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A Study of the H^3+He^3 Reactions*

C. D. Moak
Oak Ridge National Laboratory, Oak Ridge, Tennessee

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The reactions $H^3(He^3,d)He^4$, $H^3(He^3,p)He^5$ and $H^3(He^3,p)He^4,n^1$ have been studied in the 100-kev to 800-kev region of bombarding energy. In the case of $H^3(He^3,p)He^5$, the proton energy was measured with a scintillation spectrometer; from this measurement, the energy of breakup of He^5 into a neutron and an α particle was found to be 0.95 ± 0.07 Mev. At a bombarding energy of 360 kev, the deuterons from the $H^3(He^3,d)He^4$ were found to be isotropic in the center-of-mass system. The spectrum of protons from the three-body breakup, $H^3(He^3,p)He^4,n^1$, was found to be flat within experimental error from 2 to 8 Mev. Competitions among the various modes of decay of the compound nucleus of Li^6 do not vary beyond an experimental uncertainty of ±2 percent from 200-kev to 600-kev bombarding energy. The shape of the total cross-section curve, measured from 100 kev to 800 kev, appears to indicate a nonresonant behavior, similar to the case of the *d-d* reaction.

INTRODUCTION

THE following three reactions are known to take place when H^3 is bombarded by He^3:

$$H^3+He^3\rightarrow Li^{6*}\rightarrow He^4+H^2+14.31\text{ Mev} \qquad (1)$$

$$\rightarrow He^4+H^1+n^1+12.08\text{ Mev} \qquad (2)$$

$$\rightarrow He^{5*}+H^1+Q. \qquad (3)$$

These reactions have been reported by Almqvist, Allen, Dewan, and Pepper.[1] In reaction (3) the value of Q will depend upon the energy of excitation left in the He^5 nucleus. If He^5 is left in its ground state Q will be equal to $12.08-E(He^5)$ where $E(He^5)$ is the energy of breakup of He^5 into a neutron and an α particle.

The purpose of the present experiments was to determine the binding energy of the ground state of He^5 and to determine the individual cross sections of reactions (1), (2), and (3) as a function of energy in the 100- to 800-kev region of bombarding energy. Some information has been obtained concerning the excited state of Li^6 formed as a compound nucleus.

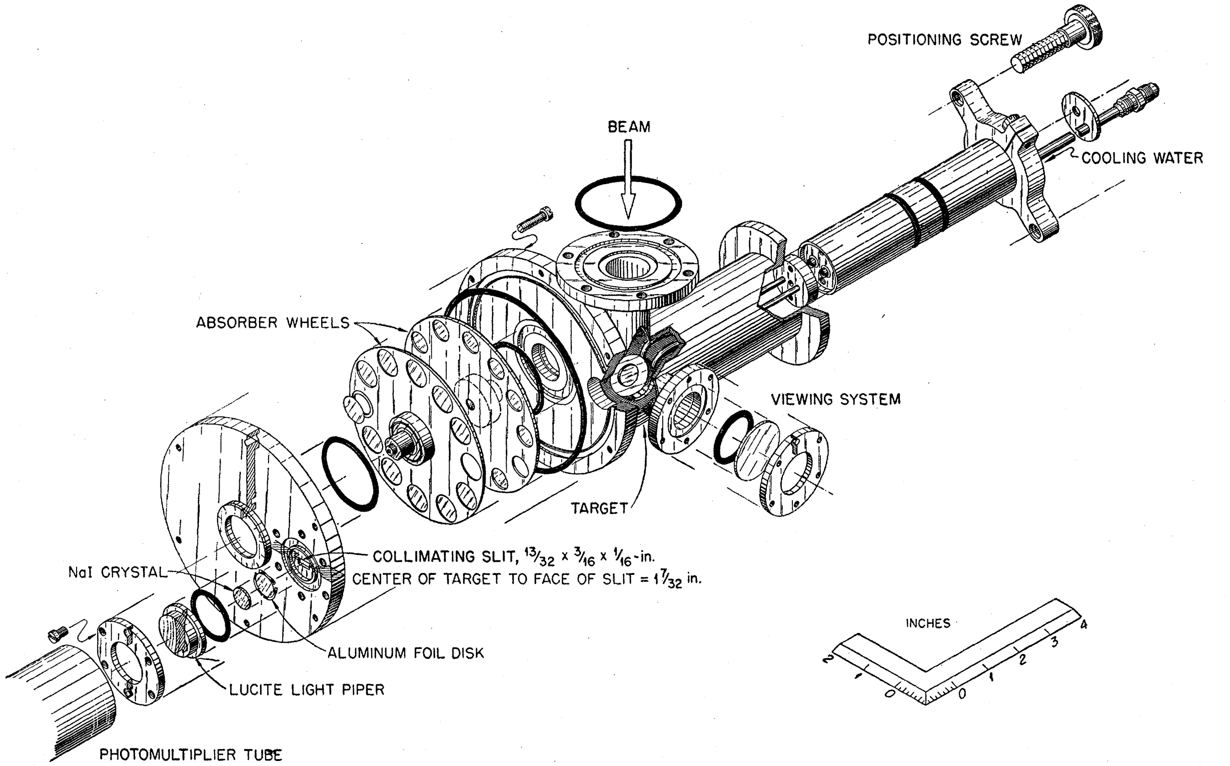

FIG. 1. Charged particle spectrometer.

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* This work represents part of a thesis being prepared in partial fulfillment of the requirements for the degree of Doctor of Philosophy at the University of Tennessee.

[1] Almqvist, Allen, Dewan, and Pepper, Phys. Rev. **83**, 202 (1951).

EXPERIMENTAL ARRANGEMENTS

Accelerator

The Cockcroft-Walton accelerator is to be described in a forthcoming article. It consists of a four-stage 400-kv voltage supply and an accelerator fitted with equipment for handling He^3, an rf ion source and a 15° analyzing magnet for separating the beam components. By using the doubly charged He^3 ions, energies up to 800 kev are made available with the 400-kv generator.

Targets

For measurements of the charged particle distributions the targets were approximately 50 kev thick (at 300 kev). In the case of the cross-section measurements the target used was less than 20 kev thick throughout the range of bombarding energies used. All targets were made by heating Zr films in a tritium atmosphere. The Zr films were evaporated onto Pt backings.

Counting Arrangements

Three counting arrangements were used. The first arrangement, shown in Fig. 1, was designed for small solid angle and high resolution for use in studying the spectrum of the charged-particle reaction-products. In the arrangement of Fig. 1 a NaI crystal was mounted behind a collimator so that particles could not strike the crystal edges. Provision was made for rotating Al foils, of thickness varying in 100 steps from zero to 300 mg/cm², into the region between the target and the NaI crystal. Light from the NaI crystal was piped out of the vacuum by a Lucite button mounted on an O-ring. The light was then collected by an RCA 5819 photomultiplier. The resultant pulses were amplified by a type A-1 linear amplifier and pulse-height distributions were taken with a single-channel differential pulse-height selector. The second arrangement is shown in Fig. 2. This arrangement has been designed for accurate measurement of target current, with provision for suppression of secondary electron currents, and was made to have a larger solid angle so that current on the thin target used in the cross section measurements could be kept at a minimum. The counting circuits were the same as those for Fig. 1. The third counting arrangement is shown in Fig. 3. A scintillation counter with a window of 1-mil Al was mounted on a goniometer. The target was mounted in the vacuum system at the center of rotation of the goniometer. A cylindrical window of 1-mil steel was used to pass charged particles from the target out of the vacuum and into the scintillation counter. With this arrangement, provision was made for tilting the target so that the scintillation counter could be rotated through the range of angles from 20° to 135° with respect to the beam.

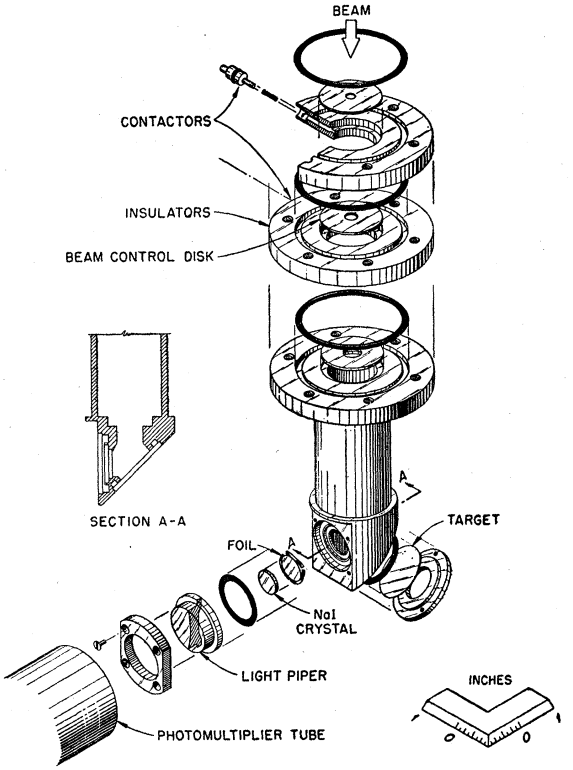

FIG. 2. Close geometry counting arrangement.

SPECTROMETER CALIBRATION

The response of the scintillation spectrometer (i.e., pulse height *vs* proton energy) has been measured by using two nuclear reactions giving protons of accurately known energies and by interpolating between these points with a set of Al absorbers. The reactions used were the following:

$$H^2+H^2\rightarrow H^3+H^1+4.036\pm0.022 \text{ Mev} \quad (4)$$

$$He^3+H^2\rightarrow He^4+H^1+18.34\pm0.024 \text{ Mev.} \quad (5)$$

For 0.3-Mev deuterons, the protons of reactions (4) and (5) have energies of 3.10±0.02 Mev and 14.77 ±0.02 Mev, respectively, at 90° to the incident beam. By using absorbers of various thicknesses, the energy of the protons from reaction (5) was reduced through the energy range bracketed by reactions (4) and (5). The residual proton energies, following passage through the various absorbers were computed using the range-energy data given by Smith.[2] The calibration data are plotted in Fig. 4. The circles shown are points gotten with Al absorbers placed between the counter and a target emitting 14.77-Mev protons. The double circles are points gotten with absorbers placed between the counter and a target emitting 3.10-Mev protons. The line drawn through the circles is quite straight, indicating that NaI responds linearly from 3 Mev to 14 Mev. It can be seen that the circles do not lie on a line (dashed line) drawn between the two points of known energy.

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[2] J. H. Smith, Phys. Rev. 71, 32 (1947).

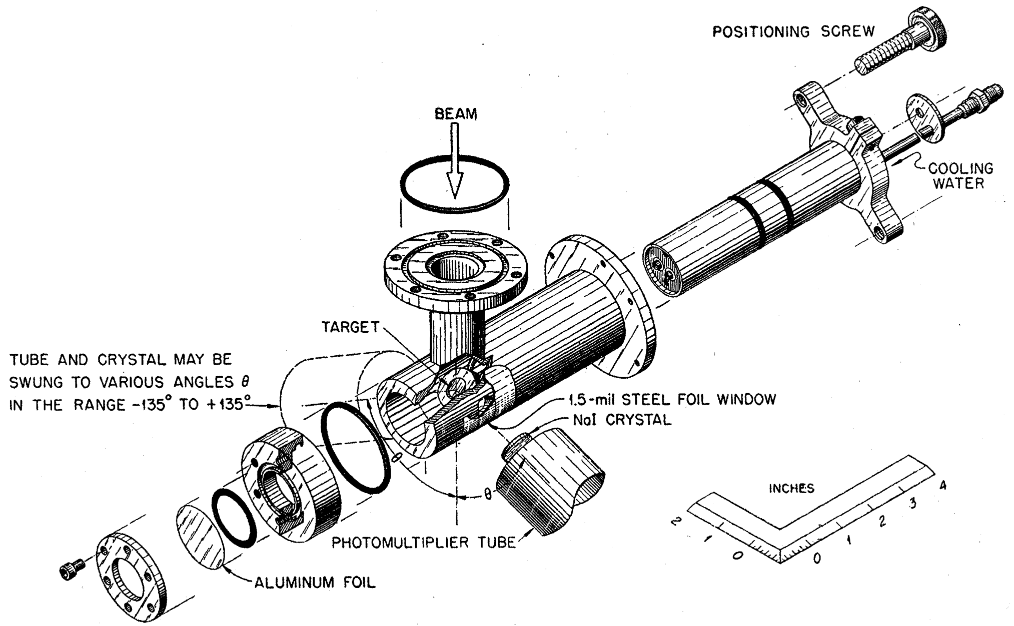

FIG. 3. Angular distribution counting arrangement.

This discrepancy indicates either that all the absorber thicknesses have been over-estimated or that the range-energy curves are slightly in error. Since all the absorbers were prepared in the same fashion, the possibility of a consistent error in the estimation of absorber thicknesses cannot be ruled out. On the other hand, some recent measurements of the range of protons in Al indicate that the values given by Smith are low by about 1 percent.[3,4] The discrepancy is in the same direction as that reported here and is of approximately the same magnitude. Until further experiments now in progress have removed this discrepancy, an error of ±50 kev, for protons with energy in the neighborhood of 10 Mev, must be added to the experimental error. Beyond this source of error is the uncertainty of ±20 kev in reactions (4) and (5). Errors of measurement are ±20 kev for protons at 10 Mev. The resultant experimental error is estimated as ±70 kev.

THE He^5 GROUND STATE

The charged particle spectrum, observed in NaI when a tritium target is bombarded with 0.3-Mev He^3 ions, is shown in Fig. 5. This curve was taken with a 600-$\mu g/cm^2$ Al absorber to stop scattered beam particles and was obtained using the geometry of Fig. 1. The peaks at each end of the spectrum are due to deuterium contamination giving rise to the protons and α particles of reaction (5). The two remaining peaks are due to the deuterons and α particles of reaction (1). Between these two peaks is the continuous spectrum of protons from reaction (2). A peak in the spectrum of protons, corresponding to the ground state of He^5 is obscured by the deuterons of reaction (1). In order to uncover this peak an absorber was used, which reduced the deuteron energy and the proton energies by different amounts; in this way the deuteron peak was displaced with respect to the spectrum of protons. The result is

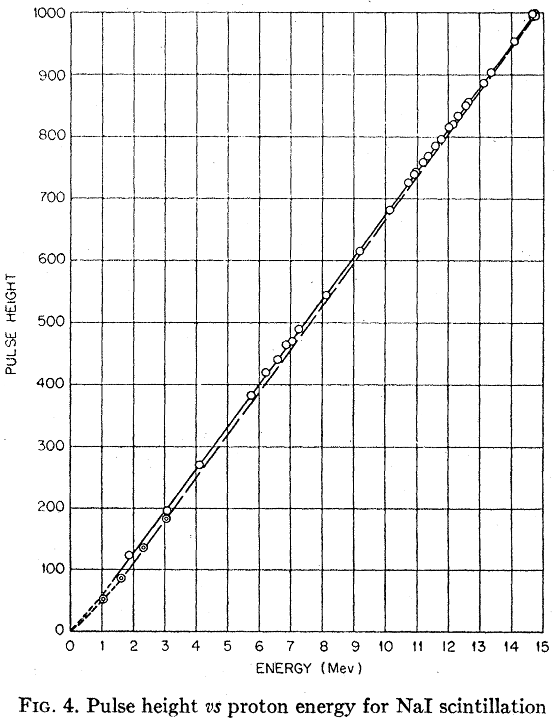

FIG. 4. Pulse height *vs* proton energy for NaI scintillation spectrometer.

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[3] E. L. Hubbard and K. R. McKenzie, Phys. Rev. **85**, 107 (1952).

[4] H. Bichsel and R. F. Mozley, Phys. Rev. **90**, 354 (1953).

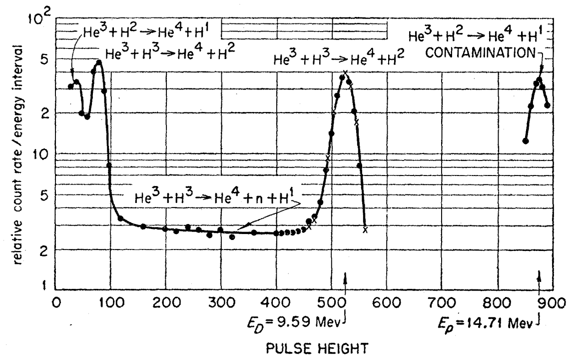

FIG. 5. Pulse spectrum in NaI of particles from H^3+He^3, bombarding energy 300 kev.

shown in Fig. 6. The first peak is that due to the deuterons of reaction (1). Displacement of this peak uncovers a peak in the proton spectrum corresponding to the formation of He^5 in its ground state. By measuring the energy of the protons in this peak, the energy of breakup of He^5 into a neutron and an α particle was determined. The upper end point of the proton spectrum is computed from the mass defect values given by Li, Whaling, Fowler, and Lauritsen.[5] Using exact masses and taking center-of-mass motion for 0.3-Mev bombarding energy into account, the end point for protons at 90° to the incident beam is at 10.16 Mev. For the energy of breakup of He^5 into an α particle and a neutron the following relation holds:

$$E(He^5)=12.20-1.201E_p, \qquad (6)$$

where E_p is the proton energy for the He^5 peak of Fig. 6 and $E(He^5)$ is the breakup energy of He^5 into an α particle and a neutron.

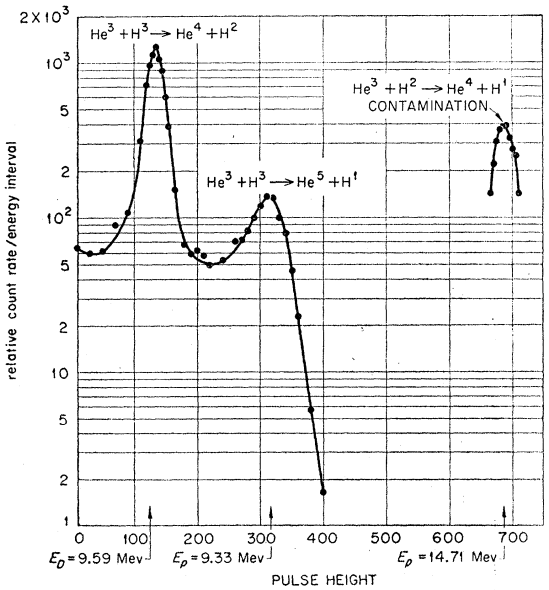

FIG. 6. Pulse spectrum in NaI of particles from H^3+He^3, bombarding energy 300 kev; particles passing through 11 mils Al into NaI crystal.

In order to eliminate as many systematic errors as possible in the measurement of E_p, the following procedure was used:

1. The pulse height of the He^5 peak was measured using a 60.2-mg/cm² Al absorber to shift the deuterons from the peak being measured, as in Fig. 6.

2. Absorbers were used to reduce the energy of the 14.71-Mev protons, obtained from reaction (5) which occurs due to deuterium contamination of the targets, down to the energy required to give the same pulse height as was measured in 1.

3. Using the range energy values of Smith,[3] the energy of the protons in the He^5 peak was obtained.

It was found that 240.5 mg/cm² Al for reaction (5) gave the same pulse height in the crystal counter as did 60.2 mg/cm² Al for the He^5 peak. The total range of a 14.71-Mev proton is 328.1 mg/cm² Al. The total range of the protons of the He^5 peak is then $328.1-240.5+60.2=147.8$ mg/cm² corresponding to a value for E_p of 9.33 Mev. From the relation (6) the energy of breakup of He^5 is

$$E(He^5)=12.20-1.201\times9.33=1.00 \text{ Mev}.$$

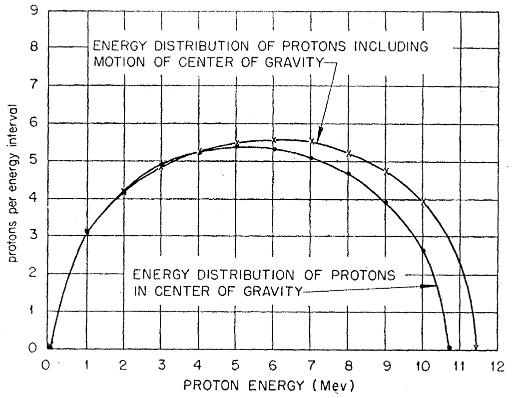

FIG. 7. Statistical mechanics energy distribution for the $H^3(He^3\,\alpha)n,p$ three-body breakup.

As pointed out in the section on calibration the absorber thicknesses may be in error by 0.8 percent; if this is the case the value of $E(He^5)$ would be 0.90 Mev. Giving equal weight to these two values and assuming the errors given in the section on calibration, the best estimate for $E(He^5)$ is 0.95±0.07 Mev. This would give for the mass of He^5 a value 5.01388±0.00007 a.m.u.

THE THREE-BODY BREAKUP

The reaction (2) may be considered as a real three-body breakup or as two distinct two-body breakups in rapid succession. Thus far no satisfactory theory of three-particle breakup has been derived. If one calculates the spectrum on the basis of simple statistical mechanical arguments, assuming constant density in

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[5] Li, Whaling, Fowler, and Lauritsen, Phys. Rev. 83, 512 (1951).

phase-space, the result is as shown in Fig. 7. Referring to Fig. 5 the observed three-body breakup spectrum is quite flat in contrast to the downward curvature seen in Fig. 7. The same disagreement with the shape of the curve in Fig. 7 is found in the case of the three-body reaction $He^3+He^3 \rightarrow He^4+H^1+H^1$.[6]

RELATIVE INTENSITIES OF THE REACTIONS

Using the curve of Fig. 6 an estimate was made of the relative intensities of reactions (1) and (3). This estimate was then used to break down the total spectrum of Fig. 5 into its components. The principal source of error lay in the fact that the He^5 peak was superimposed over a three-body breakup spectrum whose shape was not known. Thus the area left under the He^5 peak was somewhat dependent upon the assumed shape of the curve subtracted for that energy region. Since the He^5 peak is small compared to the other components of the spectrum, the competition between reaction (1) and (2) could be estimated with a fair degree of accuracy. By measuring the areas under the various components of the total spectrum the following was found:

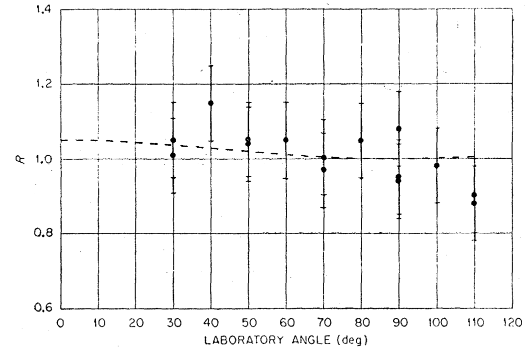

FIG. 8. Ratio (R) of $H^3(He^3,\alpha)d$ count to $H^2(He^3,\alpha)p$ count as a function of laboratory angle.

	Reaction	*Percent of the times occurring*
(1)	$H^3+He^3 \rightarrow He^4+H^2$	43±2 percent
(2)	$H^3+He^3 \rightarrow He^4+H^1+n^1$	51±2 percent
(3)	$H^3+He^3 \rightarrow He^5+H^1$	6±2 percent

The relative intensities were measured for various bombarding energies ranging from 225 kev to 600 kev. No variation of the relative intensities beyond experimental error was found through the range of bombarding energies used.

ANGULAR DISTRIBUTION OF THE DEUTERONS

The counting arrangement of Fig. 3 was used to measure the angular distribution of the deuterons from reaction (1). The bombarding energy used was 360 kev. For this experiment the $H^2(He^3,\alpha)H^1$ reaction (5) was used as a control. The protons from this reaction are known to be isotropic in the center of mass with respect to the incident beam at bombarding energies below 500 kev.[7] A target containing both deuterium and tritium was used to produce simultaneously the isotropic protons of reaction (5) and the deuterons of unknown angular distribution from reaction (1). The electronic circuits were arranged to count the deuterons of reaction (1) and the protons of reaction (5) separately. Measurements of the ratio of deuteron counts to proton counts were made for various laboratory angles. The ratio was normalized to unity at 90° and the results are shown in Fig. 8. The smooth curve is the variation of the ratio in the laboratory assuming isotropy of the deuterons in the center-of-mass system. The experimental points indicate either that the deuterons are isotropic or that the variations with angle are smaller than the present experimental error. In particular, if the angular distribution is $1+a\cos^2\theta$, then the value of $|a|$ must be less than 0.1.

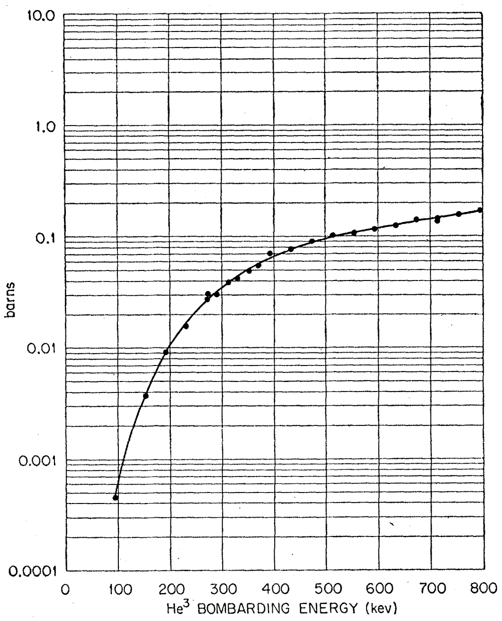

FIG. 9. Total reaction cross section for the H^3+He^3 reactions.

THE CROSS SECTION

The counting arrangement of Fig. 2 was used for the measurement of the cross section for reactions (1), (2), and (3). The electronic instruments were so arranged that counts due to deuterium giving rise to reaction (5) could be subtracted out. The differential cross section was measured at 90° for the total spectrum of protons and deuterons from reactions (1), (2), and (3). The cross section was obtained by dividing the differential cross section by the solid angle subtended by the crystal counter on the assumption that all particles

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[6] Good, Kunz, and Moak, Oak Ridge National Laboratory Report ORNL-1415, p. 5.

[7] W. E. Kunz (private communication).

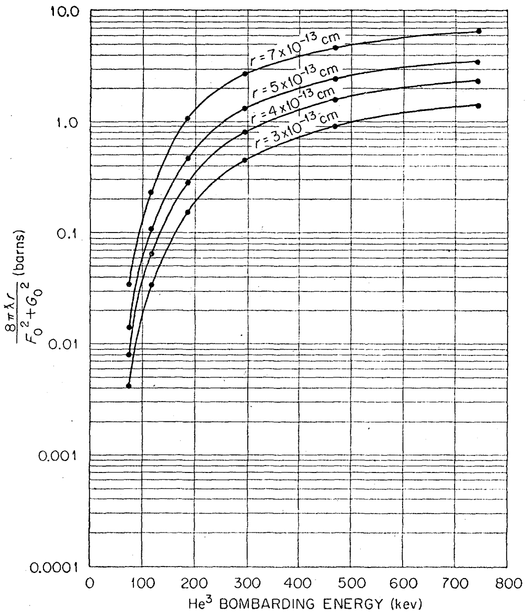

FIG. 10. Theoretical energy dependence of the H^3+He^3 cross section for $L=0$.

emerged isotropically with respect to the beam. The result is shown in Fig. 9. The effective target thickness in kev and the number of tritium atoms per cm^2 were measured by analysis of the geometric peak at the threshold of the $H^3(p,n)He^3$ reaction. The target used was 8±1 kev thick for 1-Mev protons and was found to have $8\pm1\times10^{16}$ tritium atoms per cm^2. Although the incident He^3 beam passed through small collimating apertures which helped to define its position on the target, there remained some uncertainty in the solid angle subtended by the crystal counter due to uncertainty in the exact position of the beam. The uncertainty in the cross section measured is estimated to be ±20 percent. Target thickness corrections were made at each value of the bombarding energy using the data of Warshaw.[8] The target thickness did not exceed 20 kev throughout the range of bombarding energies used.

Coulomb penetrability curves for the *s*-wave and *p*-wave cases have been calculated using the tables of Bloch, Hull, Broyles, Bouricius, Freeman, and Breit,[9] for various values of the interaction radius. The results are plotted without statistical factor in Figs. 10 and 11. Comparison of the shape of the experimental curve of Fig. 9 to the theoretical curves of Figs. 10 and 11 indicates no pronounced resonance behavior and seems to indicate a behavior similar to that of the *d-d* reactions.

SUMMARY

The value of 0.95±0.07 Mev for the energy of breakup of He^5 into a proton and an α-particle is in close agreement with the value of 1.00±0.1 Mev assumed by Ajzenberg and Lauritsen.[10] Their value was derived from analyses of neutron scattering on He^4,[11–13] and from experiments on the reaction $He^4(d,p)He^5$.[14]

The isotropy of the deuterons from reaction (1) does not rule out a mixture of *s*-wave and *p*-wave interactions because the *p*-wave part of the interactions could proceed through a $J=0$ level in Li^6. The constancy of the relative intensities of reactions (1), (2), and (3) with bombarding energy does not rule out a similar mixture since all three reactions may proceed through the same set of entrance channels.

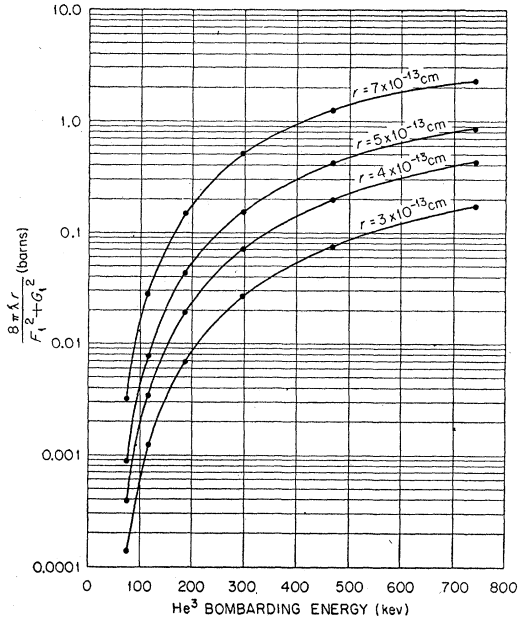

FIG. 11. Theoretical energy dependence of the H^3+He^3 cross section for $L=1$.

The author wishes to thank Dr. W. M. Good for his help and advice in performing the experiments. The author is indebted to Dr. M. E. Rose for discussions concerning the problem of three-body breakup, to Dr. A. Simon for discussions of the angular distribution problem, to Dr. H. B. Willard and the 6-Mev Van de Graaff group for the thin target calibrations, and to Dr. H. E. Banta of Instrument Division at Oak Ridge National Laboratory for the preparation of the tritium targets.

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

[9] Bloch, Hull, Broyles, Bouricius, Freeman, and Breit, Revs. Modern Phys. **23**, 147 (1951).

[10] F. Ajzenberg and T. Lauritsen, Revs. Modern Phys. **24**, 321 (1952).

[11] Bashkin, Mooring, and Petree, Phys. Rev. **82**, 378 (1951).

[12] R. K. Adair, Phys. Rev. **86**, 155 (1952).

[13] P. Huber and E. Baldinger, Helv. Phys. Acta **25**, 435 (1952).

[14] Burge, Burrows, Gibson, and Rotblat, Proc. Roy. Soc. (London) **A210**, 534 (1951).