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Low Energy Yield of D(D,*p*)H^3 and the Angular Distribution of the Emitted Protons†

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The thick target yield $N(E)$ of the reaction

$$D^2+D^2\rightarrow H^3+H^1+4.0 \text{ Mev}$$

has been studied using a heavy ice target, and the angular distribution of the protons observed. Experiments have been carried out from 15 to 105 kev incident deuteron energy. There is evidence that even for very small bombarding energies the angular distribution of protons in the c.g. system does not become isotropic. Evaluation of the cross sections $\sigma(E)$ from $N(E)$ involves an estimate of the energy loss of deuterons in heavy ice. The variation of cross section $\sigma(E)$ with energy E can only approximately be represented by a Gamow function, i.e.,

$$\sigma(E)\propto(1/E)\exp[-c/(E)^{\frac{1}{2}}].$$

INTRODUCTION

A STUDY of the D−D reaction at small bombarding energies was considered to be of general interest, especially in view of the anisotropic angular distribution of the reaction products.[1,2,3] The present work concerns the reaction

$$D^2+D^2\rightarrow H^3+H^1+4.0 \text{ Mev} \quad (1)$$

which is only one of two possible reactions, the other being[4]

$$D^2+D^2\rightarrow He^3+n^1+3.3 \text{ Mev.} \quad (2)$$

The experimental arrangement was as follows: A well-collimated monoenergetic beam of deuterons was directed onto a freshly formed D_2O ice target. The intensity of the incident beam was measured by the charge transferred to the target per unit time, and the number of protons emitted from the target per unit time was counted as a function of their angle θ with the direction of the incident beam and as a function of incident deuteron energy E between 15 and 105 kev.

APPARATUS

The experimental apparatus used in these investigations was mostly of a conventional type

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†† Professor H. Staub, now at Stanford University, joined in the direction of this research in its later stages. Considerable contributions have also been made by M. J. Poole and H. L. Wiser.

[1] H. P. Manning, R. D. Huntoon, F. E. Myers, and V. J. Young, Phys. Rev. **61**, 371 (1942).

[2] R. D. Huntoon, A. Ellett, D. S. Bayley, and J. A. Van Allen, Phys. Rev. **58**, 97 (1940).

[3] W. E. Bennett, C. E. Mandeville, and H. T. Richards, Phys. Rev. **69**, 418 (1946).

[4] T. W. Bonner, Phys. Rev. **59**, 237 (1941).

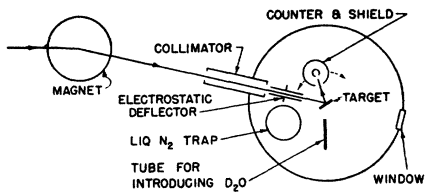

FIG. 1. Experimental arrangement (diagrammatic).

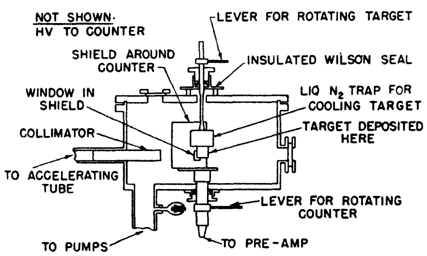

FIG. 2. Vacuum tank (sectional view).

and, consequently, we shall give a cursory description dwelling only on the points where special care was taken.

A full-wave kenotron rectifier was constructed to produce a deuteron beam of from 15 kev to 50 kev energy. At the *HV* end a small electron-arc ion source was mounted, having a cylindrical permanent magnet to lengthen the electron paths for ionizing collisions. Later a second *HV* set was built for voltages up to 125 kv, and again the ion source was of the arc type which was surrounded by a solenoidal electromagnet with an adjustable field. Adjustment of the magnetic field was desirable for obtaining optimum beam currents.

Accurate measurements of the bombarding voltages were essential; e.g., a change of incident deuteron energy of 1 kev at 20 kev produces a 30 percent change in reaction yield. Consequently, care was taken to measure the bombarding voltage to ± 1 percent. On the 50-kev set a 1-milliamp. meter was put in series with two 20-megohm precision resistors, and a further 10 megohms was later added in extending the measurements up to the full 50 kev. For the 125-kev set, a stack of 300 1-megohm precision resistors was made, and the leakage current down this stack was measured by a 30-microampere meter arranged in a potential-divider circuit across the bottom megohm of the stack. The ratio of the arms of the potential divider was measured by a Wheatstone-bridge circuit and was found to vary by less than 0.3 percent under full load. Furthermore, the calibrations of both the 1-milliamp. and the 30-microampere meters were checked.

After acceleration the deuteron beam was magnetically analyzed in order to select D_1^+, or D_2^+ ions. The beam was then collimated and entered the target chamber along a horizontal radius. It passed between a pair of electrostatic analyzer plates (used to investigate neutralization of incident beam but normally kept grounded) and impinged upon the target. The target chamber is illustrated by Figs. 1 and 2.

The target was deposited on a copper plate whose plane was vertical. It was soldered to the under side of a liquid-nitrogen container, which in turn was supported on a thin-walled steel tube passing through a Wilson seal in the lid of the chamber. The target could thus be rotated. The axis of rotation coincided with the vertical axis of the chamber itself, and was carefully arranged to lie in the front face of the target plate. Under these circumstances the spot produced at the front face of the target by a radial beam lay always on the axis of the chamber, and did not change its position as the target rotated.

After the cooling trap had been filled, a layer of heavy ice could be deposited on the target, which could then be turned to any desired orientation for carrying out a measurement.

The protons from the nuclear reaction were detected in a proportional counter having a mica window of about 8-cm air equivalent. (The proton range was about 14 cm; all other charged-particle ranges were less than 2 cm.) A small solid angle ($\sim 4\pi/1000$) was subtended at the target spot by the counter window. The arrangement was therefore one having "good" geometry. The counter could be rotated in a horizontal plane about a vertical axis passing through the target spot. Adjustment was made through a Wilson seal at the bottom of the tank (Fig. 2), so that the position of the counter could be altered without breaking the vacuum. The setting of the counter θ, defined as the angle between the direction of the incident beam and the radius joining target spot to counter window, could be varied from 40° to 150°. Moreover, the counter was electrostatically shielded against strong disturbances from the target.

The glass windows were provided in the chamber to permit an optical check on the alignment of the system.

A determination of the incident deuteron intensity was accomplished by measuring the beam current on the target and, in order to measure this current, a current integrator for use in the range 0.01 to 2.5 microamperes was, designed and built by W. J. Poole. The circuit is shown in Fig. 3. Charge was accumulated on a 0.005-μf silver mica condenser which was automatically discharged when the potential reached 110 v; and, to ensure proper functioning of this circuit, care was taken that the leakage resistance across the condenser from target to ground was higher than 10^5 megohms. The calibration was effected with a galvanometer and the change in sensitivity of the circuit was tested at intervals during the investigation.

The target was held at a positive potential of 100 v so as to eliminate influences of secondary electrons on the recorded target current. However, there was some concern as to whether secondaries produced at the second slit of the beam collimator (Fig. 1) were attracted to the target. To test this point, a hollow, cylindrical, permanent magnet was mounted coaxially around the collimator. The field of this magnet was chosen so as to cause electrons to spiral away from the target without appreciably affecting the deuterons. Nevertheless, the reaction yield per microcoulomb of effective beam current was found to be the same before and after inserting the magnet.

At low energies a beam of charged particles tends to suffer neutralization. Since the number of deuterons reaching the target was measured in terms of the positive charge collected, any neutralization in the incident beam, occurring between the analyzing magnetic field and the target, could well invalidate these measurements. Therefore, an attempt was made to achieve as low a pressure as possible in this region by pumping it from both ends. A 4-in. oil diffusion pump and a liquid-nitrogen trap were located in front of the magnetic analyzer; another such pumping system was mounted below the target chamber behind the analyzer and a third liquid-nitrogen trap was suspended in the target tank itself. To test the efficiency of the system, the electrostatic deflector (Fig. 1) was used on a 17-kev deuteron beam. The conclusion was that only about 1.5 percent of this beam was neutralized, and at higher energies the neutralization would, of course, be less.

A high vacuum was also essential to reduce any target contamination; e.g., traces of oil become attached to the surface and are carbonized by the beam. Since the target was cooled by liquid nitrogen, this possibility could have been very

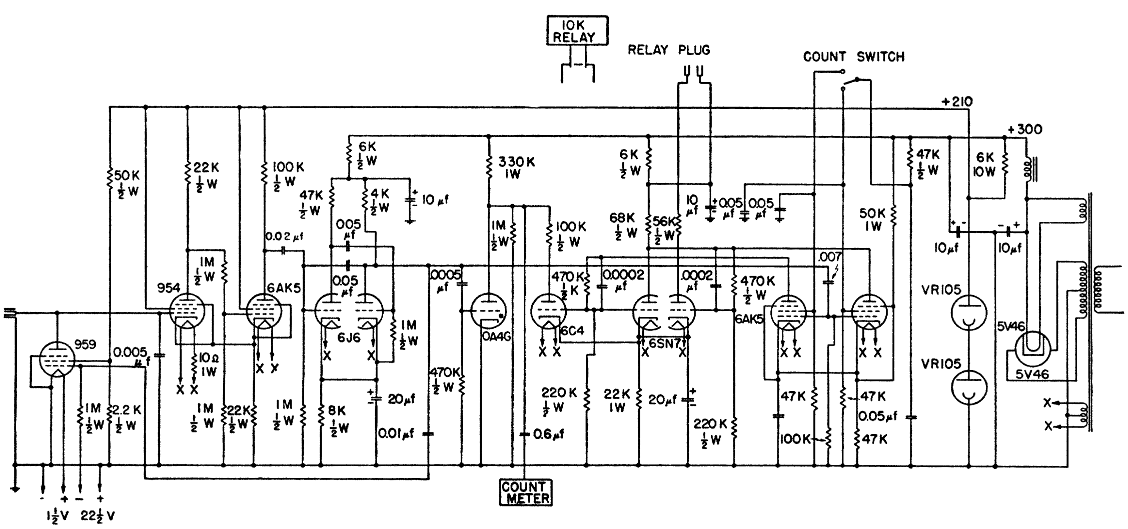

FIG. 3. Automatic current integrator.

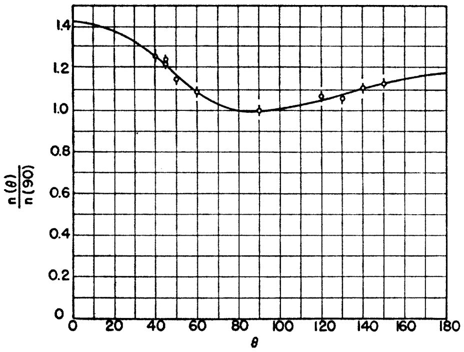

FIG. 4. Angular distribution D+D 50 kev. Laboratory system. $A=0.30\pm0.03$.

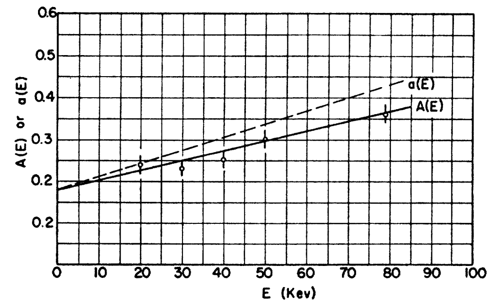

FIG. 6. $A(E)$ and $a(E)$ *vs.* E. ⸸ Observed values of $A(E)$ $A(E)=0.175+0.0023E$; $a(E)=0.175+0.0031E$. (The bottom symbol marking the ordinate should be 0.1.)

marked, in which case some energy would be lost from the incident beam before it actually reached the D_2O. To remove condensable material at the start of a run, the three liquid-nitrogen traps were kept filled for several hours before the target trap itself was cooled. Two checks were possible on the effect of target contamination: an observation of the change with time of the reaction yield at a given bombarding voltage and a search at a given deuteron energy for any dependence of yield on the angle of the target face relative to the incident beam. Upon applying these checks the contamination problem was found to be negligible.

ANGULAR DISTRIBUTION MEASUREMENTS

In Fig. 4 is shown a typical experimental result of the angular distribution measurements. A curve has been drawn through the experimental points corresponding to the relations:

$$n'(\theta')=n'(90°)[1+A(E)\cos^2\theta'], \quad (3)$$

$$n'(\theta')=g(\theta)\cdot n(\theta). \quad (4)$$

$n(\theta)/n(90°)$ has been plotted, where $n(\theta)$ is the number of protons per microcoulomb of beam observed in the counter at setting θ for the bombarding energy E. $n'(\theta')$ denotes the hypothetical count at an angle θ' in the c.g. frame corresponding to the observed count $n(\theta)$ in the laboratory system and $g(\theta)$ is the functional factor connecting the two distributions. The quantities in (3) and (4) refer to thick target yields. $g(\theta)$, which in the case of a thin target may be evaluated from the incident deuteron energy E and heat of reaction Q, has been taken as the weighted mean value corresponding to a thick target and can be arrived at from an

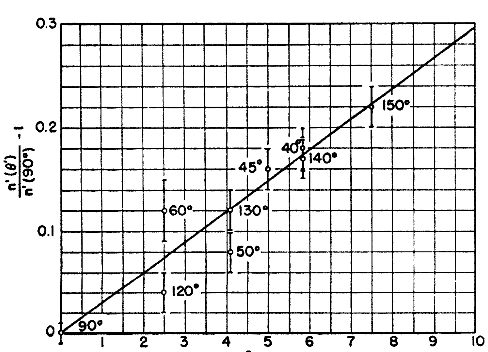

FIG. 5. D+D 50 kev. Test of $\cos^2\theta'$ law.

$$\left[\frac{n'(\theta')}{n'(90)}-1\right] \quad vs. \quad \cos^2\theta'. \quad A=0.30\pm0.03.$$

TABLE I.

E kev	$E^{-\frac{1}{2}}$ (Mev)$^{-\frac{1}{2}}$	$(1/F)n(125°)$ counts	$g(125°)$*	$N(E)$ per microcoulomb
15.4	8.05	2.47×10^2	1.025	2.53×10^2
18.1	7.45	6.24×10^2	1.028	6.40×10^2
20.5	7.00	1.18×10^3	1.030	1.21×10^3
23.0	6.60	2.29×10^3	1.031	2.36×10^3
23.8	6.47	2.71×10^3	1.032	2.79×10^3
26.4	6.15	4.30×10^3	1.033	4.43×10^3
30.6	5.67	8.60×10^3	1.035	8.88×10^3
31.6	5.60	9.90×10^3	1.037	1.03×10^4
35.6	5.25	1.73×10^4	1.040	1.80×10^4
39.6	5.02	2.32×10^4	1.042	2.41×10^4
40.9	4.92	2.81×10^4	1.044	2.93×10^4
45.6	4.68	4.13×10^4	1.046	4.32×10^4
47.7	4.56	4.90×10^4	1.047	5.13×10^4
52.8	4.35	6.29×10^4	1.050	6.59×10^4
63.2	3.97	1.11×10^5	1.055	1.17×10^5
79.2	3.56	2.19×10^5	1.061	2.32×10^5
95.0	3.25	3.60×10^5	1.070	3.85×10^5
105.6	3.08	4.45×10^5	1.075	4.78×10^5

* Thick target values of $g(125°)$.

approximate knowledge of the excitation curve. The value of $A(E)$ has been obtained by a best fit of the data. A more exacting test of the validity of (3) consists in plotting

$$\frac{n'(\theta')}{n'(90°)}-1$$

against $\cos^2\theta'$; since the degree of anisotropy is small, experimental errors are thus magnified (Fig. 5).

The angular distribution has been studied for five bombarding energies E (20 kev to 80 kev)

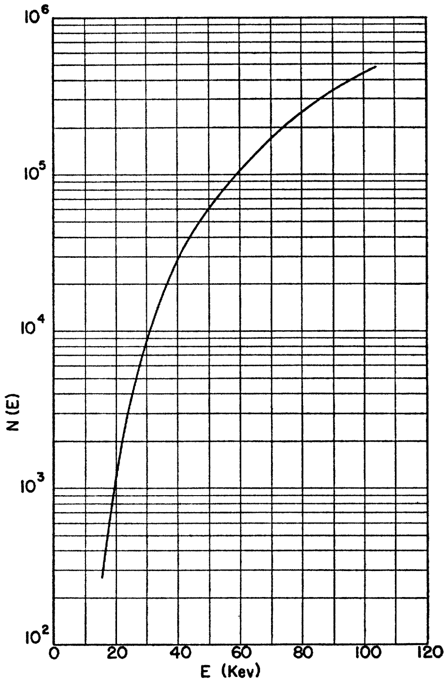

FIG. 7. Complete excitation curve, 15 kev to 105 kev. $N(E)$ *vs.* E. $N(E)$ is in units of protons per microcoulomb of incident deuteron beams.

and in each case plots similar to Figs. 4 and 5 have been prepared. During these investigations the angle ϕ between the target face and forward direction of the incident beam was set about 20°; but variations in ϕ apparently did not modify the angular distribution, provided the protons being counted did not leave the target surface at too slight an angle. $A(E)$ as a function of E is given by Fig. 6. The corresponding thin target quantities††† $a(E)$ were calculated and are indicated

††† I.e., in the c.g. frame $\eta'(\theta')=\eta'(90°)[1+a(E)\cos^2\theta']$, where the number of protons emitted per solid angle $\sin\theta' d\theta' d\phi'$ is given by $\eta'(\theta')\sin\theta' d\theta' d\phi'$.

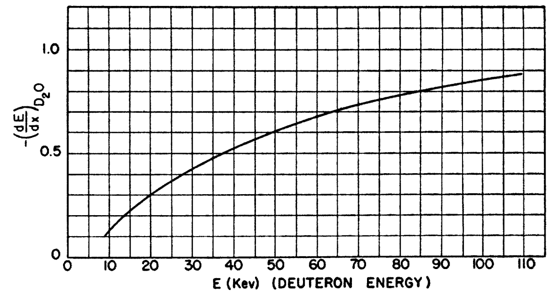

FIG. 8. Energy loss of deuterons in D_2O. dE/dX in kev per cm in D_2O vapor at 1-mm pressure, 15°C.

by the dashed line (Fig. 6). When these results for $a(E)$ are plotted against E together with values for $a(E)$ as have been obtained (cf. reference 1) in the region 89 to 246 kev by workers at New York University, all the points appear to fall on the same straight line. Using our data only, empirical *linear* relations between $A(E)$ and $a(E)$ and energy E were computed by a least square fit, although the results in themselves are not accurate enough to completely justify this assumption of linearity. It is interesting that the asymmetry coefficient $a(E)$ shows no sign of tending to zero at zero bombarding energy.

EXCITATION-CURVE MEASUREMENTS

If (3) is obeyed, the total yield $N(E)$ can be found from observations at a single angle, without a knowledge of the asymmetry coefficient $A(E)$. This statement may be demonstrated as follows: If $n(\theta)$ is the number of protons observed per microcoulomb of beam by a counter of effective solid-angle factor F, then the number per unit solid angle is $n(\theta)/4\pi F$ and

$$N(E)=\frac{1}{2F}\int n(\theta)\sin\theta d\theta=\frac{1}{2F}\int n'(\theta')\sin\theta' d\theta',$$

where $n'(\theta')$ is given by (3). Using (3) we may show that

$$N(E)=\frac{1}{F}n'(\theta_0'), \qquad (5)$$

provided $\cos^2\theta_0'=\frac{1}{3}$, i.e., $\theta_0'=54°44'$ or $125°16'$. The corresponding angles θ_0 in the laboratory system depend on E; in this work $E\leq 105$ kev, so that values of θ_0 never differ from angles in the c.g. system by even as much as 3°.

It is apparent from analysis that the errors are least appreciable when observations are made at $\theta_0 = 125°$; consequently, the relation which was used to determine the thick target yield $N(E)$ as a function of energy (E) is

$$N(E) = \frac{g(125°)}{F} n(125°). \quad (6)$$

Observations of $n(125°)$ were made using both mass 4 and mass 2 beams. The mass 4 was assumed to be pure D_2^+ so that a measurement of the yield per microcoulomb of target current led directly to the number of protons produced by the nuclear reaction per incident deuteron. With mass 4, however, only half the maximum bombarding energy could be obtained. The full energy was obtainable with mass 2 which contained H_2^+ as well as D_1^+. To find the absolute yield of the mass 2 beam a correspondence was made between respective curves for mass 2 and mass 4 of the form $\log N(E)$ *vs.* $E^{-\frac{1}{2}}$, $N(E)$ representing here either apparent yield by mass 2 or absolute yield by mass 4. For both cases such a plot was found to give a straight line within experimental error, and the lines were parallel.

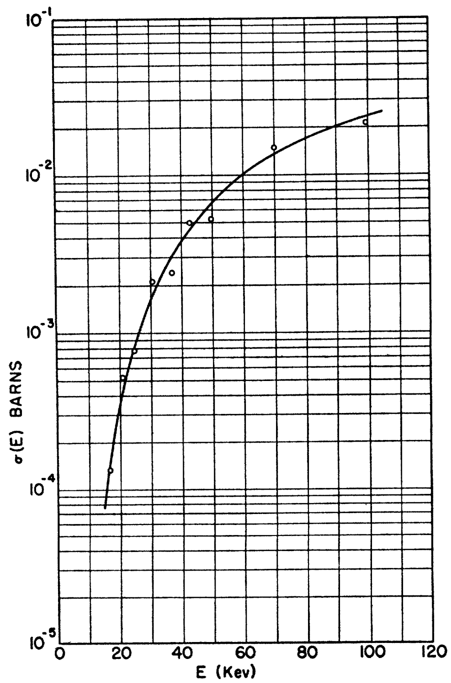

FIG. 9. D+D cross section for proton emission, 15 kev to 105 kev.

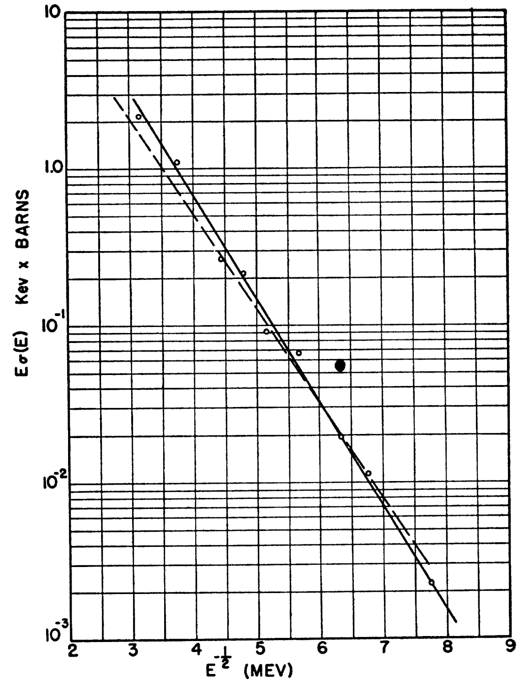

FIG. 10. ——— experimental curve. - - - - - theoretical slope. Gamow plot: $\log[E\cdot\sigma(E)]$ *vs.* $E^{\frac{1}{2}}$. Theoretically, $\sigma(E) = \text{const.}\ 1/E.\ \exp[-1.408E^{-\frac{1}{2}}]$.

Moreover, the resulting straight line for mass 2 indicates that the H_2^+ content of this beam was independent of energy. The distance between the lines determined the constant factor by which the observed mass 2 yields were to be multiplied to give the true values.

The experimental data are set out in Table I. $N(E)$ *vs.* E is shown in Fig. 7.

CROSS SECTION

The cross section for reaction (1) may be found from the data in Table I by using the relation

$$\sigma(E) = 1/A \cdot dN/dE \cdot dE/dx, \quad (7)$$

where A contains the product of the number of incident deuterons per unit of beam current and the number of deuterium nuclei per cm^3 in the target and dE/dx is the rate of energy loss of incident deuterons in the D_2O ice target.

dN/dE as a function of energy E has been evaluated by two closely related methods. According to the first, $\Delta N/\Delta E$ was taken from the differences of the yield $N(E)$ for adjacent energies E_1, E_2, and the energy E associated with each $\Delta N/\Delta E$ was obtained as‡

$$E^{-\frac{1}{2}}=\tfrac{1}{2}(E_1^{-\frac{1}{2}}+E_2^{-\frac{1}{2}}),$$

which is an average along the experimentally straight line $\log N(E)$ *vs.* $E^{-\frac{1}{2}}$. According to the second, the data in Table I were fitted to the form

$$\log_{10}N(E)=A-BE^{-\frac{1}{2}} \quad (8)$$

which was then differentiated.

However, in absence of suitable experimental work, the evaluation of dE/dx in D_2O ice for deuterons between 10 and 100 kev gives trouble. An endeavor has been made to estimate this quantity on the basis of certain experiments[5–8] by Gerthsen and his co-workers, concerning the energy loss of slow protons in various media (air, hydrogen, and celluloid). Their results are applicable to our case through the following assumptions: (a) that the rates of energy loss of a proton and a deuteron having the same velocity are identical in any given medium; (b) that the atomic stopping powers of H and D are nearly identical; (c) that the molecular stopping power of D_2O can be found by adding the atomic stopping powers of two atoms of H and one atom of O, and (d) that the stopping power of D_2O is roughly independent of its physical state.[9] By subjecting to least square analyses the data from the various experiments by Gerthsen, Eckardt, and Reusse through the energy region 5–50 kev, expressions for the rate of energy loss dE/dx of protons in air, hydrogen, and celluloid were obtained. These values of dE/dx were combined according to assumptions (a) to (d) into the variation with E of dE/dx for deuterons in D_2O, and the result is given in Fig. 8. This curve was used in the derivation of $\sigma(E)$.

The resulting dependence of $\sigma(E)$ for reaction (1) upon E is shown by Figs. 9 and 10. The individual points were derived from $\Delta N/\Delta E$; while the full curves correspond to values obtained by differentiating (8). It may be seen that the Gamow plot of Fig. 10 is a straight line, but with a slightly different slope from the theoretical curve.

ERRORS

During most measurements the counting errors did not exceed 1 percent, except at the lowest energies (~15 kev) where the intensities were weak. The bombarding energy was known to within 1 percent. Determinations of beam current by the integrator should be good to ±2 percent. And as far as could be discovered, errors resulting from target contamination or secondary-electron emission were together not more than 1 percent. The error due to observing at 125° in the laboratory system instead of 125° in the c.g. system was always less than 1.5 percent. The presence of neutral particles in the beam amounted to less than 1 percent, except at the lowest energies employed. Geometrical errors, as arise from measurements of the counter solid-angle factor F, are considered to be ±2 percent. Combination of these considerations leads to an aggregate error in the thick target yield $N(E)$ amounting to ±4 percent at most energies, but reaching ±8 percent at 15 kev.

CONCLUSIONS

The experiments described here appear to be a reliable measure of the thick target yield of reaction (1) for bombarding energies 15 to 105 kev. However, if these thick target yield measurements are to be translated with any certainty into values for cross sections, a far better knowledge of dE/dx for deuterons in heavy ice is required.

‡ It may be more correct to use $E=\frac{1}{2}(E_1+E_2)$, although it makes no practical difference.

[5] Chr. Gerthsen, Ann. d. Physik **5**, 657 (1930).

[6] Chr. Gerthsen, Physik. Zeits. **31**, 948 (1931).

[7] A. Eckardt, Ann. d. Physik **5**, 401 (1930).

[8] W. Reusse, Ann. d. Physik **15**, 256 (1932).

[9] Some discussion of assumptions (c) and (d) as concerns α-particles appears in a paper by L. H. Gray, Proc. Camb. Phil. Soc. **40**, 72 (1944).