data are presented in Fig. 4. The parameters are $a=5.0\times10^{-13}$ cm, $E_\lambda=-464$ kev, $\gamma_d^2=10^{-9}$ kev cm, and $\gamma_n^2=2.8\times10^{-11}$ kev cm. The quality of the fit is not sensitive to the value of a which is used if the other parameters are suitably changed. Total cross-section values were obtained from the measured differential cross section by assuming a symmetrical angular distribution in the center-of-mass system. At the higher energies, where the calculated curve falls below the experimental points, the angular distribution is probably not exactly symmetrical. Deviations from a one level formula might be expected at the highest energies because of higher levels in He^5, the compound nucleus. Also at higher energies the stripping process[12] must account for some of the effects since the results of Allred[13] and others at 10 Mev can be almost entirely explained by stripping.

An alternative explanation of the cross-section curve for the $H^3(d,n)He^4$ reaction is that proposed by Flowers.[14] His theory does not make use of an isolated state of the compound nucleus. An experimental study of the inverse process, the scattering of high energy neutrons in He^4, would serve as a means of testing the application of the two theories to this reaction. If an isolated compound state of $^*He^5$ is important in the $H^3(d,n)He^4$ reaction, an anomaly in the scattering cross section of 20–21 Mev neutrons would be expected.

[12] S. T. Butler, Proc. Roy. Soc. (London) **A208**, 599 (1951); S. T. Butler and J. L. Symonds, Phys. Rev. **83**, 858 (1951).

[13] J. C. Allred, Phys. Rev. **84**, 695 (1951); Brolley, Fowler, and Stovall, Phys. Rev. **82**, 502 (1951).

[14] B. H. Flowers, Proc. Roy. Soc. (London) **A204**, 503 (1950).

PHYSICAL REVIEW VOLUME 88, NUMBER 3 NOVEMBER 1, 1952

Cross Section and Angular Distribution of the $He^3(d,p)He^4$ Nuclear Reaction*

T. W. Bonner, J. P. Conner,† and A. B. Lillie
Rice Institute, Houston, Texas

(Received July 7, 1952)

The cross section for the reaction $He^3(d,p)He^4$ has been studied for deuteron energies from 188 kev to 1597 kev. The yield of protons at 0° to the deuteron beam exhibits a maximum at 400-kev deuteron energy. At this energy the angular distribution of the disintegration particles is spherically symmetrical and the total cross section is 0.69×10^{-24} cm^2. At higher energies there is a preferential emission of protons at 0°. At 1600 kev the ratio of the number of protons at 0° to that at 90° is 1.08. The variation of total cross section with bombarding energy agrees with a calculated single level resonance formula from 188 kev to 600 kev. At higher energies the theoretical values give too small a cross section.

INTRODUCTION

THE reaction $He^3(d,p)He^4$ is quite similar to the reaction[1] $H^3(d,n)He^4$ which has a very large cross section at low deuteron energies. Consequently a large cross section at a low bombarding energy might be expected for this reaction. The double nuclear charge on the He^3 nucleus, however, would decrease the penetrability of the deuterons into this nucleus as compared to a H^3 nucleus. Previous experiments[2] on this reaction which were carried out by slowing down He^3 particles from a cyclotron and sending these into deuterium gas, indicate a large cross section at low bombarding energies. The purpose of the present experiments was to study this reaction with deuterons of a well-defined energy from a Van de Graaff accelerator.

EXPERIMENTAL APPARATUS AND PROCEDURE

Deuterons were accelerated by the Rice Van de Graaff accelerator and passed through a 90° analyzing magnet before reaching the He^3 gas target holder. A diagram of the gas target holder is shown in Fig. 1. The beam of deuterons was collimated by aperture A

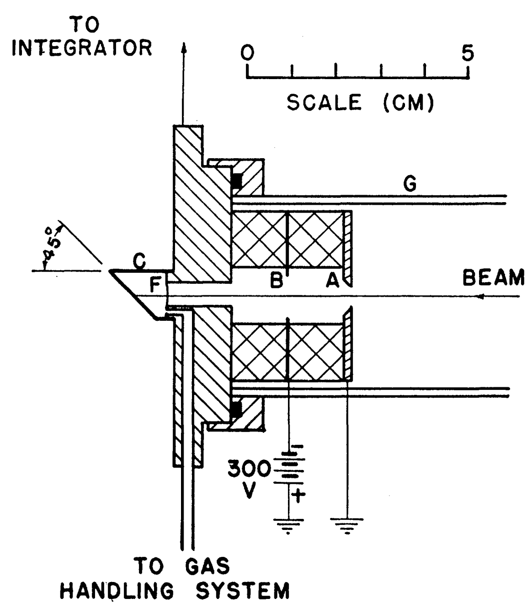

Fig. 1. The gas target holder showing the collimating aperture A, the electron repelling electrode B, the thin aluminum foil F, and the gas chamber C.

* Supported by the AEC. A preliminary report of this work was given at the New York Meeting (January, 1952) of the American Physical Society.

† AEC Predoctoral Fellow.

[1] Conner, Bonner, and Smith, Phys. Rev. **88**, 468 (1952).

[2] Baker, Holloway, King, and Schreiber, Atomic Energy Commission Declassified Report. AECD 2189 (1948) (unpublished).

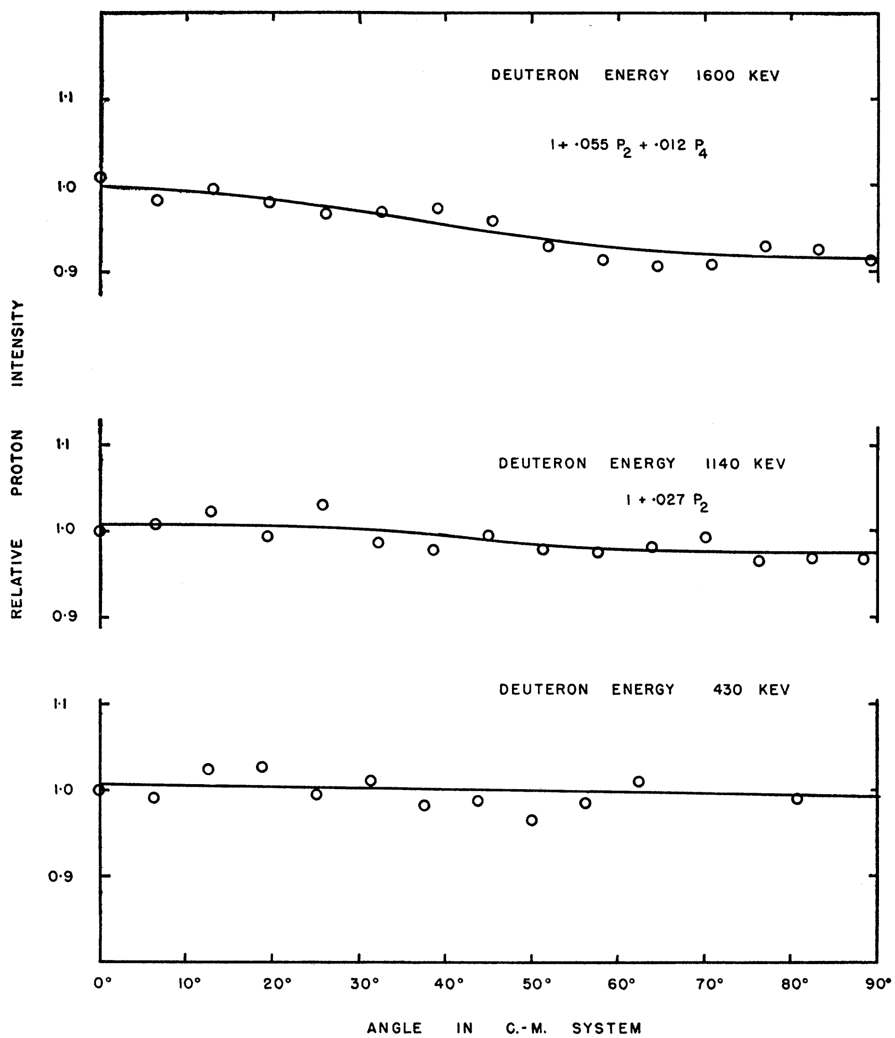

FIG. 2. The angular distribution of the disintegration protons at deuteron energies of 430, 1140, and 1600 kev. The relative intensities at each energy are the counting rates per equal solid angle in the center of mass system. The solid curves are theoretical fits in terms of Legendre polynomials.

TABLE I. Differential cross section at 0°, σ, *versus* the bombarding deuteron energy, E, for the $He^3(d, p)He^4$ reaction.

E kev	σ millibarns/steradian
188	16.6
247	28.8
307	44.4
363	53.6
420	54.4
478	50.8
536	44.4
593	37.6
648	33.4
712	30.4
769	27.7
828	24.4
883	21.8
972	19.2
1102	15.5
1229	14.3
1355	13.4
1487	11.8
1597	10.8

before striking a thin aluminum foil at F. This foil was 1.26 mg/cm^2 in thickness. After passing through the foil the beam entered a gas chamber which was made of thin aluminum. In the first experiments on cross-section measurements, the gas chamber was cylindrical and 0.973 cm long; in experiments on angular distributions the gas chamber had a diagonal end as indicated in Fig. 1. The energy loss of the deuteron beam in the aluminum foil was calculated from the results of Warshaw[3] and also measured directly at emerging deuteron energies of 313, 370, and 423 kev. The measured losses agreed with the calculated losses within 5 percent. The energy losses at different bombarding energies that were subsequently used were the calculated ones after they were normalized to the experimental values at 400 kev. The gas pressure of He^3 that was used was in the range 0.8–1.0 cm of Hg; this pressure was measured with a mercury manometer.

In the first experiments on cross-section measure-

[3] S. D. Warshaw, Phys. Rev. 76, 1759 (1949).

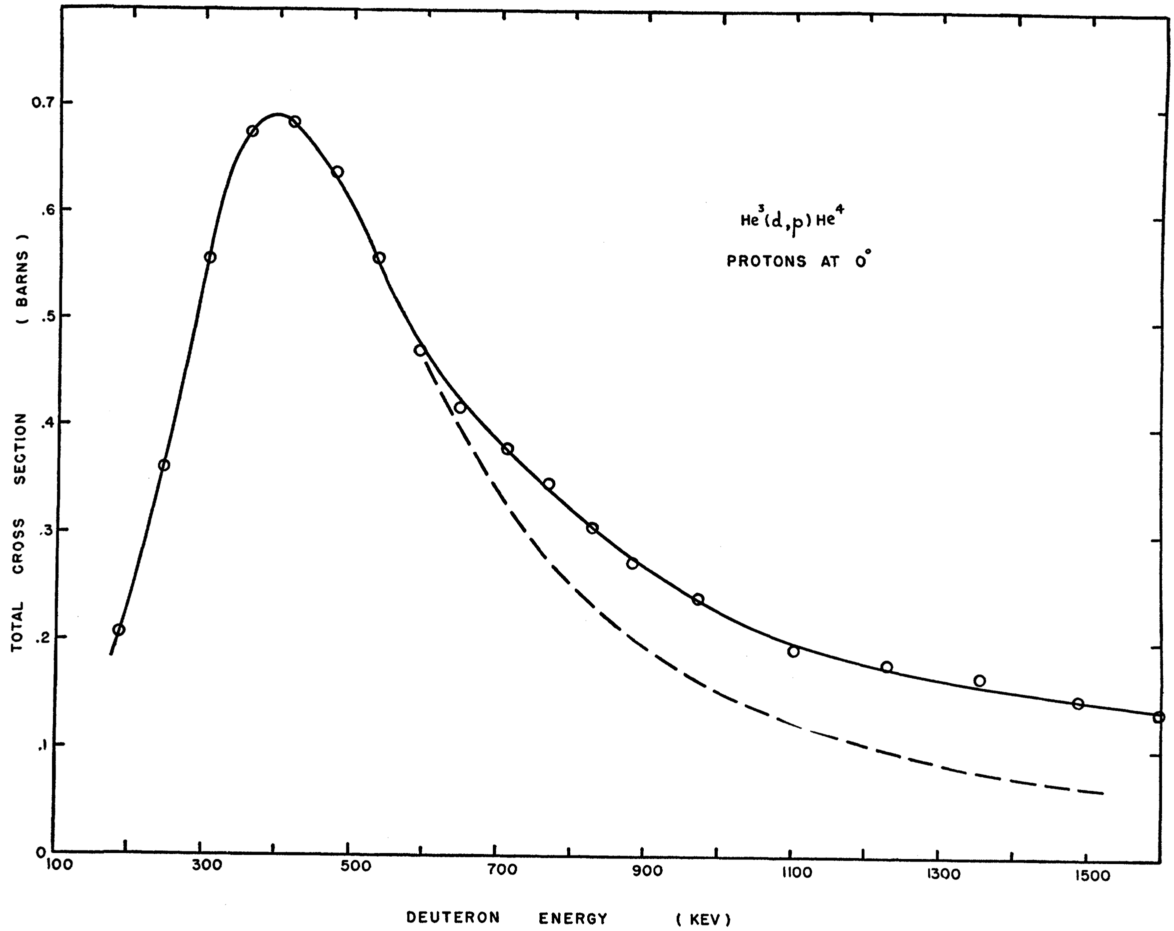

FIG. 3. Experimental values of the total cross section (solid curve) compared to the theoretical curve (dashed), computed with a nuclear interaction distance $a=7.6\times10^{-13}$ cm.

ments, a long proportional counter filled with argon at atmospheric pressure was used to detect protons from the reaction at 0° to the incident beam. The counter aperture of 0.632 cm was placed 5.5 cm from the center of the target and thus subtended a solid angle of 0.0104 steradian. In the experiments to determine the angular distributions, a thin anthracene crystal cemented to a 5819 photomultiplier tube was used as a proton detector. The angular resolution was 4° and points were taken at 6° intervals.

The statistical probable errors of the points were about 1 percent near 400 kev and less than 2 percent elsewhere; the estimated probable errors of the current integrator and number of He^3 atoms were 1 percent each; the solid angle contributed a probable error of 3 percent. Background counts with each type of counter were negligible.

RESULTS

Cross-section data as given in Table I are differential cross sections at 0° to the deuteron beam, after making center-of-mass corrections for the varying solid angle.

The experimental data for the angular distributions at 430-, 1140- and 1600-kev deuteron energy are shown in Fig. 2. The relative proton intensities at different angles (center-of-mass system) are given. At the lowest energy the distribution is symmetrical from 0° to 90° within the experimental accuracy of about 2 percent. At the higher energies there are more protons at 0° than at 90°. The ratio of protons at 0° to that at 90° amounts to about 1.04 at 1140-kev deuteron energy and 1.08 at 1600-kev.

Since the angular distribution is spherically symmetrical at low energies, the total cross section for the reaction can be calculated. This maximum cross section is 0.69 barn at 400-kev deuteron energy. Figure 3 shows the calculated total cross sections for the reaction as a function of the bombarding deuteron energy. The total cross sections were calculated assuming a spherical distribution in center-of-mass coordinates. At the higher energies the total cross section will be in error because the distribution is not exactly spherical. Exact values could not be calculated since our angular distributions did not go to angles greater than 90°. The cross sections below 300 kev are not as accurate

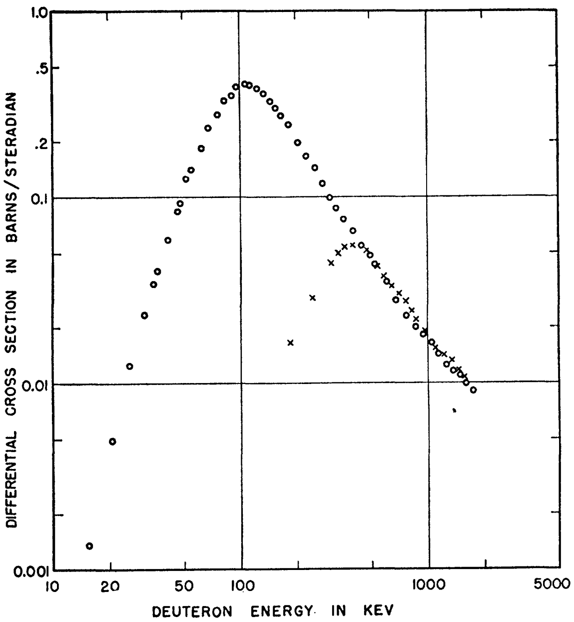

FIG. 4. A comparison of the cross sections for the reactions $H^3(d, n)He^4$ (open circles), and the reaction $He^3(d, p)He^4$ (crosses).

as those at higher energies because of a spread in the energy of the deuteron beam caused by straggling in the aluminum foil.

Figure 4 is a plot of the $He^3(d, p)He^4$ and the $H^3(d, n)He^4$ differential cross section as a function of bombarding energy. Above 500 kev the cross sections for the two reactions are nearly the same. This fact suggests that corresponding states of intermediate nuclei $*Li^5$ and $*He^5$ are involved. Since the spin of the intermediate $*He^5$ nucleus,[1] formed in the reaction $H^3(d, n)He^4$, appears to be $\frac{3}{2}$, a value of $J=\frac{3}{2}$ is assigned to the intermediate $*Li^5$. The $*Li^5$ also would be expected to have even parity as does the $*He^5$. Further, one might expect that the nuclear parameters which are used in the resonance equation for the two reactions to be nearly the same. A fit to the experimental data has been obtained using the modified Breit-Wigner relation[4] using a radius of interaction $a=5.0\times10^{-13}$ cm, a value of $E_\lambda=+175$ kev, $\gamma_d^2=0.7\times10^{-10}$ kev cm, and $\gamma_p^2=2.6\times10^{-11}$ kev cm. These nuclear parameters are of the same order of magnitude but somewhat different from those used in the $H^3(d, n)He^4$ reaction. The value of γ_d^2 is a factor of 14 larger and the value of γ_n^2 is approximately the same as the corresponding γ_p^2. The value of E_λ is larger for the $He^3(d, p)He^4$ reaction as would be expected for these mirror nuclei. A somewhat better fit to the experimental curve was obtained with the slightly different parameters $a=7.6\times10^{-13}$ cm, $E_\lambda=+195$ kev, $\gamma_d^2=5.0\times10^{-10}$ kev cm, and $\gamma_p^2=9.7\times10^{-12}$ kev cm.

Both theoretical curves fit the data within the experimental errors below 600 kev, but both give too small a cross section at the higher energies. Possible reasons for the larger experimental cross sections at higher energies are (1) deuterons with $l=2$ may contribute a considerable amount to the cross section at the higher energies, (2) the "stripping reaction" may account for an appreciable fraction of the cross section at the higher energies. Stripping seems to be the predominant process at 10 Mev,[5] and the results at 3.17 Mev[6] indicate that stripping is beginning to be important at this energy.

As in the case of the $H^3(d, n)He^4$ reaction,[1] an alternative explanation of the cross section curve for the reaction $He^3(d, p)He^4$ is that proposed by Flowers.[7] His theory does not make use of an isolated state of the compound nucleus. If an isolated compound state of $*Li^5$ is important in this reaction, an anomaly in the large angle scattering cross section of 21–22 Mev protons in He^4 would be expected.

[4] E. P. Wigner and L. Eisenbud, Phys. Rev. **72**, 29 (1947); R. G. Thomas, Phys. Rev. **81**, 148 (1951).
[5] J. C. Allred, Phys. Rev. **84**, 695 (1951); S. T. Butler and J. L. Symonds, Phys. Rev. **83**, 858 (1951).
[6] Wyley, Sailor, and Ott, Phys. Rev. **76**, 1532 (1949).
[7] B. H. Flowers, Proc. Roy. Soc. (London) **A204**, 503 (1950).