compared with the measured energy of 5.095 Mev. With a ground-state alpha energy of 5.099 Mev, the disintegration energy, Q_α, equals 5.187 Mev.

The disintegration energy of the electron capture branch of Np^{235} was calculated from the closed energy cycle shown in Table II. The result, 163±16 kev, is in approximate agreement with the value of 123 kev calculated from the K/L capture ratio.[4]

The authors wish to thank W. Ramler, A. Schulke, and other members of the Argonne 60-inch cyclotron group for their assistance in producing the Np^{235} samples.

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Interaction of 6- to 14-Mev Deuterons with Helium Three and Tritium*

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The angular distributions of the cross sections for the $T(d,n)He^4$ and $He^3(d,p)He^4$ reactions have been measured at five incident deuteron energies between 6 and 14 Mev. The data have been fitted with Legendre expansions. A search for excited states in He^4 near 22 Mev and for evidence of the formation of H^4 gave negative results.

INTRODUCTION

THE present paper concludes that portion of a program, on the interactions between the hydrogen and helium isotopes, which has been concerned with the emission probabilities for charged products from reactions induced by 6- to 14-Mev deuterons on He^3 and T.

The elastic scattering experiments[1,2] have already been described, as have also the results[3] on the identification and systematics of the reaction $d+T\rightarrow He^3+n+n$.

The present measurements evaluate the differential cross sections, at a number of incident energies, for the reactions $He^3(d,p)He^4$ ($Q=18.4$ Mev) and $T(d,n)He^4$ ($Q=17.6$ Mev). A search has also been made for excited states in He^4, at ~22 Mev, and for evidence of the formation of H^4 by investigating the range distributions of the protons emitted from the breakup of the intermediate Li^5 and He^5 nuclei, respectively.

Both the $He^3(d,p)He^4$ and $T(d,n)He^4$ reactions have been previously studied at ~10 Mev.[4,5] In addition, the $T(d,n)$ reaction has been extensively surveyed at lower energies.[6,7] Prior to the present work, however, all experiments on the $T(d,n)He^4$ reaction have been performed by detecting the monoenergetic group of high-energy neutrons in a counter telescope.

Theoretical work on the subject reactions is limited to a "stripping" analysis of the 10-Mev data.[8]

EXPERIMENTAL DETAILS

The source of deuterons is the Los Alamos variable-energy cyclotron. A portion of the deflected beam is brought to a focus at the center of a scattering chamber. Brass diaphragms limit the maximum beam divergence to 0.5°, the greatest part of which is due to multiple small-angle scattering in the beam entrance window and target gas. The target gas is confined to the center of the scattering chamber by a hollow cylinder whose axis of symmetry is perpendicular to the plane of scattering and whose vertical wall incorporates a window of 0.0005-in. duraluminum. After traversing the target, the beam enters a well-evacuated Faraday cup which is magnetically and electrically biased to avert the capture of externally produced electrons as well as the loss of those generated inside the cup.

Nuclear emulsions mounted around the periphery of the scattering chamber record the charged particles and each detector views a precise portion of the reaction volume through its own slit system at a well-defined angle with respect to the incident beam.

Most of the experimental techniques utilized in the present investigation have been carried over from previous experiments. Thus, the ion-optical system for conducting the beam to the reaction volume, as well as the Faraday-cup construction and method of current integration, has been described in a previous paper by

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† One of the authors wishes to acknowledge the hospitality of the medium-energy nuclear physics division of le Centre d'Etudes Nucleaires de Saclay during the preparation of this manuscript.

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TABLE I. Evaluation of errors and corrections.

	$He^3(d,p)He^4$	$T(d,n)He^4$
Y: Track identification and counting efficiency	1.5%	2.5%
Slit edge penetration correction error	0.5%	
n: Current integration	1.0%	1.0%
N: Pressure and temperature measurement	1.0%	1.0%
Gas purity	1.0%	1.5%
G: Slit geometry	1.0%	1.0%
Absorber correction error	1.5%	
High-order angle-dependent corrections (applicable only where cross section changes rapidly with angle)	<1.0%	<1.0%

Putnam, Brolley, and Rosen.[9] Also previously described have been the multiplate camera,[10] the method of calculating cross sections for the camera geometry[11] and the procedure for gas purification, handling and confinement.[2]

In order to avoid significant corrections for slit-edge penetration as well as to facilitate the analysis of those plates which were used to obtain the differential cross sections for the $He^3(d,p)He^4$ reaction, a feature of the nuclear plate camera is invoked which permits interposing absorbers between target and detectors. Although made of aluminum and advantageously situated close to the detectors, these absorbers slightly diminish the particle density on the detectors due to multiple small-angle scattering. The necessary corrections to the observed cross sections were graphically evaluated according to the method devised by Dickinson and Dodder.[12] The identification and counting of the tracks due to He^4 ions from the $T(d,n)He^4$ reaction had to be accomplished in a very intense background of elastically scattered deuterons and tritons. The plate analysis work was greatly facilitated by the use of Ilford *E*1 emulsions developed in such a way as to accentuate the tracks of doubly charged ions over those of singly charged ions.

In the experiments designed to investigate the possible formation of He^{4*} and H^4, it was necessary to minimize the number of spurious particles recorded by the detectors. This required improving the beam collimation system so that not even twice-scattered deuterons could enter the detectors. This was accomplished by doubling both the length of the collimating tube and the number of collimation and antiscattering baffles over that shown in reference 10. The new collimating assembly is terminated by an anti-scattering aperture which is large enough to clear the incident beam, taking due account of divergence produced by scattering in window and gas, but small enough to shadow the first set of defining slits through which the detectors view the reaction volume. Furthermore, the last collimation aperture can now see only that part of the collimator tube wall between it and the second antiscattering baffle.

The experiments under discussion were carried out over a period of about two years, during which time numerous repeat runs were made. The method of measuring deuteron energy and of setting the cyclotron for any given energy was identical to that employed during our study of the *d*-D reactions.[13]

EVALUATION OF ERRORS

For purposes of calculating the standard error appropriate to our measurements, we may write the differential cross section as $\sigma(\theta)=Y/nNG$, where Y is the measured yield, n is the total number of incident deuterons, N is the number of target atoms per unit volume and G is the geometrical factor resulting from integration over the reaction volume defined by the slit system, and the detector area which views the reaction volume.

Since the cross sections for the subject reactions are small, rather high beam intensities (up to 0.5 μa) were used. It was therefore felt necessary to ascertain that the measured temperature and pressure of the target gas were effectively those which prevailed in the volume swept out by the beam during the run. This was done by showing that the measured value of $\sigma(\theta)$ was not a function of beam current. The uncertainty of this measurement is included in the uncertainties associated with measurement of n.

Although calculation showed that the beam divergence due to multiple scattering in the target gas and windows was not so great as to cause incomplete collection by the Faraday cup, we checked this point, too, by demonstrating that the measured $\sigma(\theta)$ was not a function of gas pressure.

The estimated uncertainties in the differential cross sections for the subject reactions are listed in Table I. To the above listing must be added the statistical errors which are approximately 2.5% in the $He^3(d,p)$ experiment and 3% in the $T(d,n)$ measurements. Finally there is the uncertainty in $\sigma(\theta)$ due to a 1% uncertainty in the incident beam energy. Since the cross section varies approximately linearly with energy, the energy uncertainty will produce $\sim$1% uncertainty in $\sigma(\theta)$.

A quadratic combination of all the above-mentioned errors yields a standard error in $\sigma(\theta)$ of $\sim$4% for the $He^3(d,p)$ data and $\sim$5% for the $T(d,n)$ data.

RESULTS

The differential cross sections, as a function of angle and energy, for the $He^3(d,p)$ and $T(d,n)$ reactions are compiled in Tables II and III and plotted in Fig. 1. The angles refer to the angle of emission of the light product with respect to the incident deuteron velocity

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TABLE II. Differential cross sections in millibarns per steradian in the center-of-mass system for the $He^3(d,p)$ reaction at various deuteron laboratory energies.

Proton c.m. angle (degrees)	5.9 Mev	Proton c.m. angle (degrees)	7.5 Mev	Proton c.m. angle (degrees)	10.4 Mev	Proton c.m. angle (degrees)	12.3 Mev	Proton c.m. angle (degrees)	13.7 Mev
11.7	15.3	11.9	14.9	12.1	13.1	12.2	11.0	12.3	12.0
14.6	14.5	17.8	12.9	18.1	9.64	18.3	8.28	18.4	7.36
17.5	14.0	23.7	9.13	24.1	6.29	24.4	4.84	24.6	4.17
20.4	12.7	29.6	6.91	30.1	4.33	30.4	3.00	30.6	2.37
23.3	11.2	35.4	5.58	36.0	3.06	36.4	2.09	36.7	1.83
26.2	10.2	44.1	4.80	44.8	3.06	42.4	2.29	42.7	1.98
29.1	9.29	46.9	4.60	56.3	4.12	48.3	2.73	48.6	2.98
32.0	8.20	52.6	4.95	64.8	4.61	59.9	4.26	60.2	3.94
34.8	7.22	58.3	5.01	78.6	3.72	65.5	4.51	66.0	4.24
37.7	6.90	63.8	4.96	99.5	1.82	71.2	4.22	71.6	3.77
40.6	6.80	69.4	5.01	109.4	2.06	79.4	3.30	79.9	2.75
46.2	6.08	74.8	4.84	128.1	3.13	90.1	1.91	90.6	1.69
51.8	5.84	82.8	3.87	145.6	3.89	100.4	1.41	95.8	1.36
57.4	5.54	88.0	3.66	158.0	4.86	105.4	1.48	100.9	1.28
62.9	5.42	93.2	3.15	162.0	4.90	110.2	1.68	105.9	1.28
68.4	5.15	98.3	2.98	166.1	5.42	119.8	2.28	110.8	1.50
73.8	5.06	103.3	2.76	170.1	5.91	128.9	2.64	120.2	2.28
79.1	4.48	108.2	2.84	174.0	5.99	137.6	3.07	129.3	2.46
84.4	4.26	117.8	3.52			146.1	3.24	138.0	2.69
89.5	3.67	127.0	4.24			154.4	3.88	146.5	2.93
94.6	3.32	136.0	5.14			162.4	4.35	154.6	3.39
99.7	3.16	144.8	5.89			170.2	4.93	162.6	3.98
104.6	3.23	153.3	6.03					170.4	4.83
109.5	3.32	161.6	6.10						
114.3	3.54	169.8	6.85						
119.1	3.94								
123.8	4.32								
128.4	4.65								
132.9	5.16								
137.4	5.77								
141.8	5.99								
146.2	5.88								

vector. It is seen that there is great similarity between the angular dependence of the differential cross sections for the two reactions and that, at the higher energies, the absolute magnitudes also coincide. (Energy normalization of the 8-Mev data removes much of the disparity between the two sets of measurements.) These observations are valid even at the backward angles where the angular distributions cannot be fit with "stripping" calculations. These results may therefore be cited as corroborative evidence for the hypothesis of charge symmetry of nuclear forces. The reason that the absolute values of the differential cross sections for the two reactions are not identical at the lower energies is probably to be found in the formation of an excited state in the intermediate systems, which state occurs at a somewhat different energy in He^5 than in Li^5. Evidence for the existence of such a state is found in the energy dependence of the total cross sections for the two reactions (Fig. 2), as well as in the energy dependence of the 90° cross sections for elastic scattering. In both cases there appears to be resonance-type behavior in the energy region between 3 and 9 Mev for the incident deuterons.

Since the present experiments were limited to the detection of charged particles, the measurements on the $T(d,n)$ reaction encompass only half of the total center-of-mass interval. However, in this interval the present data are in excellent accord with the 6-Mev neutron data of Bame and Perry and in reasonable agreement with the 10-Mev neutron data of Brolley, Fowler, and Stovall, as displayed in Fig. 3. The present 10-Mev data on the $He^3(d,p)$ reaction confirm and extend the previous data of Allred.

Each of the angular distributions is characterized by a strong forward peak and two minima, one at approximately 40° and the other at approximately 100°. In addition there is exhibited a gradual and continuous rise in cross section following the second minimum.

Butler and Symonds[8] have shown that, up to the second minimum, the angular distribution for both $He^3(d,p)$ and $T(d,n)$ can be reasonably well fitted by a straightforward stripping calculation assuming zero

TABLE III. Differential cross sections in millibarns per steradian in the center-of-mass system for the T(d,n) reaction at various deuteron laboratory energies.

Neutron c.m. angle (degrees)	6.1 Mev	Neutron c.m. angle (degrees)	8.4 Mev	Neutron c.m. angle (degrees)	9.9 Mev	Neutron c.m. angle (degrees)	12.3 Mev	Neutron c.m. angle (degrees)	14.2 Mev
99.2	3.47	91.0	3.60	78.9	3.84	74.5	3.35	67.1	4.58
106.8	3.48	94.9	2.89	83.0	3.27	78.8	2.86	71.6	4.07
110.7	3.30	98.9	2.48	87.1	2.64	83.1	2.65	76.0	3.62
114.5	4.24	103.0	2.31	99.7	2.02	87.5	2.01	80.6	2.85
118.5	4.29	107.0	2.37	104.0	1.91	91.9	1.83	85.1	2.48
122.5	4.86	111.2	2.08	108.3	1.97	96.4	1.61	89.7	1.92
126.5	5.30	115.3	2.59	112.6	2.15	100.9	1.46	94.4	1.42
130.5	5.44	119.5	3.04	117.0	2.42	105.4	1.52	99.0	1.25
134.5	5.90	123.7	3.15	121.4	2.55	110.0	1.79	103.7	1.40
138.6	6.16	128.0	4.08	125.9	3.04	114.6	2.06	108.4	1.52
142.7	6.26	132.2	4.20	130.3	3.28	119.2	2.16	113.1	1.86
146.8	6.65	136.5	4.62	134.8	3.48	123.8	2.52	117.8	2.10
150.9	6.15	140.8	4.75	139.3	4.06	128.4	2.58	122.6	2.33
155.0	6.47	145.1	5.25	143.8	4.16	133.1	2.86	127.3	2.64
159.2	6.59	149.4	5.60	148.3	4.10	137.8	2.92	132.1	2.67
163.3	6.68	153.8	5.84	152.8	4.98	142.4	3.64	136.8	2.57
		158.2	5.82	157.3	5.17	147.1	3.55	141.6	2.72
		162.5	6.30	161.8	5.58	151.8	3.94	146.4	2.67
						156.5	4.07	151.2	3.38
						161.2	4.87	156.0	3.47
								160.8	4.11

angular momentum transfer by the captured nucleon. This result, which is qualitatively apparent from the data, is completely consistent with the spins and parities of the nuclei involved. Beyond the second minimum, however, the data are in sharp contrast with the above stripping calculations and it is not at all obvious how the two can be reconciled without invoking another mechanism, such as compound nucleus formation.[13a]

Since the Legendre expansions provide convenient relations for the interpolation and extrapolation of differential cross-section data, we have fit the angular distributions with a series of Legendre polynominals: $\sigma(\theta)=\sum_{n=0}^{n} a_n P_n(\cos\theta)$. The coefficients are listed in

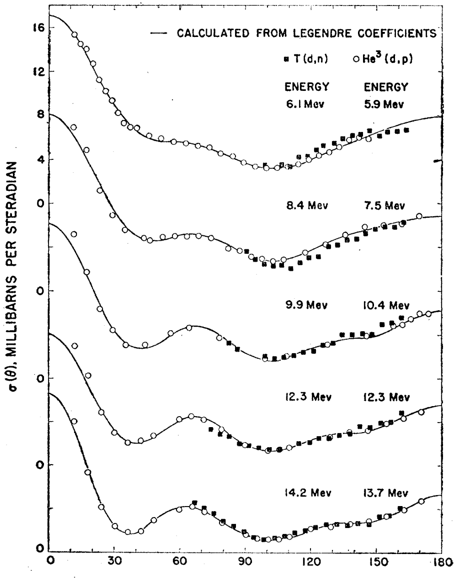

FIG. 1. Differential cross sections in the center-of-mass system for the T(d,n)He^4 and He$^3(d,p)$He^4 reaction at deuteron laboratory energies indicated for each reaction on the graphs. The smooth curves are obtained from the Legendre coefficients in Table IV.

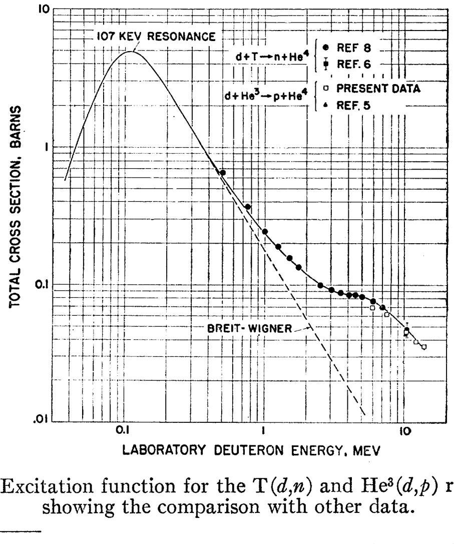

FIG. 2. Excitation function for the T(d,n) and He$^3(d,p)$ reactions showing the comparison with other data.

[13a] *Note added in proof.*—The angular distributions can be fitted if "heavy-particle stripping" (removal of the proton from He^3) is included. The results of this stripping calculation, as well as the angular distributions and polarizations obtained using a distorted-wave method, will be given in a separate paper being prepared by L. S. Rodberg and L. Stewart.

TABLE IV. Legendre polynomial coefficients (in mb/steradian, center of mass) representing the angular distributions for the $He^3(d,p)He^4$ reaction. Δ_{av} is the average percent deviation of the experimental points. The last column is the integrated cross section given by the Legendre coefficients. The asterisks refer to the coefficients obtained from the $T(d,n)$ reaction by Bame and Perry.[a]

Deuteron energy (Mev)	a_0	a_1	a_2	a_3	a_4	a_5	a_6	a_7	a_8	Δ_{av} percent	σ_T millibarns
5.00*	6.56	2.14	4.83	1.23	0.85	1.89	0.79				82.5
6.00*	6.12	2.28	4.18	1.11	1.36	2.53	1.22				76.9
7.00*	5.54	1.88	3.34	0.75	2.02	3.31	1.55				69.6
5.9	5.44	1.77	4.21	0.77	1.71	2.05	1.08			2.7	69
7.5	4.88	1.29	3.45	0.62	1.79	2.67	1.39			4.0	62
10.4	3.66	1.07	2.35	0.01	1.80	2.86	2.44			4.7	46
12.3	3.12	0.88	1.77	−0.42	1.47	2.75	2.49			5.9	39
13.7	2.88	1.00	1.95	−0.19	1.46	2.80	2.97	0.97	0.69	4.4	36

[a] See reference 7.

Table IV and the calculated cross sections shown as the smooth curves in Fig. 1. Also included, for the $T(d,n)$ reaction, are the coefficients which describe the lower energy data of Bame and Perry.[7] Integration of the Legendre expansions provides a comparison with the total cross sections for the $T(d,n)$ reaction presented in Fig. 2.

We now turn to a consideration of that part of the experiment which is concerned with the possible formation of He^{4*} and H^4.

Figure 4 shows a typical range distribution of charged particles from the $He^3(d,p)$ reaction. The formation of an excited state in He^4 would reveal itself by the presence of a monoenergetic group of protons of energy well below that of the main group. From the absence of such a group and from the reaction kinematics we conclude that the cross section for formation of an excited state in He^4 below an excitation energy of 26 Mev is everywhere less than 5% of the cross section for the $He^3(d,p)He^4$ reaction. This result is in complete accord with the most recent evidence on this subject.[14,15] The strongest evidence to the contrary comes from experiments on the $T(d,n)$ reaction in which were observed a group of neutrons of such energy as to indicate an excited state in He^4 at 22 Mev. The probable explanation for this apparent discrepancy has already been given.[3]

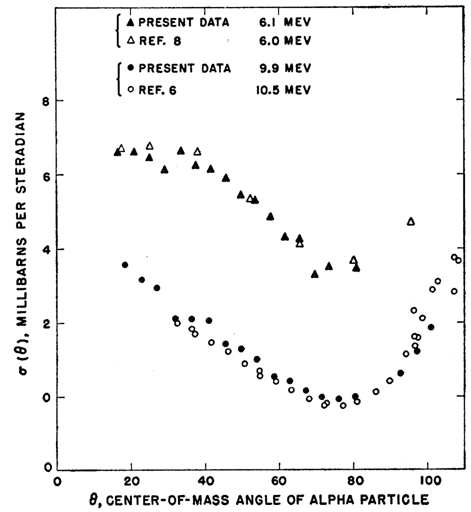

FIG. 3. Comparison of the $T(d,n)$ cross sections with previously published data.

We have likewise measured the distribution of the charged particles from the $d+T$ reaction. The formation[16] of H^4 with a Q value between −2 and +2 Mev would be evidenced by a group of singly charged particles of range greater than that of the elastically scattered deuterons or tritons. No such group was found.

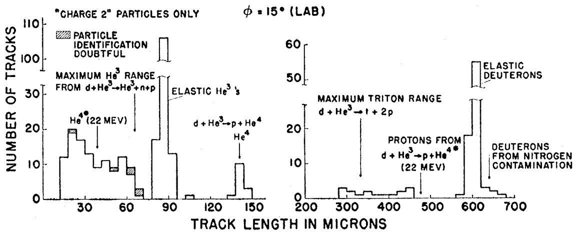

FIG. 4. Range distributions of the charged particles produced from the $d+He^3$ reaction at 13.7 Mev.

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On the theoretical side we wish to acknowledge many fruitful discussions with Dr. James E. Young and Professor Leonard Rodberg.

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