results are shown in Fig. 1 and do not drastically depend upon the change of the D-state probability P_D. In other words, the isotropic part of the cross section is still insufficient even if P_D were as large as 8 percent. Thus we may conclude that the possibility (a) is not satisfactory by itself.

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Reaction D$(t,\alpha)n$ at 1.5 Mev*†

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The differential cross section for the reaction D$(t,\alpha)n$ has been measured at 10° intervals from 10° to 140° in the laboratory system for a triton energy of 1.5 Mev. The total cross section is 280±8 mb.

INTRODUCTION

THE D-T reaction has been used so extensively as a source of monoergic neutrons[1] that the knowledge of precise values of differential cross sections has become a practical problem. For this reason and also because of general theoretical interest in the reaction constants of light elements a study of the reaction was undertaken at this laboratory, the results of which, at one energy, are here reported.

A beam of 2-Mev HT^+ ions from the new Los Alamos 2.5-megavolt electrostatic accelerator traversed a deuterium-filled scattering chamber. The HT^+ beam was more suitable than T^+ because the relatively great admixture of HHH^+ ions in the ion beam would have melted the entrance foil at much lower triton currents. The obvious problems associated with the acceleration of tritons and collection of tritium at the forevacuum will be discussed elsewhere and it need only be stated that it is a routine operation to accelerate tritons in this machine. There are distinct advantages in accelerating the triton rather than the deuteron: The target gas is not so costly that it cannot be discarded when it becomes contaminated; if a beam window into the target breaks, the gas lost need not be recovered; the inside of the chamber does not become so radioactive as to make it hazardous to handle; and small leaks of target gas into a counter do not produce counter background.

EXPERIMENTAL PROCEDURE

The scattering chamber, 14 inches in diameter and 4 inches high, was provided with two proportional counters for the observation of the alpha particles from D(t,α); one was fixed at $-15°$ and the other could be rotated about the chamber center. Details of the chamber appear elsewhere,[2] but the geometry used in this experiment is shown schematically in Fig. 1.

Entrance Window

The ion beam entered the scattering chamber through a thin Pyrex foil. The thickness of this foil was measured by removing the exit foil, inserting in the Faraday cage a thick Zr-T target, and measuring the threshold voltage for the reaction T(p,n). Deuterium gas at a pressure of 0.5 mm Hg was kept in the chamber to cool the entrance window and the energy loss in the gas was computed. The thickness t measured in this way is the energy loss of a proton which has an energy of 1.019 Mev after traversing the foil; usual values were between 8 and 30 kev. The entrance foil was thin enough that only a few percent of the beam was lost due to scattering. The glass foil appears to be uniquely suitable for this experiment[3]; counting rates would have been prohibitively small with any of the usual metal foils.

The energy loss for 1.5-Mev tritons in the entrance foil was found by assuming Pyrex (Corning No. 774) to have an energy loss nearly the same as Al and

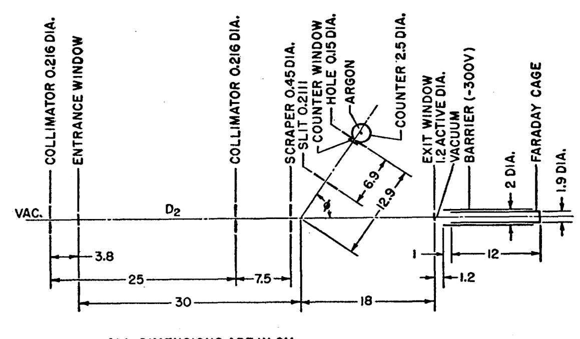

FIG. 1. Schematic diagram showing essential details of apertures.

* Work performed under the auspices of the U. S. Atomic Energy Commission.

† A preliminary report on this work was given by H. V. Argo and A. Hemmendinger, Phys. Rev. **96**, 851 (1954).

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

[2] M. E. Ennis and A. Hemmendinger, Phys. Rev. **95**, 772 (1954).

[3] Some notes on the preparation and use of these foils will appear in the Review of Scientific Instruments.

referring to the stopping power curves of Allison and Warshaw.[4] From these data we find that the value of dE/dx for 0.5-Mev protons is 240 kev cm^2 mg^{-1} and for 1-Mev protons it is 183 kev cm^2 mg^{-1}. Inasmuch as the value of dE/dx is the same for 0.5-Mev protons and 1.5-Mev tritons, we find the window thickness for tritons to be $240t/183$. Even if the assumption concerning the similarity of Pyrex and Al is off by 50 percent, the error in the ratio will not be excessive. The triton beam energy was adjusted to exceed 1.5 Mev by the sum of the losses in the entrance window and deuterium path to the chamber center.

Exit Window

With a beam of 2-Mev HT^+ ions incident on the entrance foil, there emerged from this foil 0.5-Mev H^+ and 1.5-Mev T^+ ions. The H^+ beam had a greater divergence due to multiple scattering. Collimation of this beam by the second defining aperture increased the T^+ to H^+ ratio, so the only way to measure the T^+ ion current in a Faraday cage was first to stop all of the H^+. This separation was accomplished by using an exit window of 0.35-mil Al.

Faraday Cage

The Faraday cage was isolated from space electron currents by a cylindrical barrier electrode surrounding the cage and overhanging for 1 cm at the front end. The barrier electrode potential was -300 volts. The cage remained close to ground potential. At first some of the triton current fell on the barrier, but the solid angle subtended by the cage was increased until the current to the barrier vanished. Furthermore, we used the method outlined by Dickinson and Dodder[5] for evaluation of particle loss due to multiple scattering in foils to compute the error in current collection. We found the rms scattering angle to be 3.5°. Assuming that the beam is uniformly distributed over the exit foil, the particle loss is 0.08 percent. Actually the beam is concentrated near the center of this foil so the particle loss will be even smaller.

Proportional Counters

The angular distribution of the alpha particles was measured at 10° intervals from 10° to 140° for a fixed number of alpha counts in the monitor. In the relative distribution this eliminated errors due to changes in target pressure, temperature, composition, and current integrator calibration. Although the alpha pulses in the monitor were much larger than those due to scattering, counting rates due to scattering were so high as to cause pileup. For this reason the monitor counter window was made of 0.65-mil Al, which was thick enough to stop all of the scattered particles. There were similar effects in the movable counter at small angles, but the solid angle subtended by the movable counter was smaller than that subtended by the monitor, and with a window of 0.25-mil Al, alpha counts were well resolved from scattered particle counts for angles up to 40°. For angles greater than 40° the window was 0.05-mil Ni, except at the largest angle of 140°; here the alpha counting rate was less than that due to neutron recoils. This situation was improved by using a glass counter window about half as thick as the 0.05-mil Ni, and this foil could have been used for all angles greater than 30°. At every angle the background, measured by moving a magnetic shutter over the counter slit, was subtracted from the observed alpha count.

Both counter fillings were argon at 40-cm pressure. Counter geometry was the same as described earlier,[2] but a redetermination was made of some of the constants, particularly A, the area of the counter hole.

Pressure Measurement

The target gas pressure was indicated by a manometer made of 0.5-inch i.d. tubing filled with Octoil-S. A density determination gave the value $0.9103[1-(t-25)0.000659]$ g cm^{-3}, where t is the centigrade temperature. The oil was partially outgassed by vacuum boiling in the manometer, but outgassing never stopped and continual pumping on the vacuum side was required.

Composition of Gas

The target gas, taken from a Stuart Oxygen Company bottle and marked 99.4 percent deuterium, was checked mass-spectrometrically and found to contain 0.38 percent hydrogen and essentially no other contaminants.

Sources of Error

The dimensions of the collimator and of the counter assembly, indicated in Fig. 1, determine an angular spread of $\pm 2°$ for each measurement. Since the angular distribution does not have a large second derivative, the error due to poor angular resolution is insignificant.

Upper limits for the errors, systematic and otherwise, in the several measurements required to determine a cross section are estimated as follows:

Current integral	0.3 percent
Pressure	0.1 percent
Counter slit and hole geometry	1.0 percent
Composition of gas	0.1 percent.

To these errors, which amount to 1.5 percent or less, we must add errors due to counting, which for most points do not exceed 1 percent; the extreme statistical error is 2.2 percent at 130°. Allowing for possible

[4] S. K. Allison and S. D. Warshaw, Revs. Modern Phys. 25, 779 (1953).
[5] W. C. Dickinson and D. C. Dodder, Rev. Sci. Instr. 24, 428 (1953).

TABLE I. The values of $D(t,\alpha)$ differential cross section in both lab and c.m. systems. The column ϵ is the percent statistical probable error.

Lab system		C.m. system		P.E.
ϕ deg	$\sigma(\phi)$ mb/sterad	θ deg	$\sigma(\theta)$ mb/sterad	ϵ %
10	50.28	14.415	24.4	0.5
20	48.12	28.716	24.1	0.9
30	45.83	42.801	24.2	0.7
40	42.18	56.547	24.0	0.7
50	37.84	69.834	23.7	0.7
60	32.80	82.568	23.1	1.2
70	28.22	94.634	22.8	1.0
80	23.22	105.877	21.9	1.0
90	19.36	116.302	21.6	1.0
100	15.43	125.874	20.5	1.1
110	12.50	134.607	19.8	1.5
120	10.24	142.566	19.2	1.6
130	8.60	149.844	18.8	2.2
140	7.60	156.549	19.0	1.8

unknown errors, we arrive at 3 percent as a maximum probable error for the differential cross section.

RESULTS

A relative angular distribution was determined by making runs at various angles, always for 10^4 counts in the monitor. Frequently the pulses from the monitor counter were displayed on the 18-channel pulse-height analyzer to determine where to set the bias on the monitor scaler, the important point being that the bias was always set at a readily identified minimum in the distribution. Pulses from the movable counter were recorded on the 18-channel analyzer. After subtraction of the background due to neutron recoils the alphas always fell in a well resolved peak.

The determination of an absolute cross-section scale was accomplished by measurements of chamber temperature and pressure, and of the current integral for 10^4 monitor counts. The cross section at the angle ϕ is

$$\sigma(\phi)=Y\sin\phi/(NnG),$$

where Y is the number of α counts per microcoulomb, $N=6.242\times10^{12}$ tritons per microcoulomb, $n=$ the volume density of deuterons, and $G(=4.082\times10^{-5}\text{ cm})$ is the usual geometry factor.[1] In terms of measured quantities,

$$\sigma(\phi)=0.20331(10)^{-27}TP^{-1}C^{-1}Y\sin\phi\ \text{cm}^2/\text{sterad},$$

where T is the absolute temperature, C is the concentration of deuterium in the target gas, and P is the pressure in mm of Hg.

The results, both in the laboratory and center-of-mass systems, are presented in Table I. The value of Q used for the c.m. transformation is 17.577 Mev. The table contains also a column for ϵ, the percent probable error due only to statistics. The total cross section is

$$\sigma=2\pi\int_0^\pi \sigma(\theta)\sin\theta d\theta.$$

Figure 2 shows how the data of Table I are plotted and extrapolated to 0 and 180°. Integration by Simpson's rule gives $\sigma=280\pm8$ mb.

There is a measurement of the d-T total cross section for $15<E_T<160$ kev,[6] one in the range $30<E_T<210$ kev,[7] another for $75<E_T<1200$ kev,[8] and a measurement of the 90° differential cross section

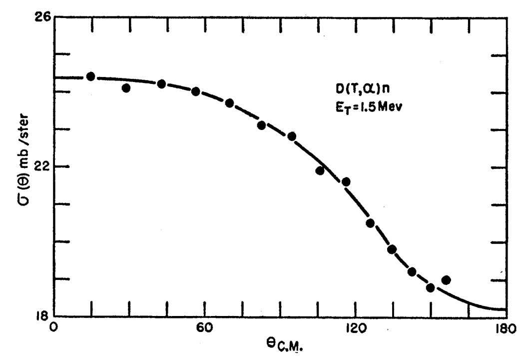

FIG. 2. Differential cross section extrapolated to 0 and 180°. Note that the scale of ordinates has a suppressed zero.

(made on the neutron yield) for $200<E_T<1450$ kev,[7] all of which measurements are mutually compatible. There is also a differential cross section measurement at 3.31 Mev[9] done by essentially the same technique (except that the deuteron was accelerated) as the present experiment. The total cross-section curve[8] is very flat at $E_T=1.2$ Mev, and extrapolation to 1.5 Mev gives good agreement with the present 280-mb measurement.

[6] Arnold, Phillips, Sawyer, Stovall, and Tuck, Phys. Rev. **93**, 483 (1954).
[7] Conner, Bonner, and Smith, Phys. Rev. **88**, 468 (1952).
[8] Argo, Taschek, Agnew, Hemmendinger, and Leland, Phys. Rev. **87**, 612 (1952).
[9] T. F. Stratton and G. D. Freier, Phys. Rev. **88**, 261 (1952).