PHYSICAL REVIEW VOLUME 82, NUMBER 4 MAY 15, 1951

The Angular Distribution of the Products of the $T(d,n)He^4$ Reaction*

J. E. Brolley, Jr., J. L. Fowler,† and E. J. Stovall, Jr.
University of California, Los Alamos Scientific Laboratory, Los Alamos, New Mexico

(Received January 18, 1951)

The differential cross section of the reaction $T(d,n)He^4$ for 10.5-Mev deuterons has been measured from 180° to 33° center-of-mass angle of the alpha-particle. Both neutrons and alpha-particles were counted. The angular distribution is similar to that of the mirror reaction, $He^3(d,p)He^4$.

I. INTRODUCTION

A very useful source of monoenergetic neutrons of high energy is furnished by the $T(d,n)He^4$ reaction.[1] The differential cross section of the mirror reaction, $He^3(d,p)He^4$, has been measured[2] at 10.2 Mev. The present investigation gives the cross section of the $T(d,n)He^4$ reaction using 10.5-Mev deuterons. It is of theoretical interest to compare the absolute differential cross sections of these two reactions. The $T(d,n)He^4$ reaction was studied from 33° to 94° in the center-of-mass system by counting alpha-particles; from 94° to 180° in the center-of-mass system by counting neutrons.

II. EXPERIMENT AND RESULTS

The deuterons were accelerated by the 42-in. cyclotron and brought to a focus outside of the water tank shield 15 feet from the cyclotron exit port.[3] The energy of the deuterons was measured several times during the course of this experiment by taking aluminum absorption curves and was found to be 10.94 Mev with a maximum spread of 0.10 Mev. Allowing for absolute errors in this determination, as well as for drift of energy between the measurements, one takes the energy to be 10.9 ± 0.3 Mev. This agreed with the energy measurement found by magnetic deflection,[3] which at the beginning of the experiments on tritium gave an energy of 11.0 ± 0.2 Mev.

The part of the experiment designed to count alpha-particles was carried out with apparatus similar to that described previously.[4] The deuteron beam entered a gas cell mounted in the center of the 58-cm diameter reaction chamber. The beam was delimited to a diameter of 0.47 cm, with an angular divergence of $\pm0.5°$ by a circular gold aperture; thence it impinged upon a thin aluminum window at the front of the target cell. The alpha-particles produced in the target cell emerged through an aluminum side window (3.4 mg/cm^2), 6.3 cm long and 1.5 cm wide. The alpha-particles were detected by a proportional counter which could be rotated to any angle in the horizontal plane. The reaction volume was defined by a 0.318-cm vertical slit mounted on the proportional counter support and located 10.8 cm from a 0.318-cm diameter hole immediately in front of the proportional counter. After passing through the gas, the deuteron beam was stopped by a gold disk soldered to the back of the gas cell. The gas cell was insulated from ground so that it could be used as a faraday cage for monitoring the beam current. In order to prevent secondary electrons from the front aluminum window from introducing an error in the current measurement a brass sleeve extending 4.5 cm beyond the window was fastened to the gas cell at the entrance end, and permanent bar magnets were fastened on either side of the gas cell.

The calibration of the apparatus, including the current measurement, was checked by measuring the differential cross section of *d-d* scattering at 45° and comparing with the value reported previously.[4] This measurement gave the differential cross section within one percent of the previous value.

The tritium gas was handled by absorbing it in uranium contained in a small stainless steel vessel. When it was desired to fill the gas cell, the tritium was evolved from the uranium by heating, and the valve to the stainless steel vessel was closed. To empty the gas cell this valve was opened and the tritium was reabsorbed rapidly. The pressure of tritium in the target cell was measured by using a Bourdon-type gauge as a null indicator. A small weight pan was attached to the sensitive element of the gauge; and, with the pressure of tritium in the system, weights were added to the pan until the indicator of the gauge reached a position it would have had if there had been a vacuum in the system. After calibration of the gauge one could determine the pressure of tritium gas to about one percent. The hydrogen impurity of the tritium sample was checked by counting scattered deuterons from the hydrogen and recoil protons at an angle of 25°. This number was compared with the recoil protons from deuterons impinging upon a sample of high purity hydrogen. The gas analysis determined in this way, which was reproducible to 1.5 percent, agreed with the analysis of the gas furnished with the samples used to the accuracy of the latter measurement which was ±3 percent.

To detect the alpha-particles with the proportional counter at various angles to the deuteron beam, the

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* Work done under the auspices of the AEC.

† Now at Oak Ridge National Laboratory, Oak Ridge, Tennessee.

[1] Hanson, Taschek, and Williams, Revs. Modern Phys. **21**, 635 (1949).

[2] J. C. Allred, Phys. Rev. **77**, 753 (1950).

[3] Curtis, Fowler, and Rosen, Rev. Sci. Instr. **20**, 388 (1949).

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

pressure in the counter was adjusted so that the track of the alpha-particle calculated from range-energy curves ended inside the back edge of the counter. The amplified pulses from the counter were analyzed by means of a ten-channel discriminator. Figure 1 gives a sample alpha-peak obtained together with the background. The abscissa is the amplified pulse height and the ordinate is the number of pulses per 5-volt interval. For determining backgrounds aluminum foils were placed in front of the counter to stop the alpha-particle before it entered the counter. This was accomplished by a selsyn-controlled foil shutter mounted in front of the proportional counter with which a hundred combinations of absorber could be selected. Background determined in this way was found to be the same as background obtained by replacing the tritium in the target cell with hydrogen. The triangles in Fig. 1 show the background obtained with the aluminum absorber. The alpha-peak was well resolved for the laboratory angles at which data are recorded here.

In Fig. 2 the points indicated by the circles give the results of the alpha-particle measurement when converted to the center-of-mass system. The open circles give the results when the entrance window of the tritium cell was 3.4-mg/cm^2 aluminum foil. In this case the deuteron energy where the detected alpha-particles are produced is reduced from 10.9±0.3 to 10.7±0.3 Mev. The solid circles give the results when a 6.8-mg/cm^2 aluminum foil is used as an entrance window. In this case the deuteron energy was 10.5±0.3 Mev. To examine the effect of scattering of the alpha-particles by the 3.4-mg/cm^2 side window of the gas cell, runs were made in which a second 3.4-mg/cm^2 foil was fastened adjacent to the side window. The increasing of this window thickness by a factor of two had no appreciable effect on the measurement of the differential cross section within 2 percent.

The random error of the data taken by counting alpha-particles, that is, the measurements over the center-of-mass angular region from 33° to 94°, amounts to about 1.5 percent as deduced from the reproducibility of the data. Other sources of error occuring in the absolute current measurements, geometrical factors, tritium pressure, and gas analysis increase the absolute error of this section of the curve to about 3.5 percent.

To extend the measurements from 94° to 180° center-of-mass angle of the alpha-particle, neutrons were counted in the laboratory system from 0° to 74.5°. In this part of the experiment the scattering chamber was removed and the target cell was replaced by a simple thin-walled gas cell fastened at the end of the tube through which the deuteron beam passes. A fourfold coincidence proton recoil telescope was employed to measure the neutrons at various angles. The description of the equipment and the alignment procedure, together with the procedure used in taking data, are given in a paper[5] on n-p scattering at 27 Mev.

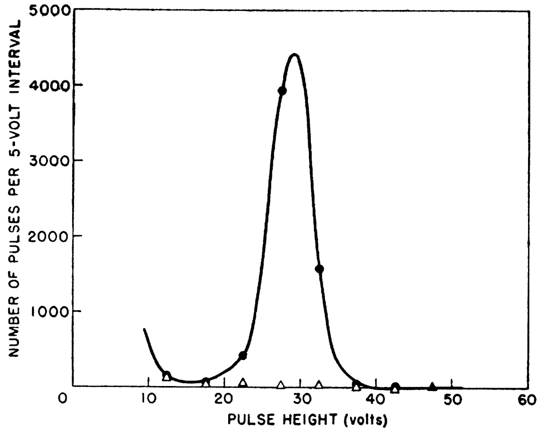

FIG. 1. Distribution of pulses from the proportional counter due to alpha-particles produced by the T(d,n)He^4 reaction at 25° to the direction of the deuteron beam plus background. Points designated by triangles give background.

For counting the absolute number of neutrons in this experiment it was necessary to find the efficiency of the counter telescope. This was done in three ways. First, a run was made using the 14-Mev d-t neutrons from the Los Alamos Cockcroft-Walton accelerator, from which the neutron flux is approximately known. The second method used the cyclotron d-t neutron flux associated with the angular region in which the detection of alpha-particles makes possible the determination of the differential cross section as described above. In

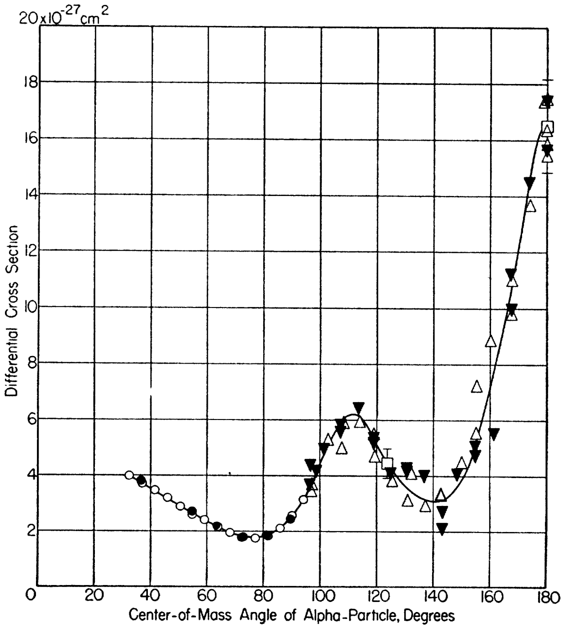

FIG. 2. The differential cross section of the T(d,n)He^4 reaction in the center-of-mass system. Circles represent data obtained by counting alpha-particles with a proportional counter. Squares give results of neutron counting with a proton recoil telescope counter. Triangles give the results of counting neutrons by means of the Cu$^{63}(n,2n)$Cu^{62} reaction. Solid symbols give the results for a deuteron bombarding energy of 10.5 Mev.

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[5] Brolley, Coon, and Fowler, Phys. Rev. 82, 190 (1951).

TABLE I. Proton recoil counter efficiency at 20.75 Mev in quadruple coincidences/sec/unit neutron flux.

With Cockcroft-Walton *d-t* neutron source	4.1×10^{-6}
With cyclotron *d-t* neutron source	4.7×10^{-6}
Calculated from geometry and *n-p* scattering cross section	4.4×10^{-6}
Average	$4.4\pm0.2\times10^{-6}$

order to use these efficiency determinations for detecting neutrons at energies different from the energy used for the calibration, one must know the ratio of the *n-p* scattering cross section in the forward direction at any energy to the cross section at the experimentally determined points. This quantity was estimated by a plot of the experimental values of the differential cross section at zero degrees taken from the literature.[5–7] For neutrons below 14 Mev, the differential cross section in the center-of-mass system was obtained by dividing the total cross section[7] by 4π. The third method of finding the counter efficiency was a calculation from the geometry of the apparatus, the known weight of the polyethylene radiator, and the absolute *n-p* scattering cross section. Table I gives the results of these different efficiency estimates when they are extrapolated to a neutron energy of 20.75 Mev.

In Fig. 2 the points designated by squares give the results of the neutron measurements at two angles as determined with the counter telescope. The estimated standard error of this absolute neutron cross section amounts to about 11 percent and is the root mean square of the standard errors in the efficiency determination (including the uncertainty due to extrapolating efficiencies to different energies), statistics of counting, deuteron current measurements, tritium gas pressure and tritium gas analysis, etc.

The points designated by triangles are the results of an extrapolation between the measured values of neutron yield by use of the $Cu^{63}(n,2n)Cu^{62}$ reaction. In this measurement one determined the product of the $Cu(n,2n)$ cross section and the differential cross section of the *d-t* reaction as a function of angle. This was done by irradiating Cu foils at various angles to the deuteron beam about one foot away from the center of the tritium cell and counting the 10-min period of the Cu^{62} isotope produced.[8] Background effects were evaluated by making runs with the tritium replaced by hydrogen. As in the case of reference 8, the Geiger counters were calibrated by use of the beta-particles from Cu^{66} produced by thermal neutrons on Cu^{65}. The $Cu(n,2n)$ cross section itself varies with angle because the energy of the neutrons varies with angle. However, the value of this cross section is determined at the angles at which the independent neutron measurement is made by use of the counter telescope or by detecting alpha-particles. Thus, a curve of the $Cu(n,2n)$ cross section as a function of energy can be drawn in this energy region. Since the $(n,2n)$ cross section does not change rapidly in this region, one can use a smooth curve through the points to estimate the value at intermediate energies. The points represented by diamonds, then, give the experimental values of the *d-t* differential cross section determined by this method and converted to the center-of-mass system.

TABLE II. Comparison of the $T(d,n)He^4$ reaction at 10.5 Mev with the $He^3(d,p)He^4$ reaction at 10.2 Mev.

	$T(d,n)He^4$		$He^3(d,p)He^4$	
Type point	Angle (CM)	$\sigma(cm^2)\times10^{27}$	Angle (CM)	$\sigma(cm^2)\times10^{27}$
Min	77°	1.76 ± 0.06	77°	1.96 ± 0.09
Max	112°	6.20 ± 0.93	115°	4.95 ± 0.23
Min	141°	3.07 ± 0.46	135°	2.90 ± 0.14

In order to obtain reasonable counting rates, as well as to make the backgrounds small relative to the real counts, considerably higher pressure of tritium gas was used for the neutron detection experiments than was necessary for counting the alpha-particles produced by the $T(d,n)He^4$ reaction. To hold this increased pressure a 13.7-mg/cm² aluminum entrance window was necessary in front of the target cell; and this, together with the increased stopping power of the tritium gas, reduced the average bombarding deuteron energy from 11.0 ± 0.3 to 9.8 ± 0.3 Mev. This condition prevailed for the case of the points marked by squares and open triangles.

The points marked by closed triangles are the results of Cu activation runs taken when the tritium gas cell had a one-mil front window, so that the average energy of the deuterons in the cell was 10.4 Mev. In these runs the relative values of the cross section were determined and the curve through the points was normalized to the alpha-data in the region of 97° in the center-of-mass system. First-order corrections (<6 percent) have been applied to that part of the curve in Fig. 2 found by counting neutrons by Cu activation to account for the angular resolution of the detectors. Also, for this part of the curve the data have been corrected for inelastic scattering of the neutrons by the walls of the target cell (<7 percent). It is apparent that these data lie within the spread of the activation data taken at 9.8 Mev and that within the accuracy of these measurements the *d-t* cross section does not change appreciably in this energy region when the energy of the deuteron is changed by 6 percent.

III. CONCLUSIONS

The composite curve through the solid points in Fig. 2 gives the differential *d-t* cross section for a bombarding energy of 10.5 ± 0.3 Mev. Since the curve in Fig. 2 has only to be extrapolated through a relatively small angle to zero degrees, it can be integrated over all solid angles to give the total cross section of the $T(d,n)He^4$

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[6] Hadley, Kelly, Leith, Segrè, Weigand, and York, Phys. Rev. **75**, 351 (1949).

[7] R. K. Adair, Revs. Modern Phys. **22**, 249 (1950).

[8] J. L. Fowler and J. M. Slye, Jr., Phys. Rev. **77**, 787 (1950).

reaction at 10.5 Mev. This gives a value for the total cross section at this energy of 48 ± 6 millibarns. Table II gives a comparison of the maximum and minimum of the absolute value together with the position of the maximum and minimum of the differential cross-section curve for the $\mathrm{T}(d,n)\mathrm{He}^4$ reaction and the mirror reaction, $\mathrm{He}^3(d,p)\mathrm{He}^4$.[2,9] It is apparent that these reactions are closely similar at this bombarding energy, where the effects of coulomb forces are small compared with purely nuclear forces. Since the intermediate nuclei formed by these two reactions differ from each other in that a neutron is substituted for a proton, this comparison suggests the approximate identity of the neutron and proton insofar as purely nuclear forces are concerned at these energies.

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[9] J. C. Allred, LA-981 (unpublished).

PHYSICAL REVIEW VOLUME 82, NUMBER 4 MAY 15, 1951

The Gamma-Ray Yield of Phosphorus Bombarded with Protons*

G. R. Grove† and John N. Cooper
Department of Physics, Ohio State University, Columbus, Ohio

(Received January 15, 1951)

Protons from a van de graaff generator have been used to bombard P^{31}, and the reaction $\mathrm{P}^{31}(p,\gamma)\mathrm{S}^{32}$ has been studied. The gamma-ray yield has been measured, as a function of proton energy, in the region between 400 and 1700 kev. Maxima in the gamma-ray yield occur at proton energies of 440, 550, 650, 817, 890, 1067, 1100, 1129, 1162, 1265, 1421, 1458, 1495, 1538, 1583, and 1610 kev. Absorption measurements of the gamma-rays from the strongest resonance, that at 1265 kev, indicate a quantum energy of 12 Mev, which is consistent with the assumption that the compound nucleus decays to the ground state by a single transition.

I. INTRODUCTION

THE gamma-rays induced by proton bombardment of phosphorus were first observed by Curran and Strothers,[1] who reported maxima of a thick target excitation curve at proton energies of 460, 580, 700, and 950 kev. They measured the energy of the gamma-rays and concluded that the radiation must be associated chiefly with the reaction

$$\mathrm{H}^1+\mathrm{P}^{31}\rightarrow\mathrm{S}^{32*}\rightarrow\mathrm{S}^{32}+h\nu,$$

which has a Q-value of approximately 10.7 Mev. In studying this same reaction, Hole, Holtsmark, and Tangen[2] found three sharp resonances situated at 347, 433, and 530 kev. More recently, Tangen[3] has reexamined these resonances, which he reported at proton energies of 355, 440, and 540 kev. Thick targets were used in these investigations of the proton-capture process in phosphorus, and proton energies above one Mev were not available.

Some work with thin phosphorus targets and proton energies above one Mev was done by Herb[4] and his collaborators, who elected to discontinue this study in favor of other problems. The present authors have made careful runs over the levels studied at Wisconsin and have discovered several new levels. Both thick and thin targets have been bombarded with protons of energies between 400 and 1700 kev, and the gamma-resonances have been studied. Preliminary results of measurements on phosphorus were reported earlier.[5]

In addition to the reaction under consideration, the bombardment of phosphorus with protons may lead to the reaction

$$\mathrm{H}^1+\mathrm{P}^{31}\rightarrow\mathrm{S}^{32*}\rightarrow\mathrm{Si}^{28}+\mathrm{He}^4,$$

which has a Q-value of approximately 1.8 Mev. The alpha-particles from this reaction have not been observed as yet.

II. EXPERIMENTAL PROCEDURE

The electrostatic generator at the Ohio State University was used as the source of bombarding protons. The voltage stability of the generator depends on corona drain to grounded needle points above the high voltage cap. With large drains the cap voltage is held constant to about $\frac{1}{4}$ percent with respect to rapid fluctuations.

An analyzing magnet located at the grounded end of the accelerating tube separates ions of the desired e/m and energy value from the several types of particles which come down the tube. A variable slit located in the path of the bombarding beam allows protons of

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* Assisted by the joint program of the ONR and AEC through a contract with The Ohio State University Research Foundation.

† AEC Predoctoral Fellow; now at the National Bureau of Standards.

[1] S. C. Curran and J. E. Strothers, Proc. Roy. Soc. (London) **A172**, 72 (1939).

[2] Hole, Holtsmark, and Tangen, Naturwiss. **28**, 668 (1940).

[3] R. Tangen, Kgl. Norske Videnskab. Selskabs Skrifter (1946), NR 1.

[4] R. G. Herb, private communication. The authors are deeply grateful to Professor Herb for suggestions and, especially, for making available the complete results of the preliminary work at Wisconsin.

[5] Grove, Cooper, and Harris, Phys. Rev. **80**, 107 and 131 (1950).