A Note on the Disintegration of Boron by Protons

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The measurements on the angular distribution of the α-particles arising from the bombardment of boron by protons given in the preceding paper are discussed. It is suggested that the particles from the continuous distribution which show an angular distribution have a common origin with the particles in the homogeneous group at 44 mm, and that further, this latter group may not be a truly homogeneous group, but may arise from a peculiarity of the three-particle disintegration.

THE general nature of the theory of the angular distribution of the products arising from nuclear reactions has been discussed by Bethe and Placzek[1] on the basis of the Breit-Wigner[2] resonance theory. If one makes the assumption that but a single resonance level of the intermediate nucleus is involved, and if some assumption about the nature of the angular momentum coupling scheme is made, then it becomes possible to draw some conclusions about the characteristics of the resulting angular distribution. Without such simplifying assumptions, it is necessary to have a detailed theory of the nuclear process in order to make progress.[3]

Unfortunately the evidence is that these simplifications are not likely to be very well satisfied even for the lighter nuclei, where it might be hoped that the "single resonance level" hypothesis would be expected to hold best. Some months ago Oppenheimer and Serber[4] discussed the proton-boron reactions

$$ {}_5B^{11} + {}_1H^1 \rightarrow [{}_6C^{12}] \rightarrow 3\,{}_2He^4 \quad (1)$$

$$\rightarrow {}_4Be^8 + {}_2He^4 \quad (2)$$

$$\rightarrow {}_6C^{12} + \gamma. \quad (3)$$

On the basis of the experimental evidence it has been assumed heretofore[4, 5] that reaction (1) arises from the capture of an s proton, and (2) and (3) arise from the capture of a p or even a d proton. The evidence is good[6, 7, 7a] that (2) and (3) arise from a single type of capture process. Oppenheimer and Serber concluded that with this interpretation it would be very difficult to find a type of resonance level of the intermediate nucleus which would satisfy the necessary selection rules, and which would lead to an angular distribution of the α-particles from (2) at all comparable with that observed experimentally. Myers has also discussed reaction (2) from substantially the same point of view and with similar results.[8]

The new information contained in the previous paper now throws considerable doubt on the basis for these calculations. Most important is the observation that at least some of the α-particles in the continuous group attributed to reaction (1) exhibit an angular distribution, and consequently arise from other than s proton capture. On the basis of the evidence it now seems likely that the continuous group consists of at least two kinds of α-particles; (1) a group arising from s proton capture which show no angular distribution, which we designate by α_0, and (2) a group showing an angular distribution which we designate by α_θ. For notational purposes we shall refer to the α-particles in the homogeneous group at 44 mm as α_h.

We cannot be sure as yet that the α_θ- and the α_h-particles have their origins in a common capture process to some definite level of the

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[1] H. Bethe and G. Placzek, Phys. Rev. **51**, 450 (1937).
[2] G. Breit and E. Wigner, Phys. Rev. **49**, 519 (1936).
[3] E. g., as in K. Ochiai, Phys. Rev. **52**, 1221 (1937).
[4] J. R. Oppenheimer and R. Serber, Phys. Rev. **53**, 636 (1938).
[5] J. H. Williams, W. H. Wells, J. T. Tate and E. L. Hill, Phys. Rev. **51**, 434 (1937).
[6] W. Gentner, Zeits. f. Physik **107**, 354 (1937).
[7] B. Waldman, R. C. Waddel, D. Callihan and W. A. Schneider, Phys. Rev. **54**, 543 (1938).
[7a] *Note added in proof:* There is as yet no evidence that the resonance γ-ray from reaction (3) leaves ${}_6C^{12}$ in its normal state.
[8] R. D. Myers, Phys. Rev. **54**, 361 (1938).

intermediate nucleus. The available yield curve data[5] are unfortunately not sufficiently accurate to determine the possible existence of a resonance for the α_θ-particles, although the rapid variation of their observed angular distribution with proton energy in the neighborhood of the resonance (Fig. 6 of the preceding paper) makes it seem quite probable that they are related. This is suggested by the following interpretation of Fig. 7 of the preceding paper. Let $n_0(E)$ and $n_\theta(E, \theta)$ be the numbers of particles measured per unit solid angle in the α_0- and α_θ-groups, respectively, where E is the energy of the incident proton and θ the angle at which the α-particles are being collected. Then the measured angular distribution curves of Fig. 6 (preceding paper) give the function

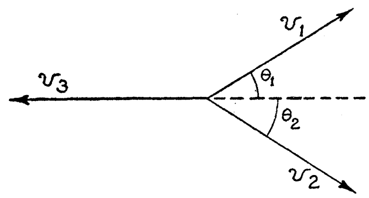

FIG. 1. The three-particle disintegration.

$$F(E, \theta)=\frac{n_0(E)+n_\theta(E, \theta)}{n_0(E)+n_\theta(E, \frac{1}{2}\pi)}\sim 1+A(E)\cos^2\theta$$

as a function of θ, for different values of E. If we set

$$n_\theta(E, \theta)=n_\theta(E, \tfrac{1}{2}\pi)+\eta(E, \theta)$$

we get

$$A(E)\cos^2\theta\sim\eta(E, \theta)/[n_0(E)+n_\theta(E, \tfrac{1}{2}\pi)].$$

Over the width of the resonance level the denominator is approximately constant, increasing gradually with E, since $n_0>n_\theta$, so that $A(E)$ follows approximately the form of $\eta(E, \theta)$ as a function of E. If η follows the resonance curve, that is, if the α_θ-particles of the continuous group follow the same resonance process as do the α_h-particles, then $A(E)$ will do likewise. Conversely, the experimental result of Fig. 7 may be interpreted as evidence that the α_θ- and the α_h-particles have a common origin. The test would be more significant if it could be performed with a thin target, in which case $A(E)$ would be expected to follow almost a simple resonance form of curve, but the small numbers of particles from a thin target would undoubtedly make the angular distribution measurements difficult. According to Professor Williams, it may be possible to test this point further by an examination of the yield curves of selected portions of the α-particle distribution with a highly differential counter. Such experiments are being initiated.

One may well question whether the long range α-particle group really is a homogeneous group arising from a definite reaction (2) in which the nucleus $_4Be^8$ is left in a stable or quasi-stable state, or whether it is only a portion of a more extended distribution overlapping the continuous group. Professor Williams has also pointed out that the homogeneity of this group may be questioned on the grounds that at proton energies above the resonance energy, the yield curve of the α-particles does not continue to decrease, but flattens out to give a measurable yield (Fig. 3 of reference 5). Recent measurements of Bowersox at the University of Chicago show[9] that at higher proton energies (up to 400 kv) the yield curve of the α_h-particles increases approximately on a Gamow curve. If the observed resonance group is not really a homogeneous group arising from a definite reaction like (2), then it either may be overlapping a true homogeneous group, or may have a somewhat lower energy than such a group, depending on the magnitude[9a] of the binding energy of $_4Be^8$.

The possibility that the α_h-particles may be only *apparently* homogeneous is suggested by the following simple consideration. Consider a three-α-particle disintegration pictured in Fig. 1, the center of mass of the system being considered at rest. The equations of momentum and energy give us three relations connecting the five variables v_1, θ_1, v_2, θ_2, v_3. Take v_1 and θ_1 as independent variables and compute the change Δv_3

[9] R. B. Bowersox, Bull. Am. Phys. Soc. **13**, 13 (1938); Phys. Rev. in course of publication.

[9a] *Note added in proof:* According to S. K. Allison, E. R. Graves, L. S. Skaggs and N. M. Smith, Bull. Am. Phys. Soc. **13**, Paper 43 (1938) the binding energy of $_4Be^8$ is 0.31 ± 0.06 Mev with respect to two α-particles.

in v_3 due to changes Δv_1 and $\Delta\theta_1$. We find

$$\Delta v_3 = -\frac{\Delta v_1[v_1 - v_2 \cos(\theta_1+\theta_2)] + \Delta\theta_1 \cdot v_1 v_2 \sin(\theta_1+\theta_2)}{v_3 + v_2 \cos\theta_2}.$$

Now for $\theta_1=\theta_2=0$, $v_1=v_2$, which corresponds to the case for which particle 3 gains the maximum energy, the other two particles going off together, we get

$$\Delta v_3 = 0 \text{ for all } \Delta v_1 \text{ and } \Delta\theta_1.$$

Thus if we measure only the *fast* particles from reactions of nearly this type we shall find a substantially homogeneous group. The small number of particles in the observed α_h-group, and its apparent relation to the continuous group may mean that it has its origin in some such peculiarity of the disintegration phenomenon, and that its existence is not contingent on the possibility of a definite reaction (2).

In order to make this argument complete we should need to know whether there is a reasonably large probability that the three-particle disintegration may occur in this way. This question cannot be discussed with any assurance since we are quite unaware of the factors governing the disintegration from the intermediate state. A rough approach to the problem may be made by a study of the "*a priori* probability distribution" along the lines discussed by Uhlenbeck and Goudsmit.[10] While the form of their distribution curve is incorrect, it does predict that about one percent of the particles would have energies within five percent of the maximum energy. This is of the order of magnitude of that found in the experiment,[5] but because of the uncertainty in the theoretical energy distribution this argument is only illustrative in character.

It may be remarked in passing that the details of the derivation of their formula (13) by Uhlenbeck and Goudsmit seem to be open to some question because of the arbitrary treatment of the coordinates $\mathbf{R}_1$ and $\mathbf{R}_2$. A more detailed analysis yields the distribution function (for equal masses)

$$f(\epsilon) \sim \epsilon^{\frac{1}{2}}(E - \tfrac{3}{2}\epsilon),$$

which is not quite symmetrical. However, the experimental results show clearly that the whole analysis is insufficient, and a more intimate picture of the nuclear process is required.

Lastly we note that the angular distribution measurements on the protons from the deuteron-deuteron reaction may be interpreted by the same method as used above for the continuous α-particles from reaction (1). Fig. 3 of the preceding paper shows that the form of the distribution is

$$1 + A\cos^2\theta,$$

where $A=$const. for E between 106 and 190 kv. The measurements of Neuert[11] show that in the neighborhood of 40 kv the distribution has a much smaller angular dependence than at the higher deuteron energies. As in the boron case this would result if the protons consisted of one group which was angular dependent and another which was not, with the former group showing a broad resonance at low deuteron energies. The data do not appear to be sufficiently detailed to permit any definite check on this hypothesis.

The authors wish to express their thanks to Professors G. Breit and J. Bardeen for various discussions of the boron reactions.

[10] G. Uhlenbeck and S. Goudsmit, *Zeeman Verhandelingen* (1935), p. 201.

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