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Angular Distributions and Absolute Cross Sections for the T(d, n)^{4}He Neutron-Source Reaction*

D. K. McDaniels, † M. Drosg, ‡ J. C. Hopkins, and J. D. Seagrave
Los Alamos Scientific Laboratory, University of California, Los Alamos, New Mexico 87544
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The T(d, n)^{4}He neutron-source reaction has been reinvestigated utilizing the neutron time-of-flight techniques. This study was motivated by the lack of cross section data above 11 MeV, by large uncertainties in the 0° absolute cross sections, and by the need to improve the accuracy of both the absolute and relative cross-section data. Angular distributions were measured at E_d = 5.0, 6.0, 7.0, 10.0, 11.0, 12.0, 13.0, 14.0, 15.0, and 15.7 MeV using a neutron detector with a well-established relative efficiency. Absolute cross sections at 0° were obtained by normalization to precise charged-particle cross sections obtained for the reaction D(t, ^{4}He)n. Below 10 MeV there is good agreement with earlier data.

I. INTRODUCTION

With an exothermic Q of 17.578 MeV, the reaction T(d, n)^{4}He has proved to be a convenient and useful source of monoenergetic neutrons. A good knowledge of the absolute differential cross sections has become of increasing importance as the precision and sophistication of neutron measurement has developed. As the analysis of the $A = 5$ systems progresses, an accurate knowledge of the reaction channel T(d, n)^{4}He can be expected to contribute to our knowledge of the levels of ^{5}He. The low-energy resonance at E_d = 109 keV is well known[1] to be due to the $J^\pi = \frac{3}{2}^+$ state in ^{5}He. The large production cross section of more than 5 b for this s-wave resonance has made this reaction extremely useful as a source of 14-MeV neutrons with a low-energy accelerator.

A review of the experimental work on this source reaction prior to 1963 has been given by Goldberg.[2] The most extensive study of the low deuteron energy range was that of Bame and Perry[3] who made angular distribution and 0° yield measurements with a proton recoil telescope over the interval E_d = 0.25–7.25 MeV. Above this energy, the most comprehensive study was that of Goldberg and LeBlanc[4] who measured angular distributions and 0° yields at 6.2-, 7.9-, 9.1-, 10.2-, and 11.4-MeV deuteron energy. Angular distributions at a few energies in the range E_d = 6–14 MeV have been reported using nuclear emulsion techniques.[5] Relative 0° cross sections over the deuteron energy range of 3–19 MeV were measured with the 1.5-m cyclotron at the I.V. Kurchatov Institute using neutron time-of-flight (TOF) techniques.[6] These latter results were then normalized to the previous low-energy absolute data.

The angular distributions near 10 MeV have been analyzed theoretically using the simple stripping model of Butler.[7] This analysis showed that the reaction involved an $l = 0$ momentum transfer and gave a reasonable fit at forward angles. Attempts to fit the rise at backward angles have been made[8] using a revised stripping model which included exchange and were more successful, but could not adequately account for the magnitude of the second maximum in the angular distribution pattern. No distorted-wave stripping calculations have been made.

The present study was motivated by the need for more accurate and more extensive data on absolute cross sections and angular distributions for this neutron-source reaction, especially above 10-MeV deuteron energy. This paper presents results up to 16-MeV deuteron energy. The relative neutron yields were measured with a liquid scintillator detector and conventional TOF technique. Absolute cross sections were obtained by normalization to accurate charged-particle cross sections measured for the reaction D(t, ^{4}He)n at 20.0 MeV,[9] corresponding to a laboratory deuteron energy of 13.36 MeV in the reaction T(d, n)^{4}He.

II. EXPERIMENTAL

Tritium gas was bombarded with a bunched deuteron beam from the Los Alamos tandem accelerator. The pulse separation time was varied from 400 nsec to 12.8 μsec as needed, with a pulse time resolution of about 1.5 nsec full width at half maximum. The target cell, defining apertures, current integration, and electron suppression arrangement are described elsewhere.[10] The tritium gas cell was designed with the beam stop at one end of the target in direct contact with the gas and was cooled by a fine jet of air. A tritium gas

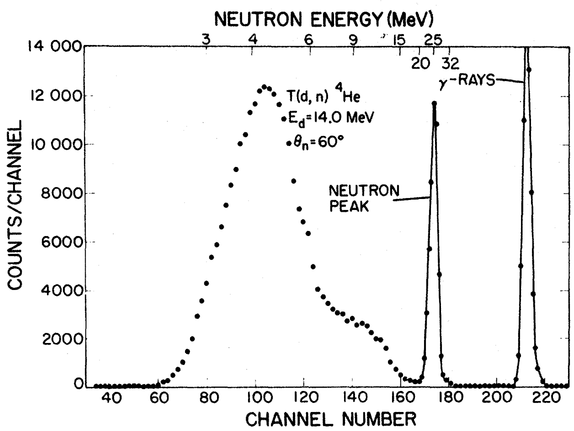

FIG. 1. Typical TOP spectrum obtained with the neutron detector at $\theta = 60°$ and with an incident deuteron energy of 14.0 MeV.

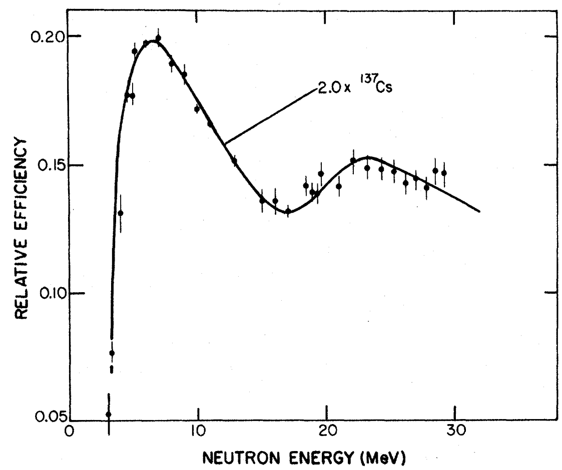

FIG. 2. Relative efficiency curve for the liquid scintillator neutron detector for a neutron energy bias of 3.2 MeV ($2.0 \times {}^{137}Cs$ Compton break). The curve was obtained as described in the text. Note suppressed zero on the ordinate.

pressure of 800 Torr was used for deuteron energies of 5–8 MeV, and 1300 Torr was used at higher deuteron energies. The energy loss in the target then varied over the range of 50–80 keV. The energy loss in the 7.92-mg/cm^2 molybdenum entrance foil varied from about 220–440 keV. The energy spread due to straggling in the entrance foil was about 50 keV.

A description of the neutron detector and shielding, neutron monitor detector, and the TOF electronics for both is presented in the companion article on the $T(p, n)^3He$ source reaction,[11] hereinafter referred to as SR1. The pulse-height discrimination bias of the detector was set at 2.0 times the Compton break of ^{137}Cs, corresponding to a recoil proton energy of about 3.2 MeV. A typical TOF spectrum obtained at $E_d = 14.0$ MeV and a laboratory angle (θ_n^L) of 60° is shown in Fig. 1. The relative efficiency of the neutron detector was obtained by scattering neutrons from hydrogen and using the n-p cross section as a standard.[12] In practice, CH_2 was used as the scattering sample for the efficiency determination, necessitating a carbon background subtraction.[13] At neutron energies above 20 MeV, the background subtraction procedure proved unreliable and the relative efficiency was determined using accurately measured charged-particle cross sections for the $D(t, {}^4He)n$ reaction.[9] The relative efficiency curve is given in Fig. 2.

Angular distributions were measured from 0–110° in 10° steps with the shielded neutron detector. Backward-angle yields from 120–140° were measured with an unshielded geometry except at E_d = 10, 12, and 14 MeV. Further details of the

TABLE I. Error estimates for the $T(d, n)^4He$ cross section measurements.

Item	Relative angular distributions [a]	Relative 0° yields	Absolute 0° yields
Statistics of counts in peak	≤1%	≤0.5%	≤0.5%
Detector bias stability	0.5%	0.3%	0.3%
Dead-time correction	≤1%	≤0.5%	≤0.5%
Relative efficiency	≤3%	≤3%	≤3%
Shape uncertainty for background subtraction	≤1.5%	0.5%	0.5%
Normalization to monitor or integrated current	1%	1%	1%
Uncertainty in charged-particle cross sections	...	...	0.8%
Attenuation corrections	≤0.5%	≤0.5%	≤0.5%
Total	≤3.8%	≤3.3%	≤3.4%

[a] These estimates apply only to data taken between 0 and 110°. Due to problems in the background subtraction for the backward-angle data, the error associated with the points at 120, 130, and 140° is ±8%.

measurement procedures can be found in SR1. Normalization of the backward-angle data to that obtained at forward angles was made by measuring the overlap region of 90–110°. The relative angular-distribution results were normalized with a neutron monitor detector placed at 54° to the beam direction. The ratio of monitor counts to charge collected was checked frequently, and remained constant within 1–2%.

0° cross sections were obtained by obtaining the relative yields from 5–16 MeV with the neutron TOF detector system and then normalizing to the 20-MeV associated particle data for the reaction $D(t, {}^4He)n$.[9] Further details of this procedure are given below in the results section. For comparison, the 0° absolute cross sections were also measured with a proton recoil telescope.[14]

The uncertainties in the relative and absolute cross sections are summarized in Table I. The principal difference between the estimates of errors given here and those for the reaction $T(p,n){}^3He$[11] is the much larger uncertainty in the relative efficiency at the higher neutron energies of this experiment.

III. RESULTS

A. Angular Distributions

Relative angular distributions were measured at E_d = 5, 6, 7, 10, 11, 12, 13, 14, 15, and 15.7 MeV. Table II summarizes the results as the ratio, $R(\theta)$, of the yield at angle θ relative to that at 0°. In Figs. 3–5 the cross sections are plotted as a function of the incident deuteron laboratory energy in order to facilitate a comparison with the earlier data of Refs. 3 and 4. These data are in good agreement with the earlier measurements.[3,4]

The laboratory cross sections were converted to the center-of-mass system and fitted to the following Legendre polynomial expression:

$$\sigma(\theta) = (1/K^2)\sum_n B_n P_n(\cos\theta), \tag{1}$$

where θ is the neutron emission angle and K is the deuteron wave number, both expressed in the center-of-mass system. The values of the coefficients up to and including $n = 8$ are summarized in Table III.

B. Absolute 0° Cross Sections

Relative 0° yields were measured from 5–16-MeV incident deuteron energy with the neutron detector TOF system. Care was taken to insure that counting rates were kept at a minimum and that all experimental conditions were kept as identical as possible as the energy was changed. The over-all uncertainty in the relative yield measurements is ≤3.3% as shown in Table I. Two different sets of 0° measurements were taken spanning an interval of over six months.

The absolute normalization was than obtained by utilizing the accurate (±0.8%) charged-particle cross sections measured for the reaction $D(t, {}^4He)n$.[9] These data span the neutron energy range of 19.2–29.1 MeV for the corresponding reaction $T(d,n){}^4He$ at 13.36 MeV. The charged-particle results are tabulated in the first three columns of Table IV. As was the procedure for the reaction

TABLE II. Laboratory relative angular distributions for the reaction $T(d,n){}^4He$. Cross sections are tabulated in terms of the ratio of the value at angle θ relative to the 0° cross section. Errors in the relative angular distributions are ±3.8% for θ = 0–110° and ±8% for θ = 120–140°.

θ (deg)	E_d (MeV) 5.00	6.00	7.00	10.00	11.00	12.00	13.00	14.00	15.00	15.70
0	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000
10	0.897	0.876	0.861	0.761	0.766	0.750	0.723	0.708	0.711	0.762
20	0.710	0.645	0.574	0.398	0.360	0.328	0.292	0.268	0.258	0.250
30	0.532	0.436	0.344	0.178	0.158	0.135	0.118	0.110	0.102	0.100
40	0.421	0.351	0.278	0.194	0.186	0.189	0.184	0.184	0.185	0.195
50	0.354	0.316	0.287	0.258	0.264	0.257	0.254	0.257	0.263	0.261
60	0.294	0.281	0.284	0.254	0.244	0.234	0.222	0.218	0.197	0.197
70	0.236	0.237	0.225	0.188	0.167	0.149	0.142	0.122	0.111	0.104
80	0.190	0.178	0.166	0.115	0.102	0.085	0.068	0.060	0.052	0.053
90	0.165	0.147	0.135	0.086	0.074	0.066	0.058	0.052	0.052	0.048
100	0.174	0.149	0.126	0.090	0.084	0.079	0.072	0.071	0.073	0.069
110	0.193	0.165	0.142	0.108	0.104	0.097	0.089	0.086	0.085	0.082
120	0.235	0.215	0.166	0.127	0.118	0.108	0.099	0.088	0.090	0.083
130	0.283	0.218	0.195	0.138	0.124	0.110	0.102	0.084	0.083	0.072
140	0.288	0.224	0.199	0.156	0.146	0.136	0.117	0.099	0.083	0.087

T(p, n)^{3}He,[11] the neutron angular distribution at 13.36 MeV was obtained both by direct measurement, and by interpolation of the data shown in Figs. 3–5. In the latter case the neutron yields at 0° were also plotted as a function of energy in order to obtain the yield at 13.36 MeV. Combining this cross section (obtained using the efficiency in Fig. 2) with the relative angular distribution gives the cross sections at 13.36 MeV from the TOF measurements. These data are summarized in columns 4, 6, and 7 of Table IV. The last column gives the ratio of the charged-particle cross sections obtained by transformation of the data in column 3 to the values obtained from the TOF measurements. The weighted average of these results is 1.288 ± 0.044, which is the normalization factor used to change the TOF yields to 0° cross sections. The values obtained in this manner are listed in the second column of Table V.

The T(d, n)^{4}He relative cross sections were also measured directly by the TOF method at 13.36 MeV in a separate measurement; at the same time the yields at 0° were measured at several energies. Normalizing these results to the charged-particle data gives the results tabulated in column 3 of Table V. The unweighted average of these two determinations was used to obtain the recommended values tabulated in the fourth column.

The 0° cross sections were also measured with a proton recoil counter telescope at $E_d = 6$, 8, 9, 10, 11, 12, 13, and 15 MeV. Experimental details are given elsewhere.[11] The telescope efficiency was calculated including corrections for the neutron-source angular distribution, the n-p angular distribution, the finite target length, attenuation in the telescope and target beam stop, and the relativistic transformation of the n-p cross section from

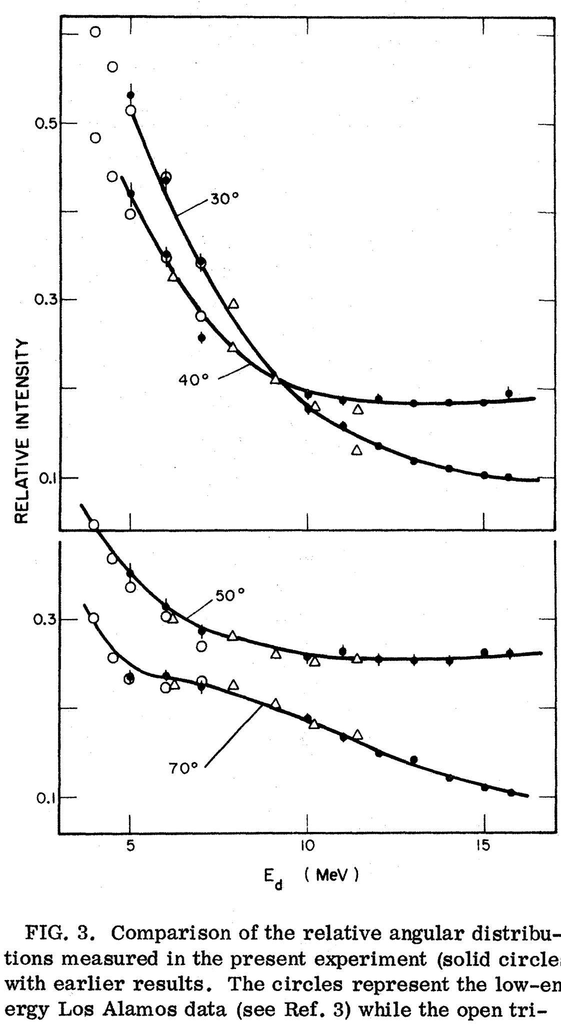

FIG. 3. Comparison of the relative angular distributions measured in the present experiment (solid circles) with earlier results. The circles represent the low-energy Los Alamos data (see Ref. 3) while the open triangles show the 6- to 11-MeV data of Goldberg and LeBlanc (see Ref. 4). The solid lines were drawn as a guide to the eye to indicate the behavior of $\sigma(\theta)/\sigma(0°)$ as a function of energy.

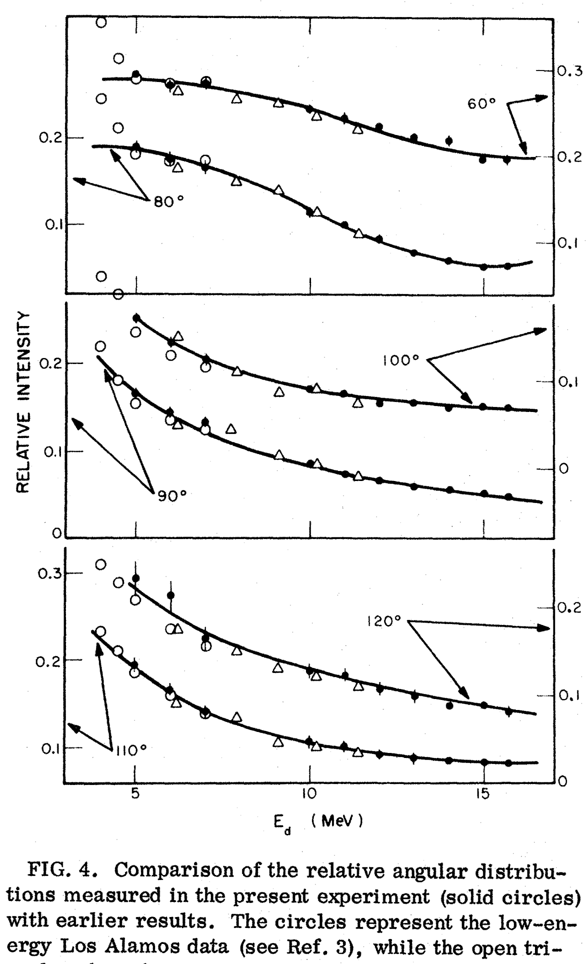

FIG. 4. Comparison of the relative angular distributions measured in the present experiment (solid circles) with earlier results. The circles represent the low-energy Los Alamos data (see Ref. 3), while the open triangles show the 6- to 11-MeV data of Goldberg and LeBlanc (see Ref. 4). The solid lines were drawn as a guide to the eye to indicate the behavior of $\sigma(\theta)/\sigma(0°)$ as a function of energy.

center-of-mass to laboratory. The exact tritium concentration was not known, resulting in a ratio of charged-particle-to-counter-telescope cross sections of 1.091 ± 0.026. This agrees well with the similar ratio for the $T(p, n)^3He$ measurements of 1.107 ± 0.019.[11] As in that experiment, the counter telescope results were multiplied by a normalization factor of 1.10.

IV. DISCUSSION

The present experiment has extended the relative angular distribution data from 11 MeV up to 16 MeV. It has confirmed the previous data for the energy range of E_d = 5–10 MeV. This is shown by the good agreement detailed in Figs. 3–5 which presents the relative distributions as a function of incident deuteron energy. This agreement is further illustrated in Fig. 6 which shows the relative angular distributions from 20–140° at 6- and 10-MeV deuteron energy. The uncertainties in the

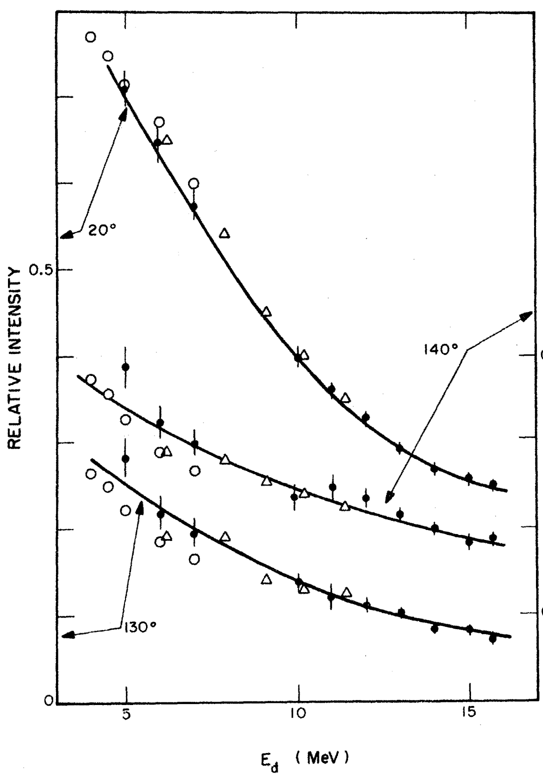

FIG. 5. Comparison of the relative angular distributions measured in the present experiment (solid circle) with earlier results. The circles represent the low-energy Los Alamos data (see Ref. 3), while the open triangles show the 6- to 11-MeV data of Goldberg and LeBlanc (see Ref. 4). The solid lines were drawn as a guide to the eye to indicate the behavior of $\sigma(\theta)/\sigma(0°)$ as a function of energy.

TABLE III. Legendre coefficients obtained from data of the present experiment.

E_d (MeV)	B_0	B_1	B_2	B_3	B_4	B_5	B_6	B_7	B_8
5.00	0.124 ± 0.003	0.030 ± 0.008	0.091 ± 0.013	0.023 ± 0.016	−0.001 ± 0.017	0.045 ± 0.016	−0.002 ± 0.012	0.014 ± 0.009	−0.000 ± 0.005
6.00	0.142 ± 0.004	0.041 ± 0.012	0.095 ± 0.018	0.026 ± 0.023	0.019 ± 0.024	0.065 ± 0.022	0.015 ± 0.018	0.009 ± 0.013	0.004 ± 0.007
7.00	0.147 ± 0.002	0.047 ± 0.006	0.085 ± 0.009	0.031 ± 0.011	0.029 ± 0.012	0.104 ± 0.011	0.020 ± 0.009	0.026 ± 0.006	−0.007 ± 0.003
10.00	0.163 ± 0.007	−0.006 ± 0.020	0.150 ± 0.031	−0.076 ± 0.039	0.138 ± 0.047	0.066 ± 0.040	0.135 ± 0.032	−0.002 ± 0.024	0.029 ± 0.013
11.00	0.162 ± 0.004	0.001 ± 0.011	0.137 ± 0.018	−0.048 ± 0.022	0.090 ± 0.024	0.125 ± 0.023	0.108 ± 0.019	0.037 ± 0.014	0.019 ± 0.008
12.00	0.166 ± 0.003	0.005 ± 0.009	0.153 ± 0.013	−0.078 ± 0.017	0.134 ± 0.019	0.082 ± 0.018	0.179 ± 0.015	0.011 ± 0.011	0.041 ± 0.006
13.00	0.166 ± 0.007	0.007 ± 0.019	0.156 ± 0.030	−0.089 ± 0.038	0.141 ± 0.042	0.083 ± 0.041	0.204 ± 0.033	0.009 ± 0.025	0.056 ± 0.014
14.00	0.168 ± 0.008	0.014 ± 0.022	0.159 ± 0.035	−0.097 ± 0.045	0.145 ± 0.049	0.076 ± 0.048	0.239 ± 0.039	0.009 ± 0.030	0.064 ± 0.017
15.00	0.166 ± 0.007	0.041 ± 0.019	0.131 ± 0.030	−0.046 ± 0.039	0.094 ± 0.042	0.126 ± 0.041	0.224 ± 0.034	0.046 ± 0.026	0.054 ± 0.015
15.70	0.178 ± 0.011	0.045 ± 0.031	0.151 ± 0.048	−0.060 ± 0.061	0.115 ± 0.068	0.127 ± 0.066	0.249 ± 0.055	0.050 ± 0.042	0.055 ± 0.025

TABLE IV. Normalization of the relative neutron data to the D(t, ^{4}He)n charged-particle results.

D(t, α)n at 20.0 MeV			T(d, n)^{4}He at 13.36 MeV				
θ_α	ϕ_α	$\sigma_\alpha(\theta_\alpha)$ [a]	θ_n	$\sigma_n(\theta_n)$	$R(\theta_n)$	$\sigma_{TOF}(\theta_n)$	$\frac{\sigma_n(\theta_n)}{\sigma_{TOF}(\theta_n)}$
15.0	35.57	10.60	29.14	2.833	0.121	2.331	1.22
17.5	41.59	11.55	34.08	3.061	0.129	2.484	1.23
20.0	47.67	16.45	39.19	4.315	0.172	3.313	1.30
22.5	53.80	21.44	44.41	5.555	0.224	4.314	1.29
25.0	60.01	24.63	49.77	6.284	0.248	4.777	1.32
27.5	66.31	24.26	55.26	6.082	0.242	4.661	1.30
30.0	72.73	21.49	60.97	5.275	0.209	4.025	1.31
32.5	79.30	16.74	66.94	4.001	0.157	3.024	1.32
35.0	86.09	11.37	73.22	2.632	0.107	2.061	1.28
37.5	93.16	7.74	79.93	1.717	0.067	1.290	1.33
40.0	100.65	6.52	88.28	1.352	0.057	1.098	1.23
41.0	102.82	7.04	90.39	1.426	0.058	1.117	1.28

[a] All cross sections are ±0.8% except for $\theta_\alpha = 40.0°$ which is ±1.6%, for $\theta_\alpha = 41.0°$ which is ±4.0%, and for $\theta_\alpha = 17.5°$ which is ±1.2%. The cross sections in column 3 are the actual measured charged-particle results. The values in column 5 are the cross sections obtained from the measured ones through use of the appropriate relativistic transformation relations. The values in column 6 are the relative angular distributions at 13.36 MeV obtained from the data shown in Figs. 3 and 4. As noted in Table I, the errors are ±3.8%. The cross sections in column 7 are the measured neutron results at 13.36-MeV incident deuteron energy, obtained and normalized as described in the text.

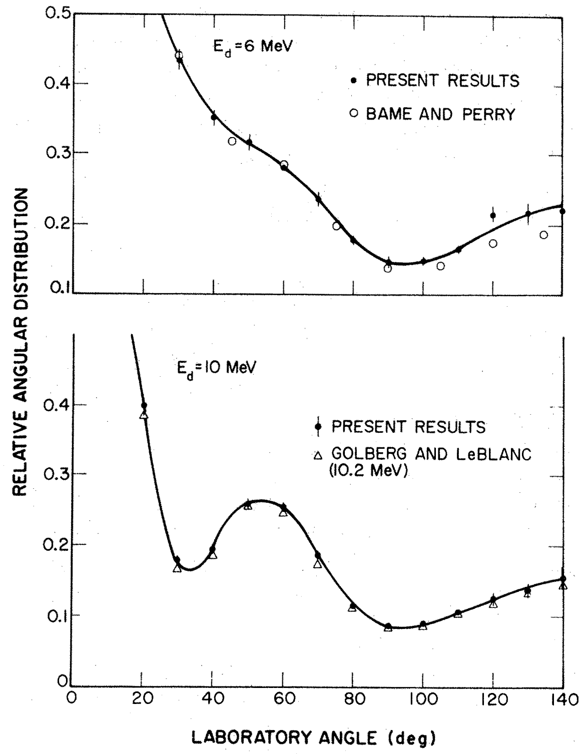

FIG. 6. Comparison of the relative angular distributions measured in the present experiment with earlier results obtained at an incident deuteron energy of 6.0 and 10.2 MeV.

TABLE V. 0° absolute cross sections for the reaction T(d, n)^{4}He in mb/sr.

E_d (MeV)	Normalized to D(t, α)n Interpolated 13.36-MeV results	Direct measurement of 13.36-MeV reaction	Recommended cross sections	Counter telescope [a]
5.00	25.3 ± 0.9		25.3 ± 0.9	
6.00	27.5 ± 0.9		27.5 ± 0.9	26.6
7.00	27.7 ± 0.9		27.7 ± 0.9	
8.00	27.2 ± 0.9		27.2 ± 0.9	27.5
9.00	26.2 ± 0.9		26.2 ± 0.9	26.6
10.00	25.7 ± 0.9	25.1 ± 0.8	25.4 ± 0.9	26.2
11.00	24.6 ± 0.8	24.6 ± 0.8	24.6 ± 0.8	25.5
12.00	25.0 ± 0.8	24.9 ± 0.8	25.0 ± 0.8	25.0
13.00	24.8 ± 0.8	25.1 ± 0.8	24.8 ± 0.8	24.4
13.36		25.6 ± 0.8	25.6 ± 0.9	
14.00	24.7 ± 0.8	25.6 ± 0.8	24.7 ± 0.8	
15.00	24.4 ± 0.8	25.4 ± 0.9	24.9 ± 0.8	25.4
15.50		25.5 ± 0.9	25.5 ± 0.9	
16.00	24.9 ± 0.8	25.9 ± 0.9	25.4 ± 0.9	

[a] The measured values were multiplied by 1.10 as described in the text.

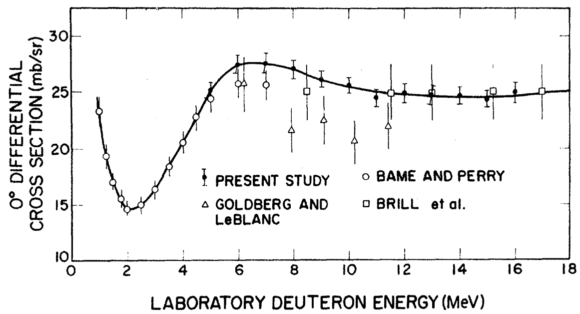

FIG. 7. The T(d, n)^{4}He differential cross section at 0° plotted as a function of lab deuteron energy. The solid curve was drawn as a guide to the eye to indicate the trend of the data.

relative angular distributions have been reduced to ±3.8%, due principally to the ultilization of the TOF technique and to a well-established neutron detector efficiency.

The absolute 0° cross sections obtained by normalizing to the charged-particle data[10] from the reaction D(t, ^{4}He)n are compared to previous work in Fig. 7. The present results agree with the extensive low-energy Los Alamos data[3] obtained with the proton recoil counter telescope technique. Above 7 MeV, the only published data are that of Goldberg and LeBlanc[4] and Brill *et al.*[6] Both of these experiments claim ±10% accuracy, and both normalized their 0° data to the lower-energy Los Alamos data.[5] The present results agree within error with the data of Brill *et al.*,[6] but are consistently higher than the Lawrence Livermore Laboratory data.[4] The uncertainty in the 0° cross sections is about ±3.4%.

The present results, coupled with those from the companion experiment on the reaction T(p, n)^{3}He,[11] can be viewed as presenting an experimental verification to about ±4% of the n-p cross section at 180°. The counter telescope cross sections for both neutron-source reaction measurements were made with the same tritium target filling. As noted above, the ratio of the cross sections determined by normalizing to the charged-particle cross section to counter telescope results was about 1.10 ± 0.02 for both reactions. The lack of any systematic trend with energy in this ratio verifies the values of the n-p 180° cross section used in the analysis of the counter telescope measurements over the neutron energy range of 9–30 MeV. The reason the approximately 10% constant deviation between the two types of results cannot be due to a constant fractional error in the n-p cross section at 180° is that at low energies the angular distribution for the n-p reaction is almost isotropic, and the differential cross section is almost $\sigma_T/4\pi$, with σ_T a very well established result.

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