# T(*d*,*n*)He$^4$ Reaction*

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The differential cross sections for neutron production in the T(*d*,*n*)He$^4$ reaction have been measured over the deuteron bombarding-energy range 0.25 to 7.0 Mev. Legendre polynomial fits to the data are presented and compared with existing data. The total cross section plotted as a function of deuteron energy has an anomalous behavior which may indicate a broad level in He$^5$ near 20-Mev excitation energy.

## INTRODUCTION

THE T(*d*,*n*)He$^4$ reaction, with a $Q$ of 17.578 Mev, is often used as a source of high-energy neutrons. Therefore, an accurate knowledge of the differential cross section of the reaction over a wide range of bombarding energies is of considerable practical importance. In addition, this information is of interest for theoretical studies of light particle reactions.

An extensive bibliography of early work on this reaction is given by Fowler and Brolley.[1] The yield of the reaction exhibits a pronounced maximum near $E_d = 107$ kev. Cross sections in the range $E_d = 10$ to 1700 kev are given by several experiments.[2–4] Differential cross sections for the production of alpha particles from the reaction have been measured at $E_t = 1.5$ Mev[5] (corresponding to $E_d = 1.0$ Mev), at $E_d = 2.21$ Mev,[6] and at $E_d = 10.5$ Mev.[7] More recently the reaction has been studied in the range $E_d = 1.0$ to 5.79 Mev by Galonsky and Johnson,[8] who used techniques similar to those of this experiment.

The work reported here covers a deuteron energy range of 0.25 to 7.25 Mev. The cross sections presented are, we believe, the most accurate yet obtained in this energy range. A preliminary report of some of the results has previously been given.[9]

## EXPERIMENTAL TECHNIQUE

Tritium gas targets[10] were bombarded with a monoenergetic deuteron beam from an electrostatic accelerator. Deuteron energies of 0.25 to 2.00 Mev were produced by a small horizontal accelerator, and the higher energies were obtained using the large vertical accelerator at Los Alamos. Fast neutrons produced in the T(*d*,*n*)He$^4$ reaction were detected with two recoil-proton counter telescopes.[11] One of these telescopes is shown schematically in Fig. 1.

Absolute cross sections were obtained with the counter telescopes at 0° over the entire range of deuteron energy, and several angular distributions were measured. Cross sections were determined from measured values of the number of incident deuterons, the number of target atoms per cm$^2$, and the computed efficiency[11] of the telescope.

## ACCURACY OF THE MEASUREMENTS

A number of unusual factors entered into the computation of cross sections from the experimental data. The telescopes used in the experiment were designed with large internal solid angles to insure high counting efficiencies. The wide range of angle available to the recoil protons made the determination of the telescope efficiency somewhat difficult because of the anisotropic angular distribution of $(n,p)$ scattering in the laboratory system. A calculation of the counter efficiency was carried out, using an IBM 701 computer.[11] This calcu-

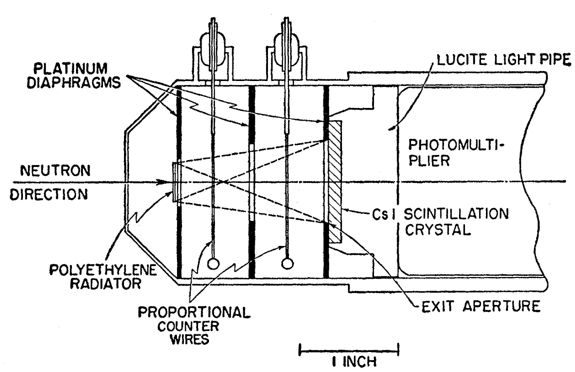


FIG. 1. Schematic drawing of one of the counter telescopes used in this experiment. Neutrons incident on the radiator scatter protons through the counter system. A threefold coincidence of the telescope is used to gate a multichannel analyzer which records the recoil-proton pulse-height distribution from the scintillation counter.

* Work performed under the auspices of the U. S. Atomic Energy Commission.
[1] J. L. Fowler and J. E. Brolley, Jr., Revs. Modern Phys. **28**, 102 (1956).
[2] Argo, Taschek, Agnew, Hemmendinger, and Leland, Phys. Rev. **87**, 612 (1952).
[3] Conner, Bonner, and Smith, Phys. Rev. **88**, 468 (1952).
[4] Arnold, Phillips, Sawyer, Stovall, and Tuck, Phys. Rev. **93**, 483 (1954).
[5] A. Hemmendinger and H. V. Argo, Phys. Rev. **98**, 70 (1955).
[6] T. F. Stratton and G. D. Freier, Phys. Rev. **88**, 261 (1952).
[7] Brolley, Fowler, and Stovall, Phys. Rev. **82**, 502 (1951).
[8] A. Galonsky and C. H. Johnson, Phys. Rev. **104**, 421 (1956).
[9] S. J. Bame, Jr., and J. E. Perry, Jr., Bull. Am. Phys. Soc. Ser. II, **1**, 93 (1956), and Los Alamos Report LA-2014 (unpublished), a compilation of charged particle cross sections. (The preliminary cross sections reported in these references are about 10% too high, due to using telescope efficiencies calculated by an approximation method.)
[10] An example of a Los Alamos gas target is shown by J. E. Perry and S. J. Bame, Phys. Rev. **99**, 1368 (1955), see Fig. 1. Gas handling equipment was similar to that described by C. H. Johnson and H. E. Banta, Rev. Sci. Instr. **27**, 132 (1956).
[11] Bame, Haddad, Perry, and Smith (to be published). See also C. H. Johnson and C. C. Trail, Rev. Sci. Instr. **27**, 468 (1956).

lation involved a double integration over the radiator and the exit aperture, taking into account the $(n,p)$ differential scattering cross section. Although the calculation assumed a point source of neutrons, all the data have been corrected for a finite target length.

The greatest uncertainty in the telescope efficiency lies in the knowledge of the $(n,p)$ scattering cross section. Gammel's semiempirical description[12] of $(n,p)$ scattering was used in the efficiency calculation. The total $(n,p)$ cross sections of this formulation agree with the best existing data within 0.4% from 1 to 20 Mev. The center-of-mass anisotropy of $(n,p)$ scattering is less well known, because experimental data exist at only three neutron energies up to 20 Mev. However, Gammel's fit falls well within the experimental errors ascribed to the measured values. We estimate an uncertainty of 2.5% in telescope efficiency due to the uncertainty in the differential $(n,p)$ scattering cross section. Additional telescope errors may arise from inaccuracies in measurement of the counter-target geometry (2%) and the number of protons in the radiator (0.5%).

The pulse-height spectra obtained from the telescope contained several small backgrounds. The inherent telescope background was determined by taking data with the radiator removed. The accelerator background was obtained by taking data with the radiator in place, but with the tritium gas removed from the target. We estimate an error of 1.5% in our data due to inaccuracies in the determination and subtraction of these backgrounds. The counting statistics throughout the experiment were maintained at about 1%.

The number of deuterons incident upon the target was determined with a standard current integrator. The current integrator used for the measurements below 2 Mev was slightly unstable, but apparently accurate to 2%. At higher energies current integration was believed accurate to 1%.

Standard techniques of measuring the target gas temperature and pressure were used when the target was filled and a valve near the target cell was closed. Periodic mass spectrometric measurements gave the tritium concentration in the gas samples. From the accuracy of these measurements we assign an error of 2% to the density of target atoms at the time the targets were filled and sealed. However, beam heating of the target cell and gas resulted in a loss in the yield of neutrons from the target, despite adequate air-cooling of the exterior of the target. This loss was attributed to a reduction in the density of tritium atoms in the region of the target through which the beam passed. With the targets used, a linear decrease of yield with increasing current was observed. Thus, the loss in yield could be corrected by measuring the yield at a number of average beam currents and extrapolating the yield to zero current. The correction was about 5% for an average current of one microampere. We estimate an error of 2% in the yield when corrected for this effect. The gas-heating effect was measured at each energy below 2 Mev and at half-Mev intervals above 2 Mev.

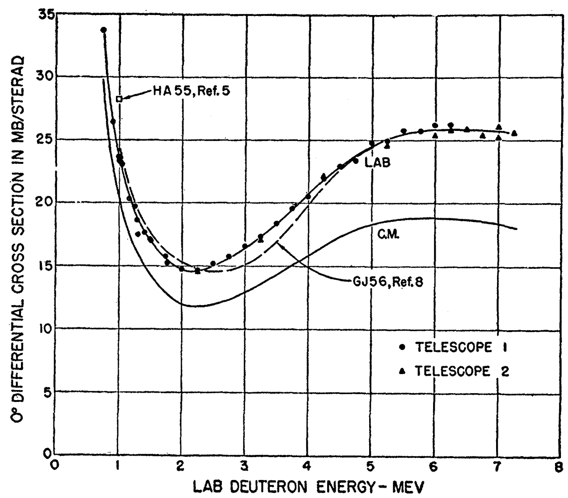


FIG. 2. Differential cross section for the production of neutrons from $T(d,n)He^4$ at 0° in both the laboratory and center-of-mass systems. The standard error is estimated to be ±5%. The point at 1.0 Mev comes from the experiment of Hemmendinger and Argo,[5] with an assigned probable error of ±3%. No explanation for the discrepancy has been found. The dashed curve comes from the (lab) data of Galonsky and Johnson,[8] who assign to their cross sections a standard error of 8–11%. The agreement with the present data is reasonable.

To reduce the effects of slow loss of tritium through the target entrance foil, a new target filling was used for each 0° cross-section measurement. In the angular distribution measurements a biased stilbene counter was used as an additional monitor of gas-loss and gas-heating effects, and beam currents were maintained as nearly constant as possible to reduce fluctuations caused by gas heating.

At proton energies above 10 Mev, inelastic events in the CsI crystal are known to remove some pulses from the main proton-recoil peak and place them in a small-pulse-height tail.[13] Rough estimates of the size of this effect at 24 Mev indicate that it should be no larger than 1%. Consequently no correction has been made for this effect.

Compounding quadratically all the errors discussed above, we assign a standard error of ±5% to the absolute cross-section measurements of this experiment. An example of the reproducibility of the measurements is given by the two sets of 0° cross sections in the 2- to 7-Mev range shown in Fig. 2. The two sets of data, which agree to within 2%, were obtained a year apart using completely different telescopes, targets, and tritium gas samples.

[12] J. L. Gammel, Los Alamos Scientific Laboratory (private communication). The results of this work are to be published in reference 11.

[13] L. H. Johnston and D. A. Swenson, Bull. Am. Phys. Soc. Ser. II, 2, 180 (1957).

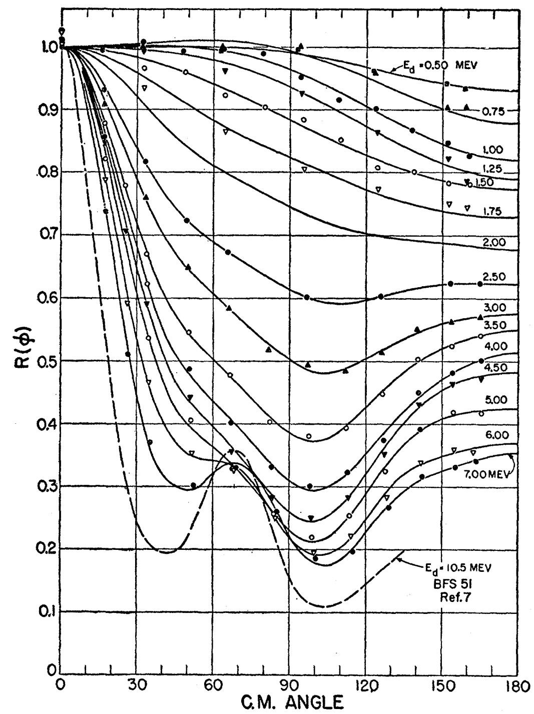


FIG. 3. Relative angular distributions of the neutrons from $T(d,n)He^4$ in the center-of-mass system. $R(\phi)$ is the ratio $\sigma(\phi)/\sigma(0°)$. The smooth curves are Legendre polynomial fits to the data; the points are experimental. The curve for $E_d=2.0$ Mev is interpolated from the other data, since no reliable experimental data were taken at that energy.

Since some of the errors discussed above are not present in relative measurements, we assign a standard error of $\pm 3.5\%$ to the angular distribution results. No corrections have been applied to the data for the finite angular spread caused by target length and radiator diameter. Calculation shows a $\pm 1\%$ distortion of the 7-Mev angular distribution due to this effect. The distortion is less than $\pm 1\%$ at all energies below 7 Mev.

### $T(d,n)He^4$ CROSS SECTIONS AND COMPARISONS

The 0° differential cross sections of this experiment are presented in Fig. 2. At 1 Mev, there is a comparison with a zero degree cross section obtained by an extrapolation of the data of Hemmendinger and Argo.[5] Their result is 18% higher than that of this experiment. At present, there is no explanation for this discrepancy. Also compared with the present work is a 0° excitation curve obtained from the results of Galonsky and Johnson[8] by using the relative angular distributions of the present experiment to change their 6° excitation curve to 0°. Since they estimate an 8–11% standard error for their measurements, and the present work has been assigned a 5% standard error, the agreement between the experiments is quite satisfactory.

In order to obtain the best estimate of the reaction cross section as a function of angle and energy, the following smoothing process was used in the analysis of the experimental results. (1) Each angular distribution, converted to the center-of-mass system, was fitted by a least squares method with a Legendre polynomial series. The resulting Legendre fits, normalized to unity at 0°, are shown in Fig. 3. Here the smooth curves are the Legendre results, the plotted points are experimental, and it is apparently fortuitous that a few of the experimental points do not lie slightly below 1.0 at 0°. (2) To obtain absolute values of the Legendre coefficients as a function of energy, the above normalized values were multiplied by smoothed values of the absolute center-of-mass 0° cross section obtained from Fig. 2. Table I and Fig. 4 show the variation of the absolute Legendre coefficients as a function of deuteron energy.

The number of Legendre terms required for a good fit to the data varies with deuteron energy. Terms through $P_2$ are sufficient up to 2 Mev, while terms through $P_6$ appear to be both necessary and sufficient

TABLE I. Legendre polynomial coefficients (in mb/sterad) for angular distributions of $T(d,n)He^4$ in the center-of-mass system.

| $E_d$ Mev | $a_0$ | $a_1$ | $a_2$ | $a_3$ | $a_4$ | $a_5$ | $a_6$ | $\sigma_T$ mb |
|---|---|---|---|---|---|---|---|---|
| 0.50 | 51.31 | 1.79 | −0.88 | | | | | 644 |
| 0.75 | 29.33 | 1.64 | −1.27 | | | | | 369 |
| 1.00 | 19.47 | 1.86 | −0.74 | | | | | 245 |
| 1.25 | 15.22 | 1.74 | −0.45 | | | | | 191 |
| 1.50 | 12.65 | 1.62 | 0.03 | | | | | 159 |
| 1.75 | 10.73 | 1.59 | 0.57 | | | | | 135 |
| 2.50 | 7.95 | 1.42 | 1.36 | 0.46 | 0.34 | 0.38 | 0.11 | 99.9 |
| 3.00 | 7.45 | 1.67 | 2.13 | 0.52 | 0.36 | 0.56 | 0.22 | 93.6 |
| 3.50 | 7.03 | 1.59 | 3.15 | 0.74 | 0.48 | 0.88 | 0.42 | 88.4 |
| 4.00 | 6.76 | 1.88 | 3.98 | 0.84 | 0.72 | 1.12 | 0.50 | 85.0 |
| 4.50 | 6.77 | 1.94 | 4.74 | 1.03 | 0.72 | 1.50 | 0.60 | 85.1 |
| 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 |

at energies from 2.5 through 6 Mev. At 7 Mev the fit appears to be somewhat improved by inclusion of terms through $P_8$. The open circles at 7 Mev in Fig. 4 represent the coefficients of the eighth-order expansion where they differ significantly from those of the sixth-order expansion. However, the accuracy of the experimental data does not allow a clear-cut choice between the sixth- and eighth-order fits.

In Fig. 5, the angular distributions of this work are compared with the distributions found in other experiments. The agreement is considered adequate except for the 1.0-Mev data. The 6.0-Mev comparison is made with the data of Brolley, Hall, and Rosen,[14] who measured the alpha-particle yields from this reaction. The comparison at 1.27 Mev is made with a differential cross section measured by Jarmie and Allen[15] using a

[14] Brolley, Hall, and Rosen (private communication) and Bull. Am. Phys. Soc. Ser. II, 2, 207 (1957).

[15] N. Jarmie and R. C. Allen, Bull. Am. Phys. Soc. Ser. II, 2, 305 (1957).

double focusing magnet to count the alpha particles from a gas target with thin glass windows.[16] The relative angular distributions can also be compared with the angular distributions of $He^3(d,p)He^4$ measured by Yarnell, Lovberg, and Stratton[17] at 0.260, 0.455, 0.978, 1.51, 2.01, 2.50, 3.01, and 3.56 Mev. The shapes of the angular distributions of the two experiments agree to within $\pm 4\%$, but the cross sections are not the same.

The total cross section of the $T(d,n)He^4$ reaction is plotted against deuteron energy in Fig. 6. The results of many other experiments are included in this figure.

For the convenience of experimentalists we have included in Table II the absolute 0° laboratory cross sections and relative laboratory angular distributions

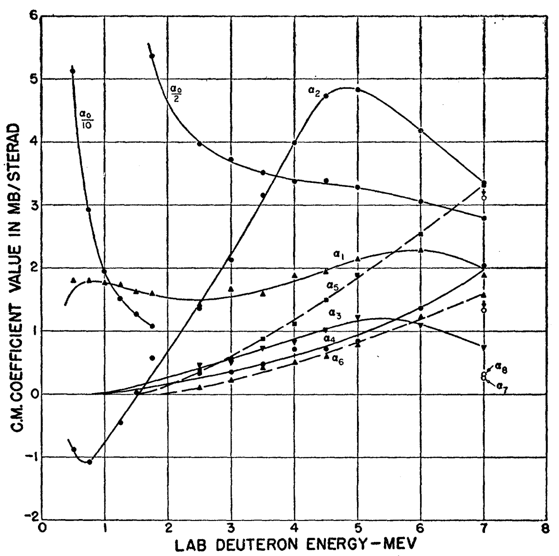


FIG. 4. Legendre polynomial coefficients plotted against deuteron energy. Each center-of-mass angular distribution has been fitted with the series $\sigma(\phi)=\sum \alpha_n P_n(\cos\phi)$, by the method outlined in the text. The number of terms necessary to fit the distributions changes with bombarding energy. At $E_d=7.0$ Mev the coefficient values are plotted for fits with both a sixth-order series (solid points) and an eighth-order series (open circle points). The eighth-order series appears to be a slightly more accurate fit of the data.

of the reaction as a function of deuteron energy. An absolute laboratory angular distribution at any energy from 0.2 to 7 Mev may be obtained by interpolation of these data. In preparing the table we have used the Legendre coefficients of Table I and the solid-angle transformations of Blumberg and Schlesinger.[18] Values of neutron energy *vs* laboratory angle and deuteron energy may be found in references 1 and 18. It should be noted that above $E_d=3.71$ Mev, low-energy con-

[16] A. Hemmendinger and A. P. Roensch, Rev. Sci. Instr. **26**, 562 (1955).
[17] Yarnell, Lovberg, and Stratton, Phys. Rev. **90**, 292 (1953).
[18] L. Blumberg and S. I. Schlesinger, Atomic Energy Commission Report AECU-3118 (unpublished).

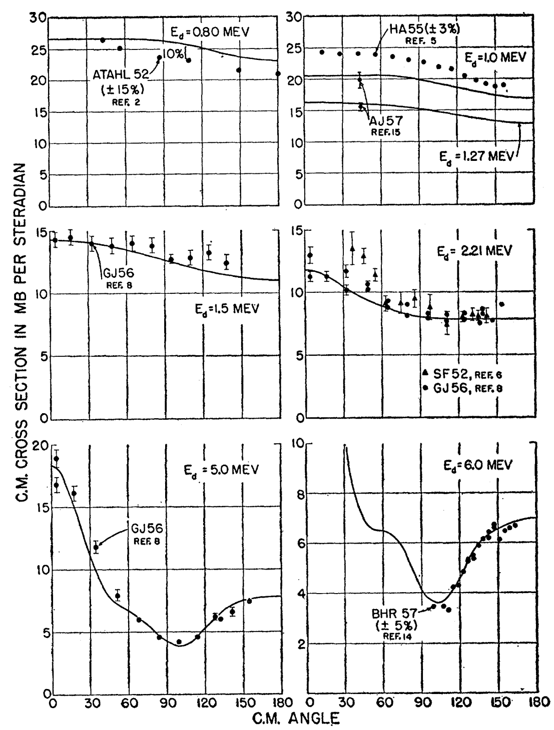


FIG. 5. Angular distributions of neutrons from $T(d,n)He^4$ compared with other experimental data. The curves shown in each graph are the Legendre polynomial fits of the data of this experiment. The points are taken from the references indicated. Where errors are not shown with the points, the probable errors of the experiment are given. The standard error for cross sections given by this experiment is $\pm 5\%$.

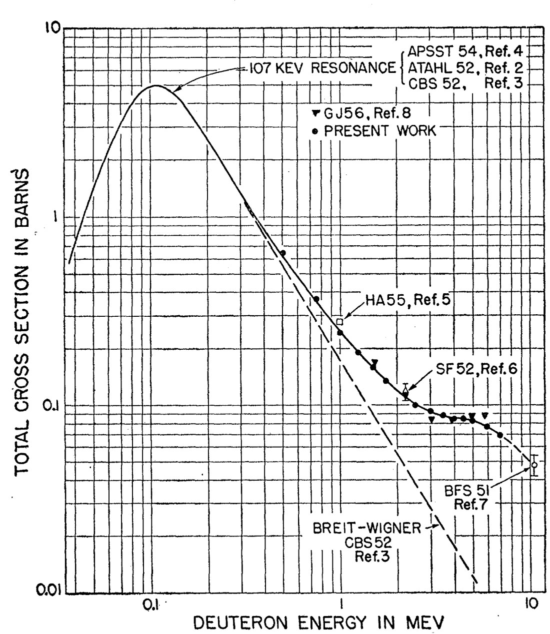


FIG. 6. Total cross section of $T(d,n)He^4$. The cross sections of other experiments are taken from the indicated references. An extrapolation of a Breit-Wigner fit[3] to the 107-kev resonance is included.

TABLE II. Relative angular distributions of $T(d,n)He^4$ in the laboratory system. $R(\theta)$ is the ratio of the cross section at the laboratory angle $\theta$ to the cross section at 0°. The 0° differential cross sections are included in the table.

| $E_d$ Mev | 0.20[a] | 0.50 | 0.75 | 1.00 | 1.25 | 1.50 | 1.75[b] | 2.00[c] | 2.50 | 3.00 | 3.50 | 4.00 | 4.50 | 5.00 | 6.00 | 7.00 |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| $\sigma(0°)$ mb/sterad | 218[a] | 57.9 | 33.7 | 23.8 | 19.4 | 17.1 | 15.6 | 14.7 | 15.0 | 16.4 | 18.4 | 20.7 | 22.9 | 24.5 | 25.8 | 25.7 |
| $R(0°)$ | 1.000 | 1.000 | 1.000 | 1.000 | 1.000 | 1.000 | 1.000 | 1.000 | 1.000 | 1.000 | 1.000 | 1.000 | 1.000 | 1.000 | 1.000 | 1.000 |
| $R(7.5°)$ | | | | | | | | | 0.981 | 0.976 | 0.966 | 0.960 | 0.956 | 0.950 | 0.937 | 0.923 |
| $R(15°)$ | 0.998 | 0.996 | 0.997 | 0.996 | 0.993 | 0.989 | 0.980 | 0.966 | 0.931 | 0.910 | 0.876 | 0.859 | 0.842 | 0.821 | 0.781 | 0.737 |
| $R(22.5°)$ | | | | | | | | | 0.860 | 0.821 | 0.760 | 0.726 | 0.698 | 0.661 | 0.591 | 0.509 |
| $R(30°)$ | 0.990 | 0.988 | 0.989 | 0.982 | 0.974 | 0.958 | 0.927 | 0.882 | 0.790 | 0.733 | 0.650 | 0.603 | 0.564 | 0.518 | 0.440 | 0.344 |
| $R(45°)$ | 0.980 | 0.972 | 0.974 | 0.958 | 0.941 | 0.910 | 0.861 | 0.806 | 0.678 | 0.602 | 0.504 | 0.443 | 0.399 | 0.361 | 0.317 | 0.267 |
| $R(60°)$ | 0.967 | 0.950 | 0.948 | 0.922 | 0.899 | 0.853 | 0.793 | 0.722 | 0.601 | 0.517 | 0.418 | 0.355 | 0.314 | 0.289 | 0.283 | 0.284 |
| $R(75°)$ | 0.951 | 0.923 | 0.913 | 0.877 | 0.844 | 0.791 | 0.730 | 0.658 | 0.536 | 0.438 | 0.338 | 0.274 | 0.230 | 0.206 | 0.197 | 0.201 |
| $R(90°)$ | 0.934 | 0.890 | 0.870 | 0.825 | 0.786 | 0.730 | 0.671 | 0.597 | 0.479 | 0.379 | 0.286 | 0.222 | 0.182 | 0.156 | 0.137 | 0.125 |
| $R(105°)$ | 0.918 | 0.856 | 0.824 | 0.769 | 0.727 | 0.673 | 0.618 | 0.548 | 0.443 | 0.356 | 0.284 | 0.225 | 0.194 | 0.171 | 0.143 | 0.128 |
| $R(120°)$ | 0.903 | 0.823 | 0.777 | 0.717 | 0.673 | 0.624 | 0.570 | 0.511 | 0.427 | 0.356 | 0.302 | 0.251 | 0.231 | 0.208 | 0.176 | 0.156 |
| $R(135°)$ | 0.890 | 0.794 | 0.737 | 0.671 | 0.629 | 0.586 | 0.536 | 0.485 | 0.415 | 0.355 | 0.315 | 0.271 | 0.255 | 0.227 | 0.187 | 0.167 |
| $R(150°)$ | 0.880 | 0.770 | 0.705 | 0.635 | 0.594 | 0.558 | 0.510 | 0.464 | 0.404 | 0.351 | 0.317 | 0.281 | 0.262 | 0.229 | 0.186 | 0.167 |
| $R(165°)$ | 0.875 | 0.757 | 0.683 | 0.613 | 0.572 | 0.541 | 0.496 | 0.450 | 0.395 | 0.346 | 0.318 | 0.286 | 0.263 | 0.226 | 0.186 | 0.168 |
| $R(180°)$ | 0.873 | 0.750 | 0.677 | 0.606 | 0.564 | 0.535 | 0.492 | 0.445 | 0.391 | 0.346 | 0.319 | 0.288 | 0.263 | 0.224 | 0.185 | 0.169 |

[a] The distribution for 0.20 Mev is calculated assuming an isotropic angular distribution in the center of mass. The cross section at 0° is taken from Argo *et al.*, Phys. Rev. **87**, 612 (1952).
[b] The 1.75-Mev distribution has been calculated, using a set of Legendre coefficients read off the plot of coefficients *vs* deuteron energy. The center-of-mass distribution used here is $\sigma(\phi)=10.76+1.57P_1(\phi)+0.32P_2(\phi)+0.18P_3(\phi)+0.10P_4(\phi)$.
[c] No experimental data were taken at $E_d=2.00$ Mev. The center-of-mass distribution used at this energy, taken from the plot of Legendre coefficients *vs* $E_d$, is $\sigma(\phi)=9.24+1.53P_1(\phi)+0.68P_2(\phi)+0.27P_3(\phi)+0.17P_4(\phi)+0.14P_5(\phi)$.

tamination neutrons appear from the breakup reaction $T(d,np)T$.[19]

## CONCLUSIONS

The main features of the theoretical interpretation of this experiment have been given previously. The resonance at $E_d=107$ kev has been attributed to the formation of a $3/2+$ excited state[3] in $He^5$. At energies approaching 10 Mev the reaction exhibits characteristics of stripping.[8,20] The reaction width might be studied by the method of Bowcock.[21] The presence of a broad peak in the total cross section at $E_d \sim 4$ to 8 Mev (Fig. 6) may indicate the presence of a second excited state in $He^5$. More detailed explanations of the interaction do not appear to be evident at the moment.[22]

[19] Henkel, Perry, and Smith, Phys. Rev. **99**, 1050L (1955).
[20] S. T. Butler and J. L. Symonds, Phys. Rev. **83**, 858 (1951).
[21] J. E. Bowcock, Proc. Phys. Soc. (London) **A68**, 512 (1955).

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[22] L. C. Biedenharn (private communication).