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Distribution in Angle of Protons from the Deuteron-Deuteron Reaction

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The distribution in angle of the protons from the deuteron-deuteron reaction has been measured with a gas target over a range of bombarding energy from 60 to 390 Kev. The results are representable by

$$N(\theta)=1+A\cos^2\theta$$

in which θ is the angle which the proton's velocity makes with the direction of the deuteron beam as measured in the center-of-mass coordinate system and $N(\theta)$ is the number observed per unit solid angle at θ. The value of A is found to be markedly dependent on bombarding energy.

INTRODUCTION

MEASUREMENTS of the angular distribution of the protons emitted in the reaction

$$H^2+H^2\rightarrow H^3+H^1$$

have shown that the distribution is markedly anisotropic and that it is probably of the form $1+A\cos^2\theta$ in the center-of-mass coordinate system.[1–5]

Different investigators have not obtained concordant results on the value of A nor on the question of its energy dependence. Satisfactory interpretation of their measurements is made difficult, however, by two practical factors inherent in the use of thick deuterium targets: (1) an uncertainty in the actual collision energy of an incident deuteron caused by surface contamination, and (2) an uncertainty in the character of the target—that is, in the distribution of deuterium and in the stopping power during prolonged bombardment.

The seriousness of these uncertainties is even greater since *both* yield and angular distribution data on the same or an equivalent thick target must be known as a function of bombarding energy in order to deduce thin-target (i.e., theoretically interesting) angular-distribution data.

A suitably arranged gaseous target is free of these uncertainties and is very attractive as an experimental possibility. It has been found feasible to use such a target of deuterium gas in a careful study of the angular distribution of the protons at several bombarding energies.

The simplicity and importance of the deuteron-deuteron reaction recommend such a study.

HIGH VOLTAGE EQUIPMENT

The magnetically analyzed deuteron beam of 10 to 20 microamperes used in this work was

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[1] Kempton, Browne and Maasdorp, Proc. Roy. Soc. **A157**, 386 (1936).
[2] H. Neuert, Physik. Zeits. **38**, 122 (1937).
[3] Haxby, Allen and Williams, Phys. Rev. **55**, 140 (1939).
[4] H. Neuert, Physik. Zeits. **39**, 890 (1938).
[5] H. Neuert, Ann. d. Physik **36**, 437 (1939).

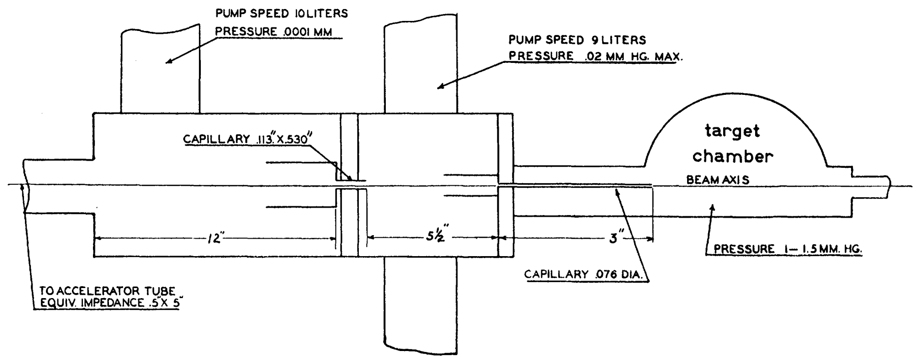

FIG. 1. Schematic diagram of pumping system used to maintain the necessary pressure differential between the target chamber and the accelerating tube.

obtained in a five-foot accelerating tube provided with a low voltage ion source. Rectified potentials up to 400 kilovolts were available from a transformer-rectifier-quadrupler of Cockcroft-Walton type.

The average energy of the deuteron beam was determined with an accuracy of about 5 percent with a high resistance voltmeter of standard type.[6] The voltmeter consisted of 455 ten-megohm IRC metalized resistors, which had been carefully calibrated for resistance as a function of current. The voltmeter was checked for linearity by setting the deflecting magnet, then raising the voltage to bring successive m/e components of the beam into the narrow entrance canal of the target chamber.

Gas Targets

A gas target can be a close approximation to an ideally thin target. The stopping power of deuterium gas at a pressure of 1 mm of Hg for 100-kev deuterons is about 0.2 kev per cm and the number of disintegrations produced by a beam of one microampere in 3 or 4 mm of path is sufficient to give a workable counting rate in a reasonably small solid angle. Thus, the energy loss of the beam in traversing the target is quite negligible for the energies used in these experiments.

At *low* bombarding energies the advantages of such a target are lost if the deuteron beam is admitted to the target chamber through a foil. Foils sufficiently thick to stand up under the intense beams necessary introduce a large energy loss difficult to measure accurately, a straggling large compared to the residual energy, and a spread in energy due to variations in foil thickness.

These difficulties are avoided by admitting the beam through a tube of sufficiently small bore to permit the maintenance of the necessary pressure difference between the target chamber and the accelerating tube. While the beam must, of course, traverse a certain minimum distance through a gas of increasing density in order to reach the effective target volume the apparatus can easily be arranged so that this path does not exceed 15 cm. The resulting total energy loss is about 2 kev per mm of gas pressure in the target chamber. The straggling produced is obviously negligible. The effective collision energies of the deuterons in the beam can thus be known with an error of less than one percent for bombarding energies greater than 50 kev.

The gas flow from such a chamber is easily handled by a two-stage differential pumping system as shown schematically in Fig. 1. With the geometrical arrangement indicated it is possible to get a beam of approximately a microampere through the target volume. With a gas pressure of 1.5 mm of Hg the yield from 5 mm of beam length is about 500 protons per minute into a solid angle of 0.007 steradian at 90°. Under these conditions one-half liter of deuterium at NTP is required per hour of operation. No provision was made for recovering the gas.

Although the use of a smooth wall capillary

[6] Hafstad, Heydenburg and Tuve, Phys. Rev. **50**, 504 (1936).

to admit the beam to the target volume is desirable because of its greater impedance to gas flow from the target chamber experience has shown that the use of such a tubular capillary introduces what appears to be a serious loss of energy in the incident beam. The result is an apparent equatorial asymmetry in the observed angular distribution.

The substitution of a series of thin diaphragms to reduce small angle scattering as shown in Fig. 2 removes this effect and gives an angular distribution with the proper equatorial symmetry.

Target Chamber

The apparatus used is shown in Fig. 2 (a, b, c). Essentially it consists of a regular twelve-sided right cylinder A whose thick walls are pierced by 12 holes with coplanar axes bored in the centers of its 12 faces. Into one of these holes is set a tube B which carries the system of 5 diaphragms through which the beam enters the target chamber.[7] The sizes of these diaphragms and the inside diameter of the intervening spacers are so chosen that no part of the spacers can be seen by *both* the incident beam and the target volume. Only the edges of the diaphragms can scatter directly into the target volume, and this scattering is minimized by making these diaphragms thin in comparison to their spacing. The beam

[7] Note that 2(a) and 2(b) are drawn with the beam entering from the bottom. In use the entrance canal was uppermost.

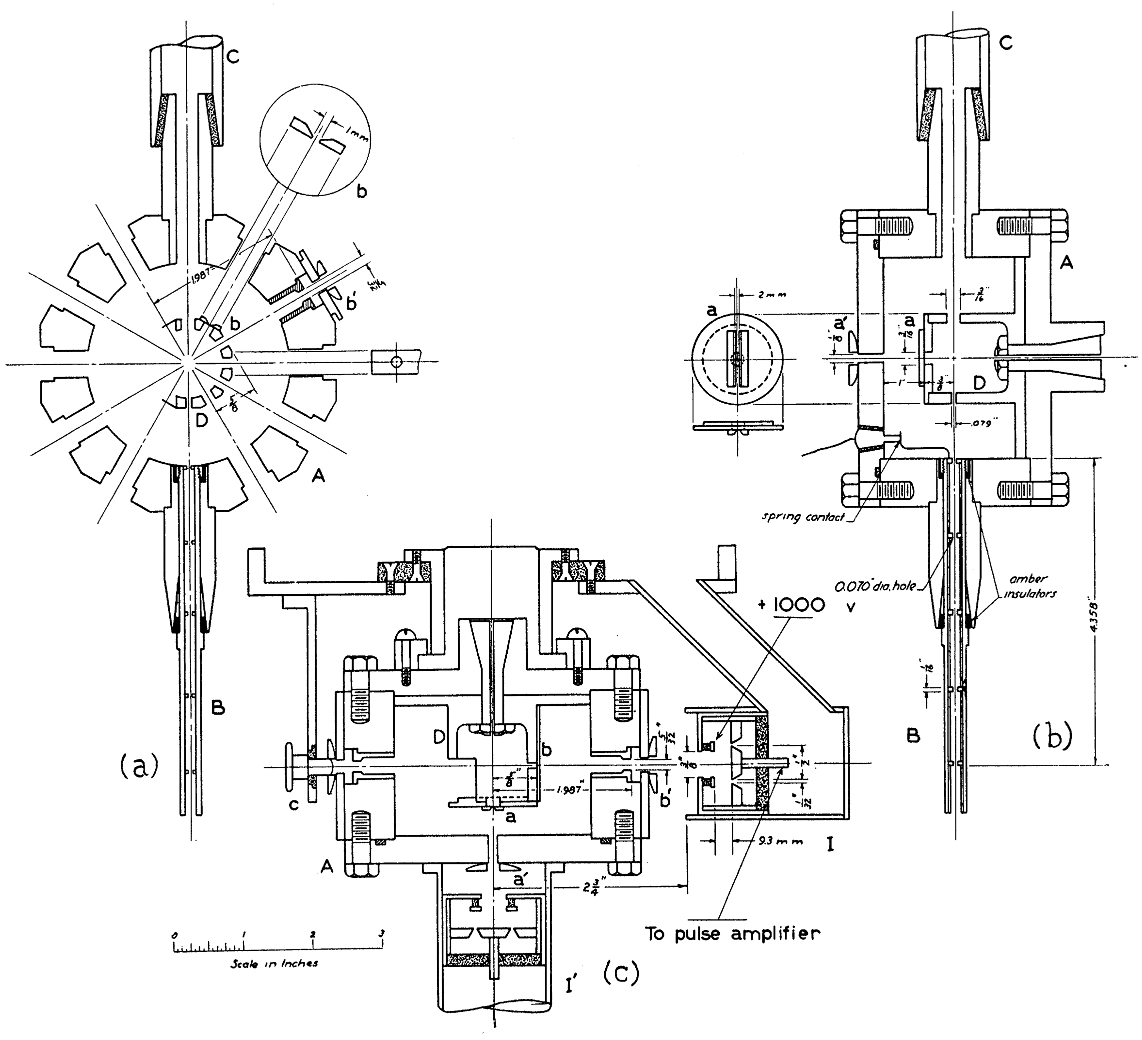

FIG. 2 (a, b, c). Final target chamber.

is allowed to escape from the target chamber before its main portion strikes a metal surface, in this case the bottom of an insulated cup C. This reduces the intensity in the vicinity of the ionization chambers of the neutrons produced where the beam is stopped, and thus aids in keeping down the background count.

The method of making observations is evident from the figures. The stationary ion chamber I' views the beam from a fixed azimuth (90°) and receives particles from a length of beam and within a solid angle determined by the diaphragms a, a'. The number of protons entering this chamber is simply a measure of the number of disintegrations produced by the bombarding beam.

The movable ion chamber I sees the beam through apertures b, b'. The aperture b' is a circular hole $\frac{5}{32}''$ in diameter in the center of a brass plug which fits tightly into one of the 12 regularly spaced holes mentioned above. Between the aperture b' and the ion chamber is a vacuum-tight aluminum window (0.0015 inch thick) supported as shown in the sketch. The hole in this window support is large enough so that it does not define the solid angle. The other defining aperture, b, is a slot perpendicular to the beam carried on another twelve-sided metal cylinder D which is mounted so as to be accurately coaxial with the cylinder A. The slots b are made amply long so that the ion chamber can see the full diameter of the beam.

The position of these slots on the cylinder D was determined as follows. Circular holes $\frac{1}{8}''$ in diameter were bored in the centers of the flat faces of the cylinder D. Into these could be fitted a cylindrical metal plug one end of which had been cut away from opposite sides so as to leave two parallel flat faces equidistant from the axis of the cylinder. This plug was inserted into the $\frac{1}{8}''$ holes mentioned above, the slit edges were set up against its flat faces, and the slits were then fastened in place. The plug could be withdrawn, rotated 180° about its axis, and reinserted with an equally good fit, showing that the center of the slit coincided with the axis of the hole. This procedure also arranged that the slits were all quite closely the same width, a fact which was subsequently checked by means of a micrometer microscope.

The placing of the cylinder D in correct azimuth relative to A was secured as follows. With the cylinder D removed it was first verified that the axes of the 12 holes in the cylinder A were coplanar and possessed a common point of intersection. This was done by passing a close fitting piece of ground rod through a pair of diametrically opposite windows and measuring the distances from this rod to the faces of the cylinder A which were parallel to it, and measuring the distances to the ends of the cylinder. By this means it was verified that the constructed chamber did not deviate from the desired geometry by more than 0.001″ in the dimensions referred to. The cylinder D was then placed in correct azimuth by inserting into the holes b rods which had on their inner ends concentric cylindrical portions of such size that they fitted closely into the holes in D.

Apertures in only one-half of the target chamber were used in the actual observations. The diametrically opposite ones were provided for convenience in checking accuracy of machining, in aligning D, and in assuring the correct location of the movable ion chamber.

Shields (not shown) were so placed that the exit windows b' could see no part of the beam save that in the effective target volume.

The entrance canal B is insulated from the target chamber and is connected to an external lead. Cup C is insulated also. These features are useful in aligning the canal with the beam and in maintaining as large a current as possible through the target chamber. None of the measurements depends on a knowledge of this current, however.

The pumping system was essentially that shown in Fig. 1. Since the impedance of the system of diaphragms (Fig. 2) was only about one-fifth that of the capillary of Fig. 1, it was necessary to operate with a deuterium pressure of 0.3 mm of Hg in the target chamber instead of the 1.5 mm referred to previously.

Counting Equipment

As described above there is a fixed ionization chamber located at $\alpha = 90°$, where α is the angle with respect to the forward direction of the beam as measured in the laboratory. A second ionization chamber is mounted on a heavy spindle whose axis coincides with the transverse axis of the scattering chamber. This second chamber counts in turn the protons ejected through each of the five windows (b' of Fig. 2c) at the angles $\alpha = 30°$, $60°$, $90°$, $120°$, $150°$. Its position with respect to a window is accurately determined by a diametrically opposite aligning pin (c of Fig. 2c).

Each chamber has a depth of 9.3 mm. The pulses were amplified by independent linear amplifiers, passed through thyratron pulse sharpeners and high vacuum-tube scale-of-two circuits.[8] The outputs of the scalers actuated multivibrator type driving circuits which delivered a power pulse to mechanical recorders.

Since the highest counting rate used was about three protons per second the counting losses due to resolving time of the mechanical recorders were negligible.

Visual checking of the amplifier output with an oscilloscope guarded against spurious counts due to sparks or acoustic disturbances.

TABLE I. *Distribution in angle of protons from deuteron-deuteron reaction.*

E (KEV)	α	$I(\alpha)$	$N(\alpha)$	θ	$N(\theta)$	STATISTICAL PROBABLE ERROR $\pm\%$
390	150°	3.25	1.62	153.7°	2.02	2.3
	120	1.43	1.24	126.3	1.41	4.3
	90	1.00	1.00	97.3	1.00	5.2
	60	1.50	1.30	66.3	1.14	4.2
	30	4.75	2.38	33.7	1.92	1.5
320	150	3.38	1.69	153.3	2.07	2.0
	120	1.42	1.23	125.8	1.38	3.3
	90	1.00	1.00	96.7	1.00	2.4
	60	1.49	1.29	65.8	1.15	3.2
	30	4.45	2.22	33.3	1.83	1.7
260	150	3.06	1.53	152.8	1.82	1.5
	120	1.32	1.14	125.1	1.27	6.3
	90	1.00	1.00	95.9	1.00	2.4
	60	1.46	1.26	65.1	1.14	4.7
	30	4.14	2.07	32.8	1.74	1.3
210	150	3.02	1.51	152.7	1.78	3.7
	120	1.37	1.19	124.6	1.30	4.8
	90	1.00	1.00	95.3	1.00	2.4
	60	1.60	1.38	64.6	1.27	3.4
	30	4.08	2.04	32.7	1.75	1.5
140	150	3.02	1.51	152.2	1.72	2.9
	120	1.38	1.19	123.7	1.29	4.7
	90	1.00	1.00	94.3	1.00	2.4
	60	1.48	1.28	63.7	1.20	4.2
	30	3.69	1.84	32.2	1.62	2.5
60	150	2.46	1.23	151.4	1.34	2.6
	120	1.33	1.15	122.4	1.20	5.2
	90	1.00	1.00	92.7	1.00	2.4
	60	1.40	1.21	62.4	1.15	4.5
	30	2.91	1.46	31.4	1.34	2.6

[8] Lifschutz and Lawson, Rev. Sci. Inst. 9, 83 (1937).

COUNTING PROCEDURE

The measurement of the angular distribution was made as follows. During a counting interval the fixed (monitor) chamber counts a number of protons F proportional to the total number of disintegrations produced in the effective target volume. In the same interval the movable chamber records a count M consisting of the protons emerging through one of the five windows[9] plus a background count apparently due to neutron recoils in the ionization chamber. The background in the fixed chamber was negligible since it counted a number of protons of the order of ten times that counted in a given interval by the movable chamber and since further the fluctuations in background count were never observed to exceed reasonable statistical expectations.

To correct for the background of the movable ionization chamber a measure of its magnitude was made at frequent intervals during a run at any one window by excluding the protons from the ionization chamber with a heavy aluminum foil and recording the background count. This was done without moving the chamber.

During a counting interval under these conditions the movable chamber records a background count B while the monitor chamber records a count F_b still proportional to the number of disintegrations in the target volume. A run at any one window then consists of several counting intervals interspersed with background counting intervals. Calling $\bar{F}$, $\bar{M}$, $\bar{B}$, $\bar{F}_b$ the total numbers of the respective counts obtained during a run, the quantity

$$\frac{1}{\bar{F}}\left(\bar{M}-\frac{\bar{F}}{\bar{F}_b}\bar{B}\right)=\frac{\bar{M}}{\bar{F}}-\frac{\bar{B}}{\bar{F}_b}$$

[9] In order to make the signal to noise ratio in the amplifier output as large as possible, the protons were slowed to within two or three centimeters of the end of their range by aluminum foils of stopping power appropriate to the value of proton energy for the window under consideration and to the bombarding energy.

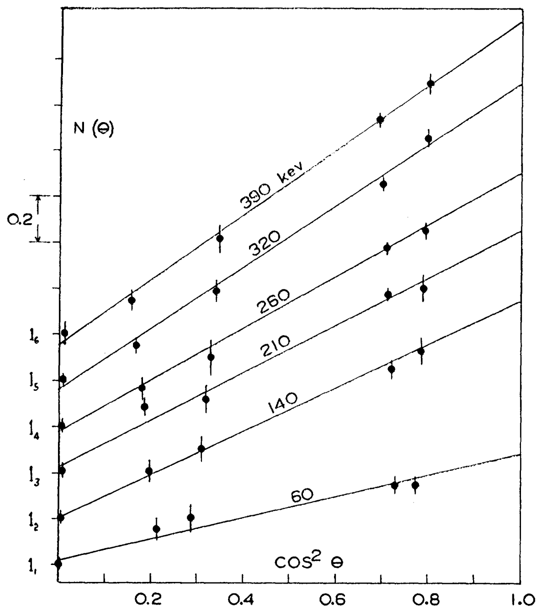

FIG. 3. Angular distribution of the ejected protons plotted against $\cos^2 \theta$. Note that the scale for successive curves is shifted 0.2 unit of ordinate. The length of the vertical bar through each point is equal to twice the statistical probable error of that point.

was calculated. The experimental values of this quantity, normalized to unity at $\alpha = 90°$, are tabulated as $I(\alpha)$ in Table I. No geometric or other corrections have been applied in calculating $I(\alpha)$, other than the background correction just described.

Several thousand protons were observed at each window at each voltage. The statistical probable errors given in the last column of Table I were calculated in the usual way, remembering that $I(\alpha)$ is the function of experimental data written in the paragraph above.

Results

Examination of the geometry of the target chamber shows that the effective target volume

TABLE II. *Values of $A(E)$ as obtained from Fig. 3.*

E(kev)	60	140	210	260	320	390
A	0.46	0.95	1.02	1.17	1.38	1.49

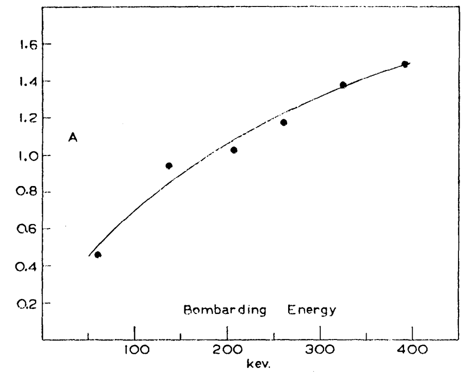

FIG. 4. Values of A as a function of the energy of the incident deuterons.

is with negligible error proportional to $1/\sin \alpha$. Thus, the laboratory angular distribution

$$N(\alpha) = I(\alpha) \sin \alpha.$$

This distribution $N(\alpha)$ has been transformed to the corresponding distribution $N(\theta)$ in the center of mass system.[3]

The results are tabulated in Table I and are exhibited graphically as a function of $\cos^2 \theta$ in Fig. 3.

It is evident that the distribution can be reasonably well represented by an equation of the form

$$N(\theta) = 1 + A(E) \cos^2 \theta$$

in which A is a function of the bombarding energy E.

Table II shows the values of $A(E)$ as obtained from the slopes and intercepts of the curves of Fig. 3. These values are quite well represented by the expression $A = A_0 E^{\frac{1}{2}}$. In Fig. 4 the data of Table II are plotted. Note that E is the bombarding energy as measured in the laboratory.

Acknowledgment

It is a pleasure to acknowledge the skilful assistance of our instrument maker, Mr. J. G. Sentinella, who constructed the target chamber and gave valuable help at all stages of the work.