoil particles (denoted by an asterisk) have rms errors of approximately 4%.

c.m. angle	5.6 Mev d-T	5.6 Mev d-He³
16.7	520	1027
20.8		456
25.0	344	333
29.1	272	272
33.2	242	225
37.3	190	176
41.4	159	134
45.5	111	107
49.5	86.8	84.8
53.5	64.3	62.3
57.6	52.6	53.6
61.5	42.4	42.1
65.4	42.5	38.7
69.4	44.8	40.2
73.2	51.0	42.0
75.0	53.0*	
77.0	56.9	44.7
80.0	65.0*	
80.8	62.7	48.6
84.5	72.2	52.0
85.0	72.3*	
88.2	76.1	53.6
90.0	74.2*	
91.8	74.4	55.2
95.0	75.0*	
95.4	74.9	54.3
98.8	67.8	51.0
100.0	68.7*	
105.0	63.4*	
110.0	54.9*	
115.0	46.6*	
120.0	46.0*	
125.0	58.5*	
130.0	84.4*	
135.0	131*	
140.0	195*	
145.0	267*	284*
150.0	375*	364*
155.0		468*
160.0	573*	604*

c.m. angle	5.9 Mev d-T	5.9 Mev d-He³
16.7	663	1080
20.8	482	491
25.0	424	375
29.1	348	283
33.2	288	237
37.3	233	199
41.4	182	155
45.5	135	
49.5	93.6	86.0
53.6	64.9	
57.6	48.5	49.7
61.5	42.3	41.6
65.5	42.3	38.8
69.4	44.7	40.5
70.0	41.2*	
73.2	50.6	44.4
75.0	56.6*	
77.0	62.5	
80.0	69.6*	
80.8	69.5	55.3
84.5	80.3	59.7
85.0	81.7*	
88.2	82.2	65.0
90.0	88.2*	
91.8	85.9	63.2
95.0	86.4*	
95.4	85.2	64.0
98.9	81.4	
100.0	83.4*	
102.3	77.2	59.1
105.0	73.8*	
105.6	67.8	
108.9		48.9
110.0	64.3*	
115.0	47.8*	
115.2		40.1
120.0	51.3*	42.9*
125.0	55.9*	54.0*
130.0	77.3	74.0*
135.0	110*	96.2*
140.0	166*	163*
145.0	240*	216*
150.0	335*	326*
155.0	421*	481*
160.0	557*	687*

c.m. angle	8.3 Mev d-T	8.3 Mev d-He³
16.7	850	947
20.8	697	683
25.0	582	564
29.1	458	460
33.2	384	366
37.3	298	278
41.4	231	234
45.5	168	
49.6	104	107
53.6	66.9	
57.6	43.6	43.4
61.5	30.6	30.4
65.5	28.8	27.3
69.4	33.9	29.5
73.2	42.1	38.5
77.0	58.4	
80.0	71.2*	
80.8	69.7	60.1
84.6	84.2	
85.0	88.5*	
88.2	93.1	83.3
90.0	105*	
91.8	99.5	91.6
95.0	104*	
95.4	106	93.6
98.9	102	96.8
100.0	104*	
102.3	97.6	91.2
105.0	92.2*	
105.6	92.5	
108.9	83.8	79.3
110.0	79.7*	70.3*
112.1	75.2	
115.0	63.0*	63.9*
115.2	63.1	63.0
118.2	56.9	
120.0	48.9*	45.0*
121.2	47.3	49.7
125.0	35.3*	36.1*
130.0	39.2*	32.9*
135.0	47.7*	47.6*
140.0	72.7*	63.8*
145.0	101*	119*
150.0	147*	175*
155.0	202*	273*
160.0	309*	344*

c.m. angle	12.3 Mev[a] d-T	12.3 Mev[a] d-He³
16.7	785	858
20.8	654	653
25.0	591	577
29.1	447	426
33.2	354	366
37.4	265	260
41.4	194	196
45.5	140	130
49.6	87.0	89.0
53.6	54.8	50.7
57.6	35.1	31.2
61.6	22.0	20.6
65.5	18.7	19.1
69.4	20.9	21.7
73.3	27.6	27.1
74.9	33.6*	
77.1	34.4	35.3
79.9	40.8*	
80.8	42.4	46.4
84.6	54.8	52.8
84.9	55.6*	
88.2	65.2	66.3
89.9	65.6*	
91.9	67.7	67.2
94.9	71.0*	
95.4	71.9	73.4
98.9	70.4	75.0
99.9	76.0*	
102.3	71.8	72.2
104.9	70.3*	67.0*
105.7	68.8	66.7
109.0	65.4	
109.9	60.6*	59.4*
112.1	57.9	
114.9	48.4*	49.3*
115.2	54.7	
118.3	41.6	
119.9	32.9*	37.8*
125.0	30.2*	28.8*
130.0	22.0*	18.9*
135.0	18.1*	16.0*
140.0	24.7*	20.9*
145.0	33.8*	33.2*
150.0	65.2*	53.6*
155.0	91.4*	86.1*
160.0	137*	137*

c.m. angle	14.4 Mev d-T	14.4 Mev d-He³
16.7	782	795
20.8	622	604
25.0	559	540
29.1	434	433
33.3	339	369
37.4	249	250
41.5	182	188
45.5	122	120
49.6	81.2	83.6
53.6	50.1	50.6
57.6	31.5	32.4
61.6	21.0	20.6
65.2	18.1*	
65.5	20.8	20.1
69.4	19.9	20.0
69.9	20.9*	
73.3	26.6	27.4
74.9	27.7*	
77.1	34.0	34.5
79.9	43.6*	
80.9	39.3	39.9
84.6	47.2	47.3
84.9	51.0*	
88.3	53.0	52.2
89.9	58.2*	52.8*
91.9	58.4	59.9
94.9	63.4*	
95.4	59.8	64.6
98.9	64.8	62.9
99.9	63.4*	60.7*
102.3	65.4	63.9
104.9	60.2*	56.1*
105.7	58.9	65.5
109.0	56.7	55.5
109.9	55.0*	50.6*
112.2	49.8	47.8
114.9	44.3*	42.0*
115.3	45.9	46.6
118.3	38.3	40.0
119.9	36.4*	34.0*
121.2	34.3	
124.0	30.3	29.5
124.9	27.2*	25.4*
126.8		24.3
129.9	21.8*	18.6*
132.0.		20.3
135.0	17.6*	13.8*
140.0	18.4*	13.5*
145.0	24.6*	19.7*
150.0	44.6*	39.6*
155.0	65.6*	60.0*
160.0	105*	98.6*

[a] The deuteron energy for the d-He^3 is ~12.6 Mev.

nating group calculations with central force approximations is encouraging. This type of calculation has also given a reasonable description[25] of the p-wave splitting of proton-helium four scattering where a suitable spin-orbit term is used in the Hamiltonian (a tensor-force term appears inadequate).

DEUTERON-DEUTERON SCATTERING

A paucity of calculations on deuteron-deuteron scattering prevails in the literature. Runge[26] has formulated a theory using central forces and a ^3S ground state of the deuteron (no admixture of D state) which does not give good agreement at a deuteron laboratory energy of 10.8 Mev with the data of Allred, Erickson, Fowler, and Stovall.[27] Runge suggests that the Born approximation may render the calculation invalid at this energy. Laskar and Burke[28] have performed a resonating group calculation using various force mixtures.

[25] Hochberg, Massey, Robertson, and Underhill, Proc. Phys. Soc. (London) **A68**, 746 (1955).

[26] R. J. Runge, Phys. Rev. **85**, 1052 (1952).

[27] Allred, Erickson, Fowler, and Stovall, Phys. Rev. **76**, 1430 (1949).

[28] We are indebted to Dr. W. Laskar, University College, London, for communicating these results (to be published).

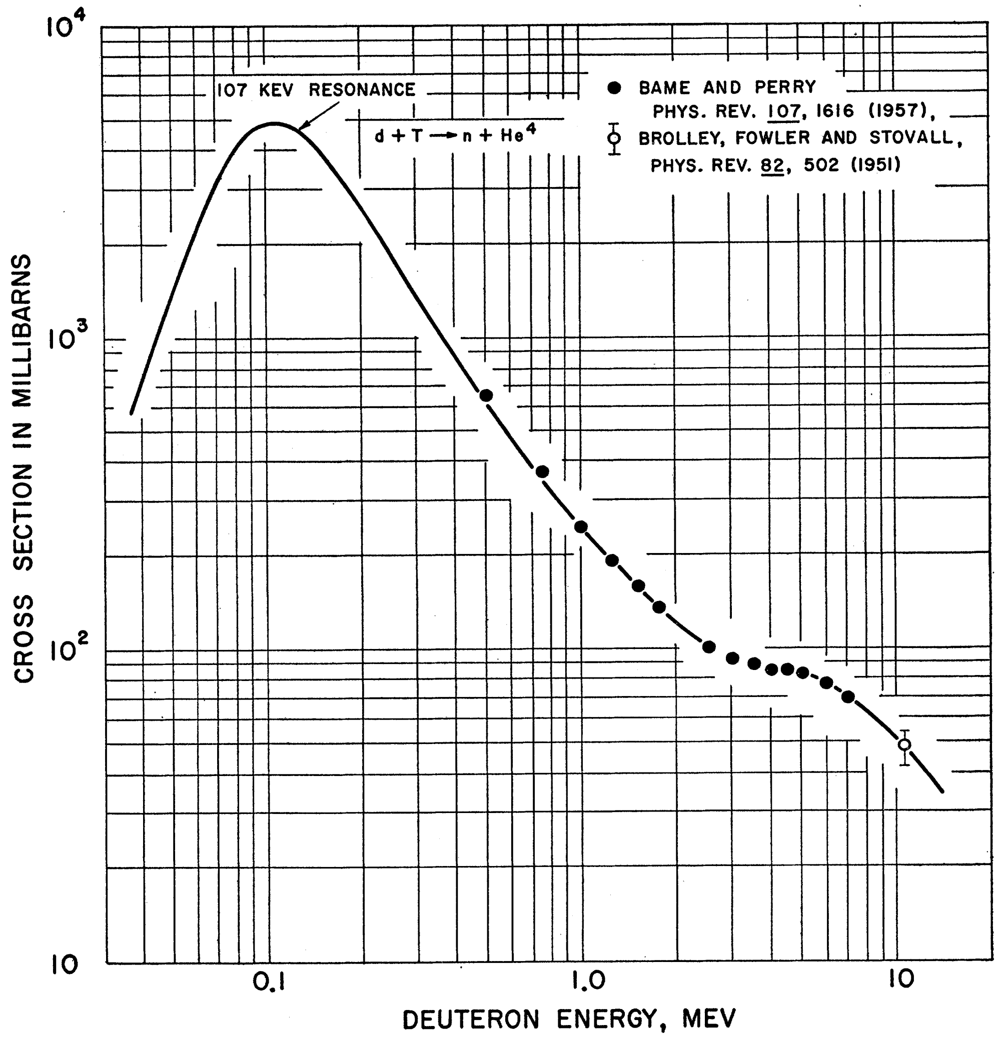

FIG. 13. Cross section as a function of laboratory deuteron energy for primary neutron production from the *d-T* reaction.

We have measured the differential scattering cross sections for a set of deuteron laboratory energies at 6.0, 8.2, 12.1, and 13.8 Mev. The results of these measurements are tabulated in Table III. In these experiments, the rare gas target cell was not required; the camera was flooded with deuterium and predesiccated emulsions were employed.

Dodder and McHale[29] have obtained a preliminary set of phase shifts from these data. Preliminary indications are that the process is predominantly hard-sphere scattering and does not seem to have any strong level splitting. Laskar and Burke have interpolated their resonating group calculations[28] to compare with our data. Of the several force mixtures employed, they find that the MHWB combination corresponds most nearly to the phase shifts of Dodder and McHale. In Fig. 11, the MHWB calculations are compared with the present data and the 10.5-Mev data of Rosen and Allred.[30]

[29] D. Dodder and J. L. McHale, Los Alamos Scientific Laboratory (private communication).

[30] L. Rosen and J. C. Allred, Phys. Rev. 88, 431 (1952).

None of the preceding sets of data seem to require any strong spin-orbit coupling in their theoretical descriptions. It is interesting to surmise that in the energy range covered by this paper the strong spin-orbit effect becomes conspicuous only when the scatterer has four nucleons at which point the binding energy per nucleon abruptly rises.[31] This would give rise to a stronger spin-orbit term as used by Hochberg and Massey. At any rate, the experiments extant on 2-, 3-, and 4-nucleon scattering systems have not indicated strong spin polarization as in the case of the 5-nucleon system, nucleon plus helium four.

DEUTERON-TRITIUM AND DEUTERON-HELIUM THREE SCATTERING[32]

One form of the five-nucleon scattering system, namely nucleon plus helium four, has received rather detailed theoretical and experimental attention. Other

[31] The authors are indebted to John L. Gammel for valuable discussions on this point.

[32] The reaction cross sections will be discussed in a subsequent report.

forms of the five-nucleon scattering system, deuteron-tritium and deuteron-helium three, have almost no theoretical or experimental elucidation.[33] These results complement the existing experimental data with a set of differential cross sections for both deuterium-tritium and deuterium-helium three elastic scattering over a laboratory range of deuteron energies 5.6 to 14.4 Mev. Analyses of scattered deuterons, tritons and helium three particle tracks yielded the differential cross sections listed in Table IV and displayed in Fig. 12. Deuteron-triton and deuteron-helium three scattering are almost indistinguishable at the present level of accuracy. The data are characterized by two minima juxtaposed about 90° and no discernible Coulomb nuclear destructive interference. The central maximum shifts toward higher angles with increasing input energy. The process is definitely not symmetric about 90° c.m.

There appears to be no theoretical study of these processes in the literature. Even a phase shift analysis would be quite rewarding as it might further illuminate the question of a broad level in helium five (alternatively, lithium five) a few Mev above the 16.7-Mev level. In Fig. 13 the cross section for primary neutron production is sketched. There is some suggestion of a broad resonance for a deuteron energy in the neighborhood of 5 Mev. Blanchard and Winter,[34] in another connection, have speculated on the existence of a broad level in this system a few Mev above the well-known level at 16.7 Mev. The broad level was envisioned as the triton moving in the diffuse domain of the deuteron. Simple excitation functions of various angles do indeed suggest that this level may be reflected in the scattering data. Nucleon-helium four scattering may also shed some light on this problem. Indeed, the 16.7-Mev level is manifest in the neutron-helium four scattering experiments of Bonner, Prosser, and Slattery.[35]

[33] Dr. Laskar has informed us that they are considering this problem using the resonating group method.

[34] C. H. Blanchard and R. G. Winter, Phys. Rev. **107**, 774 (1957).

[35] Bonner, Prosser, and Slattery, Bull. Am. Phys. Soc. **2**, 180 (1957).