PRELIMINARY RESULTS ON THE CROSS-SECTION OF
THE REACTION T²(d,n)He⁴ BETWEEN 1.0 MEV AND
2.5 MEV DEUTERON ENERGY

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Abstract

Results on the absolute total and differential cross sections for $^3\text{d}(d,n)^4\text{He}$ at deuteron energies of 1.0 MeV, 1.5 MeV, 2.0 MeV and 2.5 MeV are reported and the use of this reaction as a neutron source is discussed.
INTRODUCTION

In the past measurements on the reaction cross section of \( \text{D}^2(T,n)\text{He}^4 \) have been made by Bretscher and French \(^1\) from about 18 kev triton energy to about 120 kev and by Baker, Holloway, Schrieber, and King \(^2\) from about 300 kev to about 900 kev. Both groups of experimenters accelerated tritons onto thick deuterium oxide targets, at a time when tritium was very rare. The experiments reported show that this reaction has an extremely large cross section somewhere near 200 kev triton energy where there is a resonance maximum. The \( Q \) for the reaction is + 17.6 Mev.

The reaction \( \text{T}^3(d,n)\text{He}^4 \) has been studied for deuterons of energies 1.0 Mev to 2.5 Mev (triton energies \( 3/2 E_d \)) both to determine the differential and total reaction cross sections and to study the use of this reaction as a source of high energy neutrons.

METHOD

The availability of small but sufficient quantities of tritium made the acceleration of deuterons of energies above 1 Mev on to gaseous tritium seem the logical method of producing the reaction and observing the reaction products, alpha-particles and neutrons. A special target allowing angular distribution measurements of alpha-particles to be made in a small gas volume has been described \(^3\) and Fig. 1 shows the essentials.
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![Diagram showing a mechanical setup with labels for Cooling coils, Filling lead, Gas volume, Foil, Non Planar Small Volume Scattering Chamber, Angle scale, Faraday Gege, and Counter.]

FIGURE- 1
Fig. 2 is a schematic diagram of the tritium storage and handling system used; heated uranium shavings provided a completely satisfactory method of evolving the tritium stored as $^{7}H_3$ in the cold uranium when not in use. Since the total amount of gas available at one time was only about 10 to 15 cm$^3$ at NTP the mercury lift through the 500 cm$^3$ bulb was used to make a complete transfer of gas at maximum efficiency from uranium pump to target and vice versa possible. Auxiliary connections could be made to supplies of hydrogen and deuterium gas as shown in the figure.

To guard against the possibility of breaking one of the thin aluminum foils sealing the precious target gas from the accelerating tube vacuum and thus losing it, the high gas impedance tube and trip valve shown in Fig. 3 were used to connect target to accelerating tube. This device was to work by having the increase in gas pressure of a broken foil fire either an ion gauge or spark plug as shown, which in turn would trip the valve at the other end of the tube before an appreciable amount of the gas escaped through the high impedance gas flow tube. The gas was then to be recovered by the uranium pump. Up to the present time this device has not had the necessity of firing under the conditions for which it was designed.

Reaction Cross Section

Since it was known that the tritium samples contained varying amounts of ordinary hydrogen and since at this time, early in 1947, no sound method for analysis existed, the method of proton-proton scattering described in LA-625(4) was devised and has been successfully used since this time. The tritium concentration must be known to fix the absolute cross section for the reaction.

The reaction product observed at a given deuteron energy was
Pump & pressure measuring manometers for hydrogen gases. Fig. 2
the alpha-particle emitted at the angle determined by the proportional counter setting, which lay between 45° and 135° in the laboratory coordinate system. In Fig. 4 is shown alpha-particle energy as a function of detector angle, together with the energies of particles which can be scattered or recoil into the counter at the same angle, because the relative energy losses of these particles in the counter compared to that for the alpha-particle determines counter voltage, gas and amplifier gain, counter window thickness and target gas pressure for optimum observation of the alphas. These curves are of course different for each deuteron energy, but only the one for \( E_d = 2.0 \) MeV is shown, since in general they are similar.

Since transformations to the center of mass coordinate system are of interest for total yield determinations and for understanding of the reaction itself, the solid angle factor for transformation (5) from laboratory to center of mass system is calculated from

\[
\left[ \frac{\sigma_{CM}(\phi)}{\sigma_{LAB}(\theta)} \right]_\alpha = \frac{dN_{LAB}}{dN_{CM}} = \cos(\phi + \theta_\alpha) \frac{\sin^2 \theta_\alpha}{\sin^2 \phi}
\]

where

\( \sigma(\theta_\alpha) \) = cross section in cm\(^2\) per unit solid angle.

\( \frac{dN_{LAB}}{dN_{CM}} \) = ratio of laboratory to center of mass solid angles for alpha particles.

\[
\pi - \phi = \theta_\alpha + \sin^{-1}\left(\frac{\sin \theta_\alpha}{0.612 \sqrt{\frac{E_d + 28.9}{E_d}}}ight), \text{ } \phi \text{ being the center of mass angle.}
\]
FOR $E_D = 2.0$ MEV

Alpha energy vs. detector angle.

$E_T$ and $E_p$ curves.

$E_D$ from $T$.
In Fig. 5 is shown a typical pulse height distribution curve showing the alpha-particle group resolution in two runs. This varies with deuteron energy and angle, of course.

The data shown in Fig. 6 gives the laboratory system differential cross sections as a function of angle over the range so far studied. The values of \( \sigma(\theta_d) \) are obtained from

\[
\sigma_{\alpha}(\theta_{\alpha}, E_d) = \frac{N_{\alpha} \sin \theta_{\alpha}}{g N_d N_T}
\]

where

- \( \theta_d \) = laboratory coordinate system angle of observation at the deuteron energy \( E_d \);
- \( N_{\alpha} \) = number of alphas during a run or per microcoulomb of deuterons;
- \( N_d \) = number of deuterons during a run or per microcoulomb of charge;
- \( N_T \) = number of tritons per cm\(^3\) of target gas;
- \( g = \frac{\pi a^2 \cdot 2b}{R_o h} \) is the counter geometry factor\(^{(6)}\), where
  - \( na^2 \) = area of counter hole, radius \( a \);
  - \( 2b \) = width of defining slit;
  - \( R_o \) = distance from hole to intersection of normal to hole with axis of deuteron beam;
  - \( h \) = distance from hole to slit.

In Fig. 7 are shown the center of mass coordinate system differential cross sections plotted at the appropriate angles in the same system. Although the data is still somewhat scanty, the angular distribution is definitely not symmetric about 90 degrees in the center.
T(\text{D},N)\text{He}^4

DIFFERENTIAL CROSS SECTION FOR \( \alpha \)'S IN LABORATORY COORDINATES

\( E_D = 10 \text{ MEV} \)
\( E_D = 1.5 \text{ MEV} \)
\( E_D = 20 \text{ MEV} \)
\( E_D = 2.5 \text{ MEV} \)
$T(D,N) \propto \frac{d\sigma}{d\Omega}$

Differential cross section for $\alpha^4$ in center of gravity coordinates

$- \times - E_D = 2.0 \text{ MEV}$
$- - E_D = 1.5 \text{ MEV}$
$- - E_D = 1.0 \text{ MEV}$

Cross section - barns per $\Omega$

Center of gravity angle - degrees

**Fig. 7**
of mass system. If a fit is made to a power series in \( \cos \phi \) one finds a reasonably adequate representation of the data given by

\[
\sigma(\phi) = A(E) + B(E) \cos \phi + C(E) \cos^2 \phi
\]

indicating an interaction between S and P waves. Until more data is obtained one can approximately fix the total reaction cross section by integration of the theoretical curve for \( \sigma(\phi) \), i.e.

\[
\sigma_{\text{Ed}}(\text{total}) = 2n \int_0^n \sin \phi \, u(\phi) \, d\phi = 2n \left[ 2A(\text{Ed}) + 2/3 C(\text{Ed}) \right]
\]

which gives the following values at 1 MeV:

\[
\sigma_{1.0}(\phi) = 0.0103 + 0.0017 \cos \phi + 0.0066 \cos^2 \phi
\]

\( \sigma_T(1.0 \text{ MeV}) = 0.15 \pm 0.02 \) barns;

at 1.5 MeV:

\[
\sigma_{1.5}(\phi) = 0.0104 + 0.0012 \cos \phi + 0.0045 \cos^2 \phi
\]

\( \sigma_T(1.5) = 0.15 \pm 0.02 \) barns;

at 2.0 MeV:

\[
\sigma_{2.0}(\phi) = 0.0089 + 0.0061 \cos \phi + 0.0090 \cos^2 \phi
\]

\( \sigma_T(2.0) = 0.15 \pm 0.02 \) barns;

at 2.5 MeV:

\[
\sigma_{2.5}(\phi) = 0.0074 + 0.0042 \cos \phi + 0.01 \cos^2 \phi
\]

\( \sigma_T(2.5) = 0.135 \pm 0.03 \) barns.

The measurements at 2.5 MeV are the least satisfactory and the total cross section derived from them is undoubtedly inaccurate. The total
cross sections are plotted at the corresponding triton energies in Fig. 8, together with the results of Bretscher and French \(^{(1)}\) and of Baker, Holloway, Schreiber and King \(^{(2)}\). The theoretical curves plotted, are Breit-Wigner fits to either one or both sets of data, and indicate the importance of knowing the width of the resonance. The target shown has had considerable use as a thick target with deuterons incident on the gas at about 600 kev and being completely stopped in the gas; if one assumes that the broad resonance of the earlier two sets of measurements combined is correct the integrated neutron yield from the thick target per microcoulomb of deuterons is in fair agreement with the calculated, whereas the narrow resonance assumed by Bretscher gives a value of yield less than half that observed. The measurements are being continued into the low energy region, but at values below about 600 kev the stragglng and window thickness begin to make such measurements poor.

Since the cross sections at energies above 1.0 Mev deuteron energy are still reasonably large, in fact considerably better than the corresponding \(D^2(d,n)He^3\) cross sections, thin targets of tritium gas make a satisfactory neutron source of energies variable between about 13 Mev and 18.5 Mev on the Los Alamos electrostatic generator. Absolute flux measurements are immediately possible with the present target from the relation

\[
\sigma_{dT}(\theta_n) = \sigma_{dT}(\theta_\alpha) \frac{d\Omega_\alpha}{d\Omega_n} = k_{\alpha n} \sigma_{dT}(\theta_\alpha)
\]

and the relationship between neutron and alpha angle

\[
\sin \theta_n = \sqrt{\frac{E_\alpha}{E_n}} \sqrt{\frac{M_\alpha}{M_n}} \sin \theta_\alpha
\]
BRETSCHER'S DATA
BRETSCHER'S RESONANCE FORMULA

\[ \sigma(E_{\text{keV}}) = \frac{325 \times 10^{28} \times e^{-\frac{472}{E}}} {E[(2.43 - E)^2(71.7)^2]} \]

PURDUE FROM 90° OBSERVATIONS
PURDUE FROM 0° OBSERVATIONS
ELECTROSTATIC GEN.—45° TO 100° OBSERVATIONS
LA.401 FIT RESONANCE FORMULA

\[ \sigma(E_{\text{meV}}) = \frac{58}{E} \times e^{-\frac{172}{E - 0.096}} \times \frac{1}{(0.174)^2} \]

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where \[ E_a = (17.6 + E_d) - E_n \] (\( E_n \))

and where

\[
\frac{d\Omega}{d\Omega_n} = k_{\alpha n} = \frac{\cos(\phi + \theta_\alpha)}{\cos(\phi - \theta_n)} \frac{\sin^2 \theta_\alpha}{\sin^2 \theta_n}
\]

Fig. 9 shows the relationship between \( E_n \) and \( \theta_n \) as a function of deuteron energy; Fig. 10 gives \( k_{\alpha n} \) as a function of \( \theta_\alpha \) for different \( E_d \) and also shows \( \theta_n \) as a function of \( \theta_\alpha \) for various values of \( E_d \). The neutron energies have been calculated from

\[
E_n = \frac{4}{25} E_d (2.56 + \cos^2 \theta_n) + 14.02 \sqrt{\frac{E_d}{5}} \left\{ 112.1 + \frac{15}{26} E_d (5 + \cos^2 \theta_n) \right\}^{1/2} \cos \theta_n
\]

assuming \( Q = 17.6 \text{ MeV} \). In this case it is preferable to use the equation above than the nomographs of McRibbon (5) since the large \( Q \) makes it impossible to read neutron energies with any accuracy from the usual type of chart.

One feels reasonably well assured that the neutrons are monoengetic in this reaction, at least to energies well above 3 MeV deuteron energy, since there are no indications in other work of excited states of \( \text{He}^4 \) at such low energies. The alpha-particle group observed in this work appears sharp, but the presence of pulses from scattered deuterons, protons and tritons does not allow examination of the whole energy spectrum of the alphas in this experimental arrangement.

It is not feasible with the present alpha-particle counting geometry to observe at laboratory angles below 45 degrees or above 135 degrees, but neutron detectors can now be calibrated on an absolute scale.
within the above angular range to allow extension of the measurements to cover nearly all of 145 degrees which should be sufficient to fix the total cross section with good accuracy.
References

(1) Bretscher and French, LA-582, LA-581.
(2) Baker, Holloway, Schreiber and King, LAMS-11.
(4) Taschek, LA-625.