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The Angular Distribution of the Disintegration Products of Light Elements

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The angular distributions of the following reactions:

$$Li^6+H^2\rightarrow 2He^4$$
$$H^2+H^2\rightarrow H^3+H^1$$
$$B^{11}+H^1\rightarrow Be^8+He^4$$
$$B^{11}+H^1\rightarrow 3He^4$$

have been investigated over the range of angles from 45° to 150° and over a range of bombarding voltages between 100 and 200 kv. The Li reaction was found to be spherically symmetrical. The deuteron-deuteron protons were found to have an angular distribution in the center of mass system of coordinates represented by $1+0.7\cos^2\theta$ over a range of bombarding voltages from 106 to 190 kv, with no measurable dependence upon deuteron energy. The third reaction, a resonance process, investigated at 190 kv, gave an angular distribution represented by $1+0.7\cos^2\theta$. The continuous energy distribution alpha-particles with ranges greater than 30 mm from the fourth reaction show an angular distribution which is dependent on the proton energy and indicate an intimate connection between the alternate modes of distintegration.

INTRODUCTION

Until recently, the few experiments performed on the angular distributions of particles emitted in artificial disintegrations showed no appreciable deviation from spherical symmetry.[1, 2] In 1936, however, Kempton, Browne and Maasdorp[3] made a careful investigation of the deuteron-deuteron reactions:

$$H^2+H^2\rightarrow H^3+H^1, \quad (1)$$

$$H^2+H^2\rightarrow He^3+n^1, \quad (2)$$

detecting both protons and neutrons in separate experiments. They discovered a very marked asymmetry in both cases when the number of particles was determined as a function of the angle with respect to the direction of the incident deuteron beam. When the observations were referred to a system of coordinates moving with the center of mass of the two particles, it was found that the angular distributions were symmetrical about 90° and that the number of particles at 0° was approximately 1.5 times that at 90°. Furthermore, the distributions were found to be insensitive to the energy of the incident deuteron between 100 and 200 kv.

Neuert[4] repeated these experiments, observing the protons from reaction (1) in an annular cloud chamber surrounding the target. His results agreed qualitatively with those of the Cambridge experimenters. He studied also the reactions:

$$Li^6+H^2\rightarrow Li^7+H^1, \quad (3)$$

$$B^{11}+H^1\rightarrow Be^8+He^4, \quad (4)$$

$$B^{11}+H^1\rightarrow 3He^4 \quad (5)$$

and established the existence of asymmetry in (4) and (5).

The importance of these observations is made evident when one notes that the assignments of nuclear resonance levels depends upon accurate experimental determinations of angular distributions of disintegration products of such resonance reactions[5] as (4). Indeed, Oppenheimer and Serber[6] definitely exclude certain possibilities for the resonance state of C^{12} on the basis of Neuert's observations. Anisotropic distributions may result only from the penetration of an incident particle with angular momentum and exact experimental data should allow some assignments of this energy state.

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[1] F. Kirchner, Physik. Zeits. **34**, 785 (1933).

[2] J. Giarratana and C. G. Brennecke, Phys. Rev. **49**, 35 (1936).

[3] A. E. Kempton, B. C. Browne and R. Maasdorp, Proc. Roy. Soc. **A157**, 386 (1936).

[4] H. Neuert, Physik. Zeits. **38**, 122, 618 (1937).

[5] J. H. Williams, W. H. Wells, J. T. Tate and E. L. Hill, Phys. Rev. **51**, 439 (1937).

[6] J. R. Oppenheimer and R. Serber, Phys. Rev. **53**, 636 (1938).

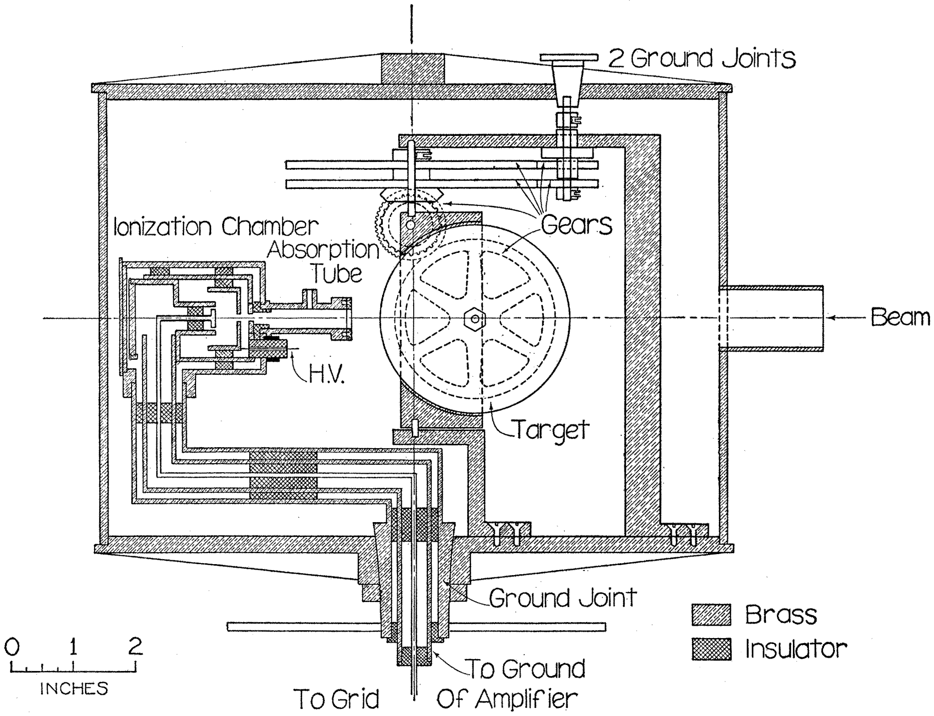

FIG. 1. Cross-sectional view of the angular distribution apparatus. The evacuated enclosure is attached to the ion accelerating tube through the opening marked "Beam" at the right. A vacuum-tight flexible connection is made through the base of the enclosure to the absorption tube.

Such further information as the energy dependence of the angular distribution should contribute much to our theories of disintegration mechanisms. For instance, the nondependence upon energy of the deuteron-deuteron reaction is not understandable from the point of view of the present theory.[7]

In view of the importance of such measurements on reactions involving light nuclei we decided to repeat and possibly extend some of the above observations.

APPARATUS

The angular detecting apparatus is shown in Fig. 1. A ten-inch diameter brass tube which was part of the vacuum system contained the target, air absorption tube and ionization chamber. The target was placed at the geometric center of this enclosure and the ionization chamber could be rotated in such a manner as always to point at this center. This angular motion was accomplished by means of a ground joint accurately centered in the base as shown in Fig. 1. A graduated scale fastened to the bottom of the tapered plug measured the angular position of the chamber with respect to the ion beam entering the side of the evacuated container.

The desirable angular motions of the target were accomplished by gears coupled to two separate ground joints which projected through the top plate. One of these rotated the target about the central axis of the vacuum container and thus varied the angle between the beam and the plane of the target surface. This adjustment was designed to keep the angle of incidence approximately equal to one-half of the angle at which the disintegration particles were observed and consequently reduce to a minimum the effect of any roughness of the target surface. The other tapered plug and set of gears rotated the annular disk target holder about an axis through its center and perpendicular to the plane of the target surface. The purpose of the latter adjustment was to present a fresh target surface

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[7] Private correspondence with Professor Oppenheimer.

to the ion beam at periodic intervals and thereby reduce the effects of surface depositions.

In order to adjust and check the position and focus of the bombarded spot on the target a telescope was inserted through the side of the container and the bright fluorescent spot was kept centered on the cross-hairs. By observing the spot for every new adjustment it was possible to reduce markedly the instrumental variations in the observations.

An adjustable pressure absorption tube was fastened to the front of the ionization chamber in order to control the amount of absorbing material between the target and the chamber. Calibrated mica windows and carefully measured air pressures allowed a continuous variation of stopping power through a range of four centimeters of air. To change the stopping power by larger amounts it was necessary to replace the mica foils covering the ends of the tube. The circular opening in the end of the absorption tube towards the target was $\frac{1}{4}$ inch in diameter which was sufficient to allow for slight variations in the position or size of the ion spot on the target. Since the opening near the ionization chamber was $\frac{5}{32}$ inch in diameter, the absorption tube served as a collimator, restricting the angular spread of the observed particles to less than ±5°. The high voltage apparatus described by Williams, Wells, Tate and Hill[5] was used to accelerate the ions in these experiments. Later modifications such as ion source,[8] voltmeter[9] and current integrator[10] have been described previously.

EXPERIMENTAL PROCEDURE

As the bombarding particle contributes energy to the disintegrating system, the range of the observed particle will depend upon the angle of observation in the laboratory system of coordinates. This change in range with angle is quite marked, particularly in the case of reactions involving light nuclei. In order to eliminate this effect the amount of absorbing material between the target and the ionization chamber was adjusted for every angle of observation in such a manner that the chosen group of particles would be recorded at the same distance from their end of range.

The momentum imparted to the disintegrating system by the bombarding particle results in a preponderance of disintegration particles being emitted in the forward direction. The momentum contribution may be eliminated by plotting the angular distributions in a system of coordinates which moves with the center of mass of the incident particle and the bombarded nucleus. Since the solid angle subtended by the detector is different for this system than for the laboratory system of coordinates, all readings must be multiplied by a factor $g(\theta)$ before the angular readings are changed by $(\theta_r-\theta)$, θ_r being given by the formula:

$$\sin(\theta_r-\theta)=(V/v_r)\sin\theta, \tag{1}$$

where V is the velocity of the center of mass, v_r the velocity of the observed particle measured in the system of coordinates moving with the center of mass, θ the angle in the laboratory system of coordinates between the direction of the observed particle and that of the bombarding beam, and θ_r the corresponding angle in the center of mass system. $g(\theta)$ is given by the formula:

$$\begin{aligned} g(\theta) &= \frac{\sin\theta\, d\theta}{\sin\theta_r\, d\theta_r} \\ &= \frac{\sin^2\theta}{\sin^2\theta_r}\cdot\cos(\theta_r-\theta). \end{aligned} \tag{2}$$

The quantitative determination of the number of particles was accomplished by a series of comparisons of the numbers emitted at neighboring angles. For example, the ratios of the number emitted per unit solid angle at 75° and 105° to those at 90°, taken as a standard angle, could be obtained without adjusting the angle between the target surface and the incident ion beam. After a sufficient number of separate observations were obtained to insure the validity of the above ratios, the experiments were then extended to another set of angles, e.g. 45°, 60°, 75°, taking 75° as the secondary standard. In this stepwise manner the total angular range available, 45° to 150°, was covered and recorded in terms of the ratio of the number of particles

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[8] J. S. Allen, Rev. Sci. Inst. **9**, 160 (1938).

[9] L. R. Hafstad, N. P. Heydenberg and M. A. Tuve, Phys. Rev. **50**, 504 (1936).

[10] J. H. Williams, W. G. Shepherd and R. O. Haxby, Phys. Rev. **52**, 390 (1937).

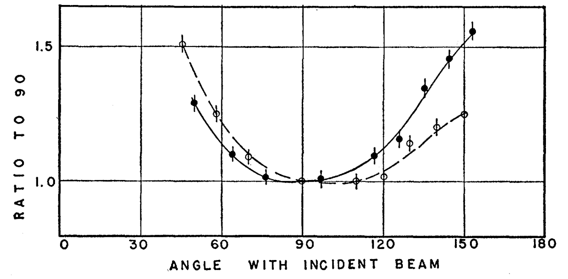

Fig. 2. The angular distribution of protons from the deuteron-deuteron reaction. ($H^2+H^2\rightarrow H^3+H^1$) at 190 kv. Dashed curve is for the laboratory system, full curve for the center-of-mass system. The ratio of the number of protons per unit solid angle observed at a given angle to the number observed at 90° as the standard is plotted as a function of the angle between the direction of the observed protons and the direction of the incident deuteron beam.

observed per unit solid angle at a given angle to those observed at 90°. These ratios were then transformed from the laboratory system of coordinates to the center of mass system of coordinates.

In order to test the reliability of the above procedure, the angular distribution of the copious, long range alpha-particles from the reaction:

$$\mathrm{Li}^6+\mathrm{H}^2\rightarrow 2\mathrm{He}^4 \tag{6}$$

was investigated. The results indicated that the distribution was spherically symmetrical to within the accuracy of the exploratory observations and the internal consistency of the readings indicated that the apparatus was sufficient for the program outlined.

Deuterium

The deuterium target used was NaOD, made by adding D_2O to Na_2O_2 and melting the resultant NaOD onto a nickel plate. This plate was mounted on the brass disk target holder adjacent to some NaOH which served as a fluorescent object in preliminary alignments of the ion beam.

Since the range of the protons from (1) changes rapidly with angle even at a bombarding deuteron energy of 190 kv, readings were taken to insure that all the protons were counted at the various angles. The ionization chamber was made 18 mm deep and the collecting voltage increased to 2000 volts. With these precautions, integral range-numbers curves demonstrated that the stopping power could be adjusted so that all the protons were detected.

The results of the final investigation of the angular distribution is shown in Fig. 2. The open circles show the experimentally determined values of the ratio of the number of protons per unit solid angle observed at a given angle to those observed at 90°. The full circles are the ratios calculated from these by transforming to a system of coordinates moving with the center of mass. It will be seen that the effect of the moving center of mass is very marked, both in the value of the ratio and in the angular coordinates. It may also be noticed that in the center of mass system the curve is symmetrical about 90° to within the statistical variations in the readings. This is obviously necessary, since in this coordinate system the two deuterons are approaching each other with equal velocities.

Following these experiments, the ratios from 90° to 150° were repeated with bombarding deuteron energies of 190 kv and 106 kv. The results of these investigations are plotted in Fig. 3. The full curve is a plot of the expression $1+0.7\cos^2\theta$ where θ is the angle in the center of mass system of coordinates between the observed disintegration protons and the incident deuterons. This curve was chosen by Kempton, Browne and Maasdorp[3] as the mathematical expression which would best fit their results. It may be seen that these results agree with theirs in showing no

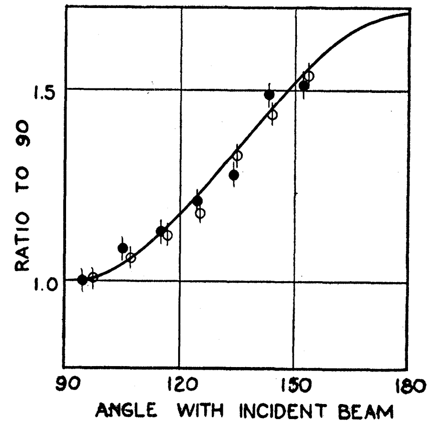

Fig. 3. The angular distribution of protons from the deuteron-deuteron reaction ($H^2+H^2\rightarrow H^3+H^1$) at incident deuteron energies of 106 kv and 190 kv. The open circles are for 190 kv, the black dots for 106 kv. The full curve is a plot of $1+0.7\cos^2\theta$. All points are in the center-of-mass system.

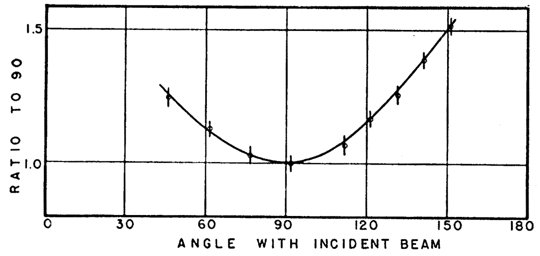

FIG. 4. The angular distribution in the center-of-mass system of the long range alpha-particles from boron under proton bombardment. ($_1H^1+_5B^{11}\rightarrow_2He^4+_4Be^8$.)

appreciable change in the angular distribution with the energy of the incident deuteron.

BORON HOMOGENEOUS GROUP

The products of bombarding boron with protons are a continuous group of alpha-particles, (3), whose excitation curve is normal and a homogeneous group, (4) of greater range which shows[11] a marked resonance at 160 kv.[12] This latter group was examined separately by interposing the necessary absorbing material between the target and the integral ionization chamber for each angle of observation. The results of these observations at 190 kv, again plotted in terms of the number of alpha-particles per unit solid angle at a given angle relative to those at 90° and transformed to the center of mass system are shown in Fig. 4. Here again, the distribution was found to be symmetrical about 90° and strangely enough, to fit the curve $(1+0.7\cos^2\theta)$. The deviation from spherical symmetry is in qualitative agreement with the cloud-chamber observations of Neuert[13] who found the distribution to be represented by $(1+\cos^2\theta)$. The difference is much larger than the indicated error in the present experiment and may be partially accounted for by transforming Neuert's observations to a center of mass system by the method outlined above which would reduce the latter expression to approximately $(1+0.9\cos^2\theta)$.

BORON CONTINUOUS GROUP

The most probable reaction occurring when boron is bombarded with protons is the emission of three alpha-particles with a continuous energy distribution up to 5.2 Mev which corresponds to a range of 37 mm. The angular distribution of the more energetic particles of this group was examined by reducing the stopping power between the target and the integral ionization chamber so that all particles with ranges greater than approximately 30 mm were recorded. These observations were corrected for the small number, less than twenty percent, of homogeneous long range alpha-particles contributed from reaction (4). The first angular distribution data were taken with a bombarding proton energy of 190 kv. The deviation from spherical symmetry shown in the upper curve of Fig. 5 bears a marked similarity to the results of the homogeneous resonance group from (4). The experiments on the short range continuous group were then repeated at a proton energy of 143 kv, this energy being below the resonance energy, 160 kv, for the competing reaction (4). The resulting angular distribution, shown in the lower curve of Fig. 5, was found to be almost spherically symmetrical to within the errors of the measurements. The rise in this curve at large angles may be caused by adverse statistical fluctuations since comparatively few particles were recorded because of the low yield at this voltage.

These results at 190 kv are very similar to those of Neuert,[4] but again show a smaller

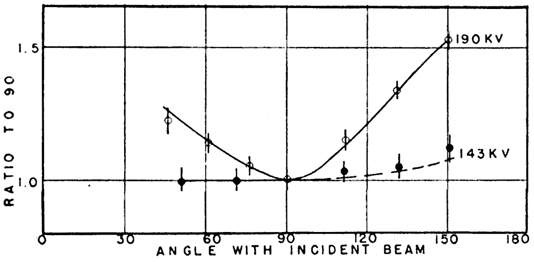

FIG. 5. The angular distribution in the center-of-mass system of alpha-particles with ranges between 30 and 38 mm from boron under bombardment with protons ($_1H^1+_5B^{11}\rightarrow3_2He^4$) of 190 and 143 kv energy.

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[11] Recent values for the resonance voltage are given by Waldman, Waddel, Callihan and Schneider, Phys. Rev. **54**, 543 (1938) as 165 kv and by Bowersox, Bull. Am. Phys. Soc. **13**, 13 (1938) as 172 kv.

[12] J. S. Allen, R. O. Haxby and J. H. Williams, Phys. Rev. **53**, 325 (1938).

[13] Because of the geometrical arrangement of the sensitive portion of the cloud chamber used by Neuert, his observations are a measure of the number of particles per unit solid angle instead of the number in an arbitrary angular range as one might infer from the text of his paper and his manner of correction to express them in the center of mass system of coordinates.

deviation from spherical symmetry. A possible explanation for the difference in the results obtained in the two laboratories might be that Neuert's measurements of ranges of the alpha-particles in his cloud chamber could not be accomplished with sufficient accuracy. Neuert did not consider the change in range with angle of emission as it was less than the probable error in his range measurements. Consequently he did not measure, at all angles, exactly the same group of particles. As there is an increasing number of alpha-particles at the lesser ranges, more particles would be observed at small angles with respect to the proton beam. Consequently the distribution would be observed to be more asymmetrical than is actually the case. Neuert further discovered that as he reduced the absorbing material in the path of the alpha-particles that the angular distribution gradually changed to spherical symmetry. Because of the difficulties of supporting two mica foils in the present apparatus, no attempt was made to investigate the distribution of particles with ranges less than 30 mm.

The surprising difference in the angular distribution of the alpha-particles from (5) when the energy of the bombarding proton was changed from 190 kv to 143 kv led to an investigation to the intermediate energy interval. The observations were restricted to the range of angles between 90° and 150° as it was assumed that the distributions would remain symmetrical about 90°. The distributions obtained are shown in Fig. 6 and it may be seen that there is a gradual change in the anisotropy in this voltage region. This change is *not* caused by the additional number of alpha-particles being contributed at the resonance voltage from reaction (4) since this small number has been subtracted from the total observed. However, there must be some intimate connection between the two competing reactions, for this phenomenon occurs in the voltage region about the resonance voltage, 160 kv, of reaction (4).

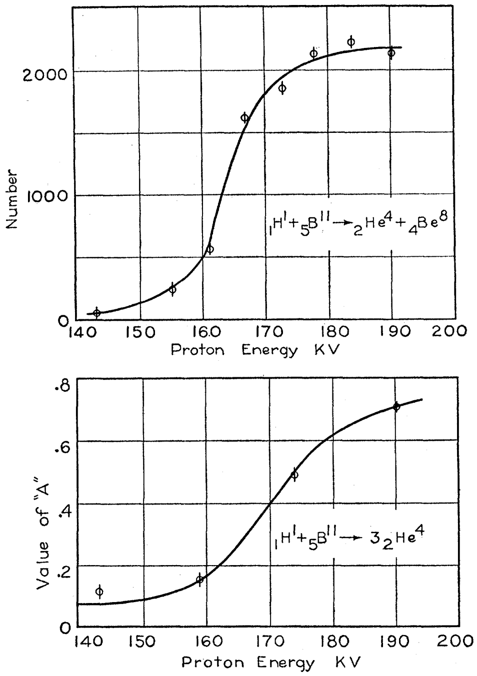

FIG. 7. The upper figure represents the *yield* of alpha-particles with ranges >40 mm from a thick target of boron as a function of the bombarding proton's energy. The lower figure represents the value of the coefficient A in $1+A\cos^2\theta$, the function chosen to represent the anisotropic angular distribution of alpha-particles with ranges >30 mm and <38 mm from a thick target of boron, as a function of the bombarding proton's energy.

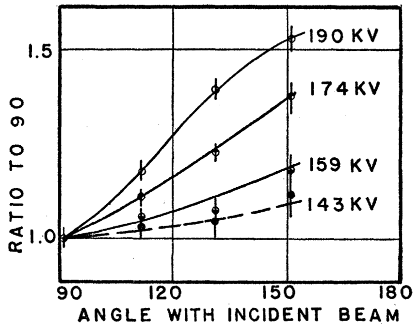

FIG. 6. The angular distribution of alpha-particles with ranges between 30 and 38 mm from boron under bombardment with protons (${}_1H^1+{}_5B^{11}\rightarrow 3{}_2He^4$) of 143, 159, 174 and 190 kv.

In order to clarify this connection the curves of Fig. 6 were fitted by the expression $1+A\cos^2\theta$ and the values of A were determined. These values are plotted as a function of the bombarding proton energy in the lower curve of Fig. 7. The upper curve shows for purposes of comparison the thick target yield curve of homogeneous, long range alpha-particles from (5). It may be seen that there is a marked similarity in the form of these curves.

Discussion of Experimental Results

Lithium

The isotropic distribution found for reaction (6) is to be expected since at low bombarding energies only those deuterons with zero orbital momentum, S waves, are responsible for the disintegration. The argument is analogous to that given by Myers[14] for the reaction,

$$Li^6+H^2\rightarrow Li^7+H^1.$$

Deuterium

The calculations of Schiff,[15] based on reasonable assumptions as to the form of the spin interaction, predict no marked deviation from an isotropic distribution. Myers,[14] on the other hand, calculated the distribution to be expected if one considered the deuteron-deuteron reaction to be of the resonance type. He chose the compound state to be $^3P_1$ and predicted that the angular distributions would be represented by $1+\cos^2\theta$. The difference between this expression and the concordant experimental results, $1+0.7\cos^2\theta$, of the Cambridge group,[3] Neuert's[16] most recent data at 120 kv, and the present experiment is quite real and entirely outside the experimental uncertainty. This disagreement is indicative of an insufficient understanding of the nuclear disintegration process, but unfortunately, the experimental result serves only as a check on any proposed theory and gives no obvious clue to a solution of the problem.

A further significant point in the experimental results is the lack of any appreciable change in the distribution function between 106 and 190 kv. Recently, Neuert[16] found that the anisotropy becomes less marked as the bombarding deuteron energy is decreased to 35 kv, the distribution then being represented by $1+0.2\cos^2\theta$. The slow change of the form of distribution as a function of energy suggests some sort of coupling between two waves having different j values. Since there is no coupling between a P and S wave, the most likely coupling is between a D and S wave. This would probably result in an additional $\cos^4\theta$ term in the distribution function which would be difficult to distinguish if it were small in magnitude.

Boron

The resonance reaction, $B^{11}+H^1\rightarrow Be^8+He^4$, is most amenable to theoretical treatment. Oppenheimer and Serber[6] have discussed the various possibilities on the basis of pertinent selection rules. They conclude that it is not possible to make a definite assignment of the nuclear resonance level of the intermediate nucleus, C^{12}, or the normal state of B^{11}. None of the distributions to be expected from the various combinations of the possible levels agrees with the experimental determination. Myers[14] assigns to C^{12} the excited state $^1D_2$, even and to B^{11} the ground state $^2P_{3/2}$, odd. On the basis of pure Russell-Saunders coupling he predicts the angular distribution $1+3\cos^2\theta$ which is in poor agreement with the present experimental value $(1+0.7\cos^2\theta)$ and those of Neuert.[4] The choice of the type of interaction between spin and orbital momenta will influence the theoretical prediction and the experimental results may act as a guide in the selection of a reasonable hypothesis.

No theoretical calculations have been made on the more complex disintegration, $B^{11}+H^1\rightarrow 3He^4$. The striking similarity between the angular distribution of the resonance group and the distribution found for the most energetic alpha-particles in this reaction at high voltages, shown in Figs. 4 and 5, suggests a more intimate connection between reactions (4) and (5) than was previously supposed. Further evidence for this hypothesis is discussed in the accompanying paper by Hill and Haxby.[17]

In conclusion we wish to express our sincere appreciation to Professor E. L. Hill for his stimulating discussions and to Messrs. J. F. Marvin and L. G. Stier for assistance in recording the data.

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[14] R. D. Myers, Phys. Rev. **54**, 361 (1938).

[15] L. I. Schiff, Phys. Rev. **51**, 783 (1937).

[16] H. Neuert, Naturwiss. **26**, 429 (1938).

[17] E. L. Hill and R. O. Haxby, Phys. Rev. **55**, 147 (1939).