Angular Yield of Neutrons from the T(d,n)He^4 Reaction for 6- to 11.5-Mev Deuterons

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The angular yield of monoenergetic neutrons from the T(d,n)He^4 reaction has been measured with 6.2-, 7.9-, 9.1-, 10.2-, and 11.4-Mev deuterons. The neutrons were detected with a proton recoil telescope which provided discrimination against neutrons from the T(d,np)T breakup reaction. The yield curves are all peaked forward, with a second maximum at about 65° which becomes more pronounced with increasing energy, and a back-angle rise. A quasi-absolute determination of the 0° cross section for this reaction is described. The measured yield curves are compared to those for the companion He$^3(d,p)$He^4 reaction and a strong similarity in shape and magnitude is noted. A simple stripping model is inadequate to describe these data. A distorted-wave calculation is required.

INTRODUCTION

THE T(d,n)He^4 reaction is the primary source of monoenergetic beams of neutrons with energies between 14 and 30 Mev, due to its very high Q value of 17.578 Mev.[1] Hence, knowledge of the angular yield of the neutrons from this reaction at different deuteron energies is of considerable experimental interest. It also provides additional information in the field of few-nucleon systems.

A review of the experimental work, with an extensive bibliography, is given by Brolley and Fowler.[2] Previously reported angular distributions in the deuteron energy region from 6 to 11.5 Mev include distributions at 6.0 and 7.0 Mev by Bame and Perry,[3] using a proton recoil telescope similar to that used in this experiment, and a distribution at 10.5 Mev by Brolley, Fowler, and Stovall[4] using various neutron detecting techniques. Recently, Stewart, Brolley, and Rosen,[5] using nuclear emulsions to detect the residual alpha particles, have reported angular distributions for neutron center-of-mass angles greater than about 70° for deuteron energies of 6.1, 8.4, 9.9, 12.3, and 14.2 Mev. They have also measured full angular distributions of the companion He$^3(d,p)$He^4 reaction at similar deuteron energies.

Butler and Symonds[6] have attempted a stripping fit to the 10.5-Mev data of Brolley *et al.*,[4] and the very similar 10.2-Mev angular distribution for the companion He$^3(d,p)$He^4 reaction.[7] A reasonable fit, assuming an $l=0$ momentum transfer, was obtained for center-of-mass angles from 0° to the second minimum at about 100°, but beyond this the data departed strongly from the theoretical stripping curve.

The experiment reported here provides angular yield curves for the T(d,n)He^4 neutrons for laboratory deuteron energies of 6.2, 7.9, 9.1, 10.2, and 11.4 Mev. These data indicate that a distorted wave calculation is required to describe the yields for this reaction.

EXPERIMENT

The deuterons were provided by the Livermore 90-inch variable energy cyclotron. Just under one atmosphere of tritium gas, of unknown purity, was contained in a stainless steel cylindrical gas cell 4 inches in length and 1 inch in diameter. Deuterons entered the target through a 0.00025-inch (about 10 mg/cm^2) tantalum foil and were stopped in a 0.020-inch tantalum beam stopper. Tantalum collimators prevented bombardment of the side walls of the target cylinder.

The neutron detector was mounted 32 inches from the center of the gas target on a remotely controllable angle changer. The selsyn control from the counting area permitted accurate changes in steps of about 0.2°

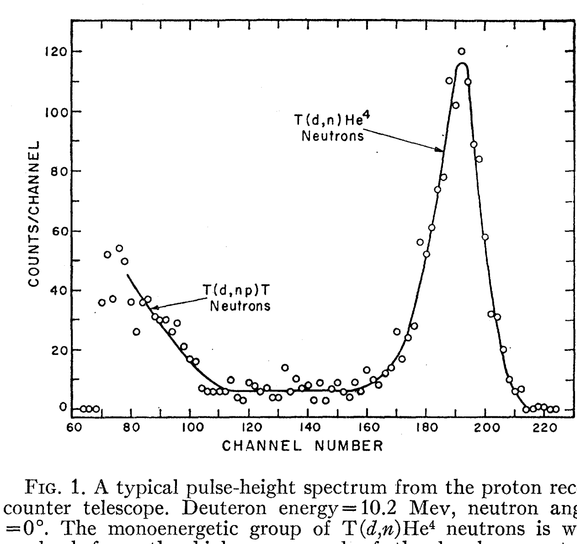

FIG. 1. A typical pulse-height spectrum from the proton recoil counter telescope. Deuteron energy = 10.2 Mev, neutron angle = 0°. The monoenergetic group of T(d,n)He^4 neutrons is well resolved from the high-energy end of the breakup neutron spectrum.

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and was reproducible over long periods of time to better than 0.5°.

The proton recoil counter telescope used to detect the neutrons has been described in a report on a similar experiment to measure the D(d,n)He^3 neutrons.[8] A typical pulse-height spectrum from the telescope, as viewed with a 256-channel pulse-height analyzer, is shown in Fig. 1. The deuteron energy is 10.2 Mev and the counter is at 0° with respect to the incident beam.

The neutron production was monitored by collecting the charge received by the gas target, which was insulated from the beampipe. In addition, an auxiliary monitor was provided by a single plastic scintillator fixed at about 15° to the deuteron beam direction and sufficiently highly biased that only the direct T(d,n)He^4 neutrons could be counted.

The incident deuteron beam energy was determined by a differential range measurement,[8] and the uncertainty in the beam energy was about $\pm 2\%$.

RESULTS

The measured angular yield curves for the T(d,n)He^4 neutrons for incident laboratory deuteron energies of 6.2, 7.9, 9.1, 10.2, and 11.4 Mev are plotted in Figs. 2–6. The open circles are the present data, shown in the center-of-mass system. The filled-in circles were extracted from the back-angle data of Stewart *et al.*,[5] by considering the variation of the cross section at each angle with their deuteron energies and picking out the values at that angle corresponding to our deuteron energies. These absolute data points were then normalized to the present experimental data at 120°.

The angular resolution, as determined by the target size, proton radiator size, and the target-to-radiator spacing, was about 2° at 0° and about 5° at 90° in the laboratory. The position of 0° was determined by taking data from about −6° through 0° to positive angles and

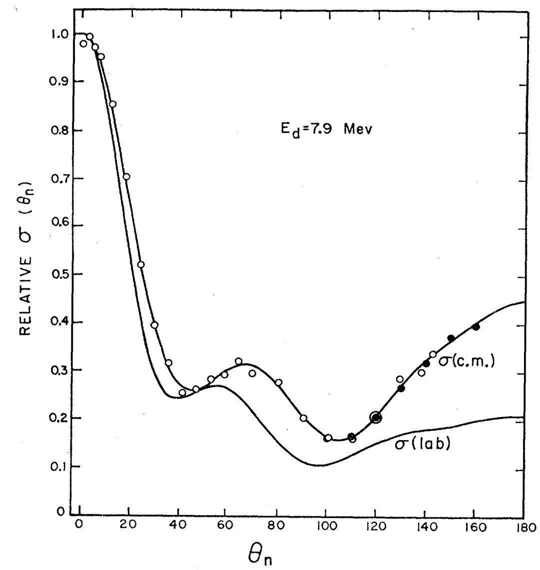

FIG. 3. Laboratory and center-of-mass angular yield curves for the T(d,n)He^4 reaction for 7.9-Mev incident deuterons. The open circles are the present data. The filled-in circles are from Stewart *et al.*[5]

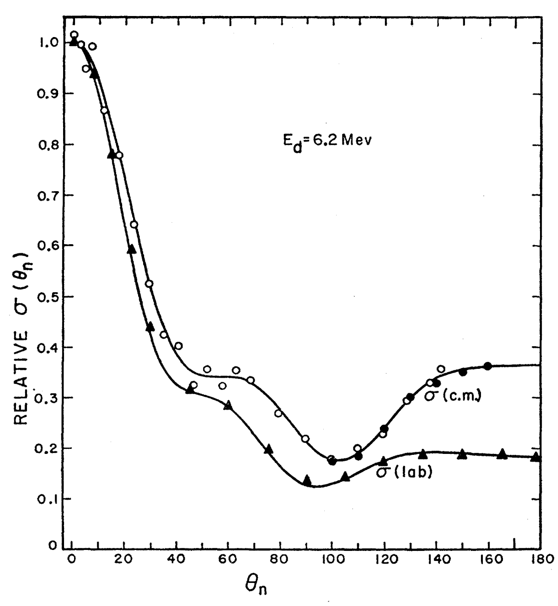

FIG. 2. Laboratory and center-of-mass angular yield curves for the T(d,n)He^4 reaction for 6.2-Mev incident deuterons. The open circles are the present data. The filled-in circles are from Stewart *et al.*[5] The triangles are from the data of Bame and Perry[3] at 6.0 Mev.

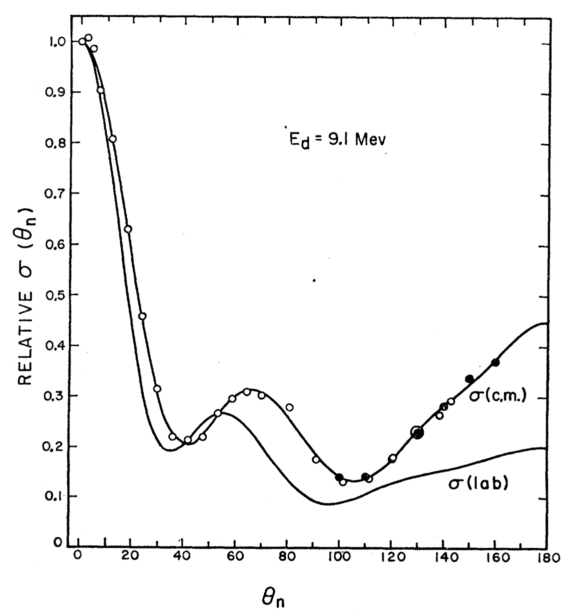

FIG. 4. Laboratory and center-of-mass angular yield curves for the T(d,n)He^4 reaction for 9.1-Mev incident deuterons. The open circles are the present data. The filled-in circles are from Stewart *et al.*[5]

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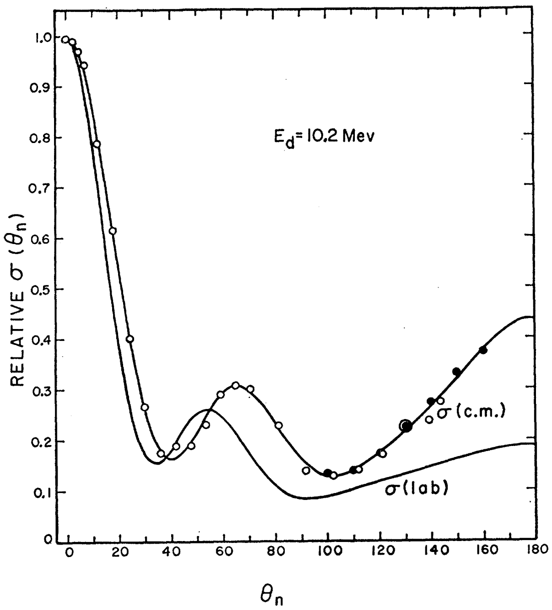

FIG. 5. Laboratory and center-of-mass angular yield curves for the $T(d,n)He^4$ reaction for 10.2-Mev incident deuterons. The open circles are the present data. The filled-in circles are from Stewart *et al.*[5]

calling the peak position of the yield curve the true 0° position. The shape of the forward peak allowed a determination of true 0° to within about ±1°. The statistical uncertainty in the values ranges from about 2% at 0° to about 6% at angles near the minimum of the angular yield curves.

The curves through the experimental center-of-mass points in Figs. 2–6 represent a least-squares fitting of the data by a sum of Legendre polynomials, i.e., $\sigma(\theta)=\sum_n a_n P_n(\cos\theta)$. Polynomials to order $n=8$ were used, providing nine parameters to fit the observed data. The variation of the Legendre coefficients with incident deuteron energy, plotted in Fig. 7, provides a means of constructing angular yield curves for any energy through the range covered. The coefficients are listed in Table I along with the integrated total cross sections, which were calculated using the absolute cross sections discussed below.

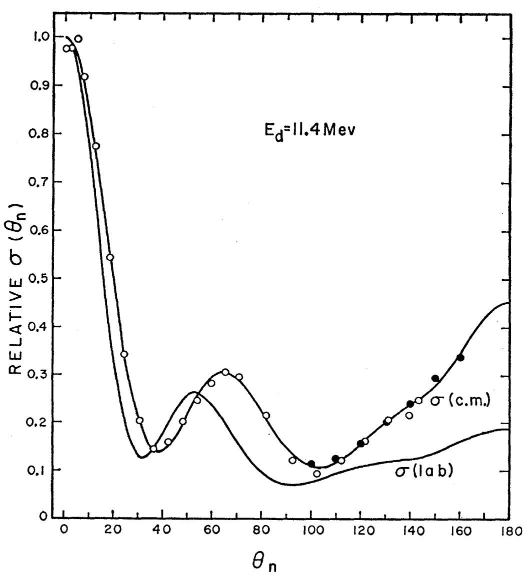

FIG. 6. Laboratory and center-of-mass angular yield curves for the $T(d,n)He^4$ reaction for 11.4-Mev incident deuterons. The open circles are the present data. The filled-in circles are from Stewart *et al.*[5]

The angular yield curves in the laboratory system, also plotted in Figs. 2–6, are easily obtained by conversion of the least-squares center-of-mass curves. Due to doubtful validity of the least-squares fitting procedure outside the range of the data, the values for angles greater than about 155° (corresponding to about 160° in the center-of-mass system) may be incorrect. The points tabulated by Bame and Perry[3] for an incident deuteron energy of 6.0 Mev are plotted (filled-in triangles) on the 6.2-Mev laboratory curve (Fig. 2) for purposes of comparison. The agreement is seen to be excellent and does corroborate the least-squares data at this energy beyond 155°.

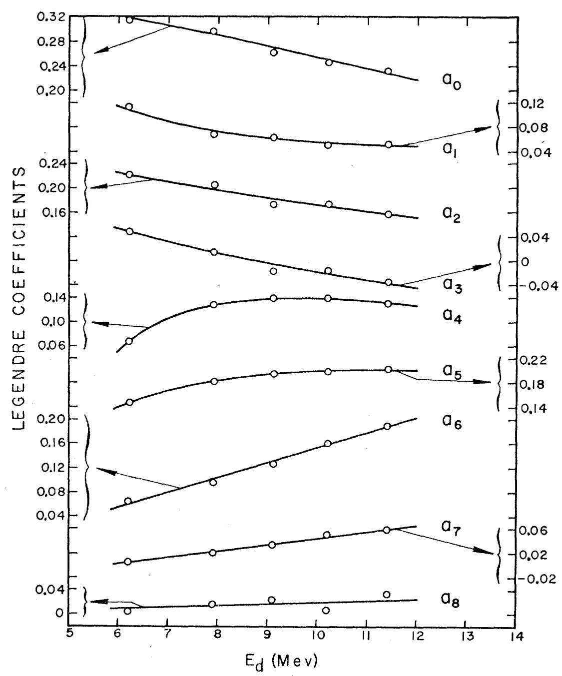

FIG. 7. Variation of Legendre coefficients with incident deuteron energy.

DISCUSSION

Since the purity of the tritium gas was unknown, absolute cross sections could not be measured. However, it was possible to make a quasi-absolute measurement of the 0° cross section as a function of deuteron energy, in which all conditions for an absolute measurement were met except for the unknown scale factor due to the number of tritium atoms present. To do this, the target gas pressure must be maintained constant, the accumulated charge on the target must be known, the variation of the efficiency of the recoil telescope with energy must be known, and the effects due to heating of the target gas by the passage of the deuteron beam must be measured. The gas pressure was monitored at frequent intervals and the charge accumulated by the gas target was integrated by standard means. The telescope efficiency, when the same hydrogenous radiator is used at all energies, depends on energy only through the variation of the *n-p* cross section with energy, and this is well known. The effects of beam heating were measured by running at several beam levels between 1 and 5 μa and extrapolating to zero beam level. The quasi-absolute measurement was done for incident deuteron energies of 6.4, 8.5, 10.4, and 11.0 Mev, to an estimated accuracy of about ±15%. Using

TABLE I. Legendre coefficients resulting from fitting angular yield curves with a sum of Legendre polynomials. Total cross sections (in millibarns) are from integration of the Legendre sum, using Fig. 8 to obtain absolute angular distributions.

	E_d(Mev)				
	6.2	7.9	9.1	10.2	11.4
a_0	0.314	0.295	0.261	0.245	0.231
a_1	0.113	0.067	0.062	0.049	0.052
a_2	0.221	0.205	0.173	0.172	0.158
a_3	0.048	0.013	−0.017	−0.016	−0.034
a_4	0.068	0.127	0.139	0.139	0.130
a_5	0.147	0.182	0.196	0.198	0.203
a_6	0.064	0.096	0.127	0.161	0.190
a_7	0.005	0.020	0.034	0.051	0.059
a_8	0.004	0.017	0.025	0.007	0.034
σ_T	73	63	53	47	41

the variation of the absolute 0° cross section with deuteron energy up to 7 Mev of Bame and Perry,[3] the 6.4-Mev point can be used to provide the scale factor for the other three points. These points are plotted in Fig. 8, along with the data of Bame and Perry between 4 and 7 Mev and the 10.5-Mev point of Brolley *et al.*[4]

The back-angle measurements of Stewart *et al.*,[5] of the $T(d,n)He^4$ neutrons are given absolutely and can be used to absolutely normalize the yield curves reported here. The resulting values of the cross section at 0° are also plotted in Fig. 8. An error of about ±10% is estimated for these points. Also plotted are the absolute 0° cross sections of Stewart *et al.*,[5] resulting from an extrapolation of their Legendre polynomial fits to the $He^3(d,p)He^4$ reaction to 0°.

The absolute 0° curve in Fig. 8 was used to normalize the angular yield curves in order to obtain the integrated total cross sections tabulated in Table I.

A composite of the angular yield curves in the center-of-mass system for both the $T(d,n)He^4$ neutrons and the $He^3(d,p)He^4$ protons at identical incident deuteron energies is shown in Fig. 9. The $He^3(d,p)He^4$

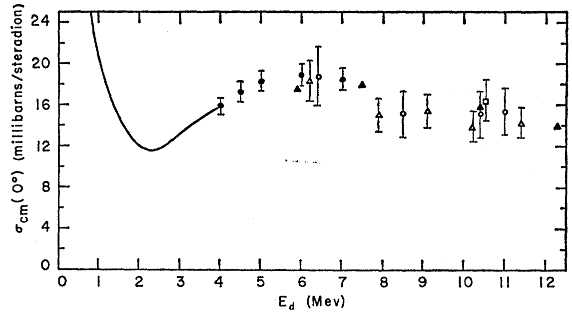

FIG. 8. The absolute 0° center-of-mass differential cross section. The line at low energies and the filled-in circles are from the data of Bame and Perry.[3] The open circles are the quasi-absolute data points, normalized at 6.4 Mev to the Bame and Perry data. The open triangles are the 0° values when the present yield curves (Figs. 2–6) are normalized to the absolute back-angle data of Stewart *et al.*[5] The square is from the data of Brolley *et al.*[4] The filled-in triangles are the values when the Legendre fits to the $He^3(d,p)He^4$ data of Stewart *et al.*, are extrapolated to 0°.

curves were obtained by plotting the variation of the Legendre coefficients of Stewart *et al.*[5] with energy and constructing angular yield curves using the coefficients corresponding to deuteron energies used in the experiment reported here.

As can be seen from Fig. 9, the two reactions have very similar features. Both show strong forward peaking, a minimum at about 40°, a maximum at about 65° which becomes more pronounced with in-

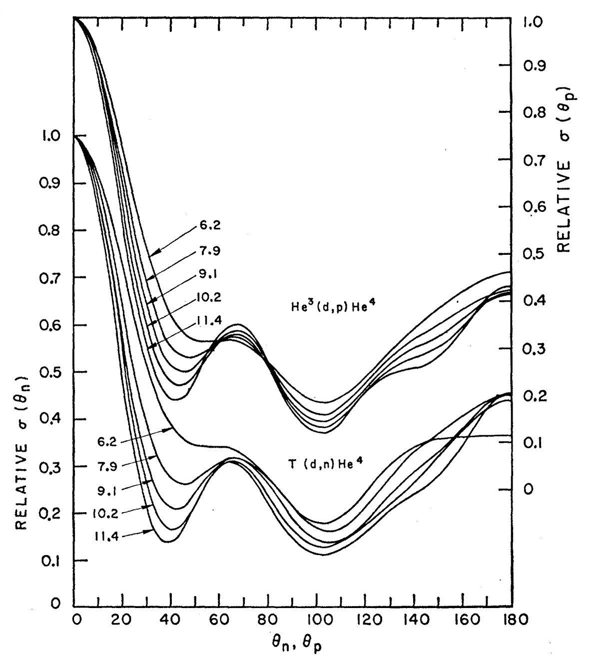

FIG. 9. Composite to show the similarities in the features of the $T(d,n)He^4$ angular yield curves and those from the companion $He^3(d,p)He^4$ reaction. The $T(d,n)He^4$ curves are the present data. The $He^3(d,p)He^4$ curves were constructed from the values of the Legendre coefficients of Stewart *et al.*[5] at energies corresponding to those of the present experiment.

creasing energy, a minimum at about 100°, and a back-angle rise. Figure 8 indicates that the absolute cross sections are also the same. This coincidence of the two cross sections for these companion reactions may be considered as a demonstration of the charge symmetry of nuclear forces.[5]

The analysis by Butler and Symonds[6] of the older 10-Mev data on these reactions[4,7] indicates that a simple stripping model can account for the shape of the distributions from the forward peak through the second minimum. Their calculation, however, cannot account for the back-angle rise. An attempt to account for this rise by considering stripping of the triton, using the exchange stripping model of Owen and Madansky,[9,8] led to the conclusion that a triton stripping amplitude that would account for the back-angle rise was inadequate to account for the magnitude of the second maximum. A triton amplitude sufficiently large to give rise to an interference term sufficiently large to account for the second maximum would indicate a cross section at 180° an order of magnitude or more higher than that observed experimentally. This would indicate that distorting effects not considered in a simple stripping model must be accounted for. Therefore, a distorted-wave stripping calculation, using an exchange wave function for the final-state neutrons, would seem to be required to fully describe the observed angular distributions for these reactions.

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14.4-Mev $(n,2n)$ Cross Sections*

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Cross sections for the $(n,2n)$ reaction have been measured at an incident neutron energy of 14.4±0.3 Mev for 27 nuclides. These measurements were made relative to the cross section for the $Cu^{63}(n,2n)Cu^{62}$ reaction. The relative cross sections were then converted to absolute cross sections by using the weighted mean of several $Cu^{63}(n,2n)Cu^{62}$ reaction-cross-section measurements made by other investigators.

INTRODUCTION

MANY $(n,2n)$ cross sections have been measured at incident neutron energies near 14 Mev,[1–12] because of the ease with which neutrons having this energy can be produced by use of low-voltage accelerators and the $H^3(d,n)He^4$ reaction. Other investigators[13–17] have measured the variation of the cross section for the $(n,2n)$ reaction as a function of neutron energy from near threshold to 18 to 20 Mev. Most of these measurements have been characterized by rather large standard deviations for the measured cross sections because of the experimental difficulties encountered. The present method eliminates some of these difficulties so that in general the standard deviations of the measured cross sections are somewhat less than those of most previously reported $(n,2n)$ cross-section measurements.

The compound nucleus model[18] has frequently been used in the theoretical evaluation of $(n,2n)$ cross

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