# A Resonance Process in the Disintegration of Boron by Protons

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An experimental investigation of the efficiency of production of $\alpha$-particles from boron as a function of the energy of the bombarding protons is reported. Of the two established processes,

$$_5B^{11}+{}_1H^1\rightarrow 3{}_2He^4+Q_1$$

and

$$_5B^{11}+{}_1H^1\rightarrow {}_4Be^8+{}_2He^4+Q_2,$$

the second exhibits peculiarities in its efficiency curve whereas the first increases exponentially with proton energy. This irregularity is interpreted as the occurrence of a resonance process in the second disintegration, the resonance peak occurring at 180 kv. A discussion of the possible theoretical interpretations of the process is given. Absolute yields for a thick boron target at various proton energies are given.

## Introduction

The disintegration of boron by proton bombardment has been studied by the Cambridge group[1] and by Kirchner and Neuert.[2] As a result the following processes appear to be established:

$$_5B^{11}+{}_1H^1\rightarrow 3\,{}_2He^4+Q_1, \tag{1}$$

$$_5B^{11}+{}_1H^1\rightarrow {}_4Be^8+{}_2He^4+Q_2. \tag{2}$$

Process (1) predominates even at low voltages, and gives rise to a continuous distribution of $\alpha$-particles having a maximum at a range of 24 mm. Reaction (2) gives about 1 percent as many $\alpha$-particles (at 150 kv) and is responsible for the appearance of a small homogeneous group having a range of about 4.5 cm.

In their careful examination of the energy distribution of the $\alpha$-particles, Cockcroft and Lewis[3] noted that the yields from the two processes did not vary in the same way with the energy of the incident protons; i.e., the two reactions have different efficiency curves. This work has been carried further in this laboratory, and the curves for the yields have been obtained up to about 250 kv. In agreement with Cockcroft and Lewis we find markedly different yield voltage curves from (1) and (2), that for the latter exhibiting a resonance effect. The preliminary results of this work have been published.[4]

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[1] Oliphant, Kempton and Rutherford, Proc. Roy. Soc. **A150**, 241 (1935).
[2] Kirchner and Neuert, Physik. Zeits. **34**, 897 (1933); Neuert, Physik. Zeits. **36**, 629 (1935).
[3] Cockcroft and Lewis, Proc. Roy. Soc. **A154**, 246 (1936).
[4] Williams and Wells, Phys. Rev. **50**, 187 (1936).

## Apparatus

A resistance controlled transformer-kenetron-condenser set was adapted to deliver potentials up to 275 kv which could be manually controlled to fluctuations in the output of one percent. The voltage was measured by a high resistance voltmeter constructed from 150 individually calibrated 10-megohm metallized resistors. This voltage accelerated protons from a low voltage arc[5] connected in such a manner that only the measured external voltage was effective. The magnetically resolved proton beam of 2 to 5 microamperes was focused to a spot diameter of less than 5 mm. By means of a high resistance potentiometer in series with the cylindrical accelerating tube elements, a constant focus was obtained over a wide range of voltages.[6] The $\alpha$-particles emitted from a *thick* fused $B_2O_3$ target inclined at 45° were observed at an angle of 90° from the proton beam. They were detected by an ionization chamber which was 7 mm deep, connected to an amplifier of the Dunning type.[7] The pulses were recorded by a scale-of-eight thyratron counter[8] adjusted to count all $\alpha$-particles which entered appreciably into the ionization chamber.

Preliminary experiments to test the apparatus included measurements of the disintegration efficiency of protons on thick LiCl targets. The fact that the values obtained agreed to within 10 percent of the absolute yields given

[5] Tuve, Dahl and Van Atta, Phys. Rev. **46**, 1072 (1934).
[6] Hansen and Webster, Rev. Sci. Inst. **7**, 17 (1936).
[7] Dunning, Rev. Sci. Inst. **5**, 387 (1934).
[8] Shepherd and Haxby, Rev. Sci. Inst. **7**, 425 (1936).

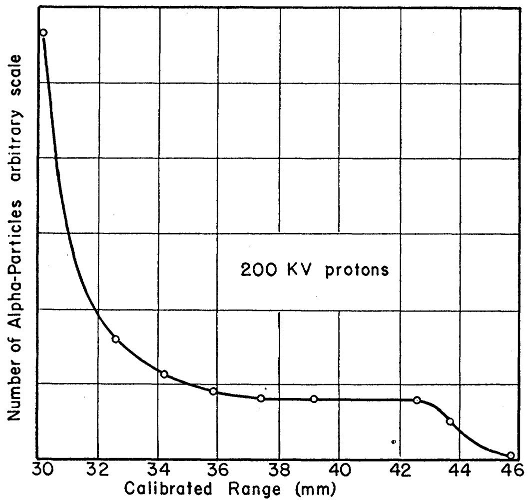


FIG. 1. Number of $\alpha$-particles from a boron target under proton bombardment reaching a deep ionization chamber as a function of absorber between target and chamber. The absolute values for the abscissae are obtained from comparison with the results of Kirchner and Neuert.

by the Wisconsin group[9] was taken as evidence for the satisfactory behavior of the apparatus.

## Experimental Procedure

Protons accelerated by a constant potential of 200 kv were allowed to strike the thick $B_2O_3$ target, and the number of emitted $\alpha$-particles entering a *deep* ionization chamber were observed when various thicknesses of mica and air were inserted between the target and the chamber. These observations are shown in Fig. 1. They serve to indicate the presence of the homogeneous group of $\alpha$-particles attributed to reaction (2) and by comparison with the results of Kirchner and Neuert[2] give a calibration of the range scale of our detecting apparatus. No attempt was made to obtain the shape of this number *vs.* range curve sufficiently accurately to contribute any information as to the nature of reaction (1), since the present method is in this respect experimentally inherently inferior to that of Kirchner and Neuert[2] and that of Dee and Gilbert.[10]

With the range scale thus calibrated we obtained, with range as a parameter, the number of $\alpha$-particles emitted in a calculated solid angle as

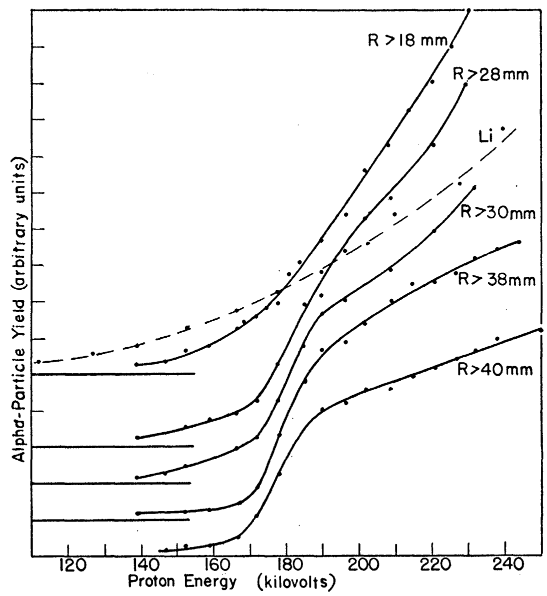


FIG. 2. Yield curves for $\alpha$-particles from the disintegration of boron by protons. The yields are in arbitrary units and the zeros for the various curves are shifted vertically as indicated. For comparison purposes the yield curve for the $\alpha$-particles from lithium bombarded with protons is included.

a function of proton energy. Since the ionization chamber records all $\alpha$-particles which enter it, the yield curves will be for all $\alpha$-particles having a range greater than that necessary to reach the ionization chamber. This experimental condition undoubtedly contributes to the difficulty of interpreting the yield curves, but does not mask their significance. Representative observed efficiency curves are shown in Fig. 2.

It is seen that the main group of $\alpha$-particles of range greater than 18 mm follows an ordinary excitation curve with no evidence of marked irregularities. However, when sufficient mica is introduced to remove most of the $\alpha$-particles from (1), so that the majority of those recorded are of range greater than 38 mm, the efficiency curve is found to be markedly different. The yield expected from a *thin* target, obtained by differentiating the thick target curve with respect to the 3/2 power of the accelerating voltage[9] is shown in Fig. 3 (cf. the next section for discussion).

The several curves of increasing range from 28 mm to 40 mm show different slopes at voltages greater than 200 kv. We interpret this as due

[9] Herb, Parkinson and Kerst, Phys. Rev. **48**, 118 (1935); Heydenberg, Zahn and King, Phys. Rev. **49**, 100 (1936).
[10] Dee and Gilbert, Proc. Roy. Soc. **A154**, 279 (1936).

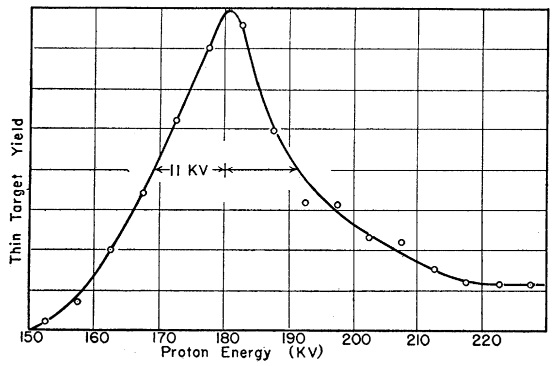


FIG. 3. The yield of long range $\alpha$-particles expected from a thin target of boron as a function of the bombarding proton's energy. The curve is obtained by differentiating the observed thick target curve with respect to (voltage)$^{\frac{3}{2}}$.

either to the onset of further modes of disintegration or to the inclusion of a small number of $\alpha$-particles from the continuous distribution of disintegration (1). An examination of Fig. 5 of Cockcroft and Lewis' paper[3] shows that the number-*vs.*-range curve for (1) changes its shape with increasing voltage in a manner such that the continuous distribution extends to greater ranges at the higher voltages. From this point of view the efficiency curve of $\alpha$-particles of some definite range, say 38 mm, would not decrease exponentially to zero with diminishing incident proton energies, but would have an apparently definite "excitation potential."

An attempt was made to overcome the effect of measuring $\alpha$-particles from (1) by working at ranges greater than 43 mm. Since the yield of $\alpha$-particles from (2) is small, it is necessary to arrange the geometry of the ionization chamber to subtend a large solid angle at the target. This imposes the condition that $\alpha$-particles pass from the focal spot to the ionization chamber over a wide range of angles distributed about 90° from the direction of the proton beam. Consequently only a certain fraction of the 45 mm range $\alpha$-particles were able to pass through the 43 mm of mica and air absorber between the target and the chamber. In changing the voltage during the measurement of an efficiency curve, very slight changes in the size and position of the focal spot gave gross changes in the number of $\alpha$-particles which were able to reach the ionization chamber. This effect, although unimportant for absorbers of less than 40 mm stopping power, made accurate relative measurements impossible at greater thicknesses of absorber.

An effort was made to investigate the similar disintegration

$$ {}_5B^{10}+{}_1H^2\rightarrow{}_4Be^8+{}_2He^4+Q_3 \qquad (3)$$

to test whether any correlation could be found in the yield curves, but with the available accelerating voltages it was not possible to obtain satisfactory efficiency curves, since the yields from (3) are small compared to those from (1) and (2) at low energies. However, we did obtain qualitative measurements on the number-*vs.*-range curve, which were in agreement with the results of Cockcroft and Lewis[3] in showing the presence of an homogeneous group of particles arising from (3).

## Experimental Results

From our voltage yield curve we can conclude that the yield from reaction (1) follows a Gamow type curve within our experimental error. The yield of 45 mm particles attributed to (2) shows, on the other hand, a distinct resonance effect in the neighborhood of 180 kv. Making reasonable corrections for the contributions of the tail end of the low energy continuous distribution to the high energy group of $\alpha$-particles, we find that the "thin target" efficiency curve[9] has a half-width of about 11 kv at half-maximum. As the energy of the incident protons was very steady, it is felt that the error in this value should not exceed 3 kv. Fig. 3 shows a typical "differentiated" curve (i.e., differentiated with respect to $V^{\frac{3}{2}}$).

Qualitative results for the yield of $\alpha$-particles per proton calculated for a pure boron target by multiplying the observations on the thick $B_2O_3$ target by 34/10 are:

| Range | >18 mm | >40 mm |
|---|---|---|
| 150 kv | $1.68\times10^{-9}$ | $1.79\times10^{-11}$ |
| 175 | 7.06 | 17.4 |
| 200 | 18.4 | 49.7 |
| 225 | 32.3 | 59.7 |

The relative yields from the two disintegrations may be compared to Kirchner and Neuert's value of 1:200 at 150 kv, Oliphant, Kempton and

Rutherford's value at 1:70 at an unstated voltage, and Cockcroft and Lewis' values 1:60 at 185 kv and 1:240 at 360 kv.

## Discussion

A general formal theory of resonances in nuclear processes has been given by Breit and Wigner,[11] with special consideration of neutron capture or scattering processes with or without $\gamma$-ray emission. As regards the latter, $\gamma$-rays have been observed[12] from boron bombarded with protons of 900 kv energy, but their intensities appeared to be very strong functions of the voltage, and were inappreciable below 700 kv. The emission of the $\gamma$-rays was postulated to be a direct capture of the proton without disintegration; i.e.,

$$_5B^{11}+{}_1H^1\rightarrow{}_6C^{12}+h\nu.$$

If this be the case, there is no obvious reason why $\gamma$-ray emission should not appear as an alternative reaction to the two modes of disintegration considered here, even at the lower voltages used by us, unless, as suggested by Crane, Delsasso, Fowler and Lauritsen, the probability of emission of the $\gamma$-rays is abnormally high in the region of 900 kv bombarding energy.[13]

The energy balance which is obtained without consideration of possible *simultaneous* $\gamma$-ray emission seems to be so good that little room is left for the disposal of much energy in this way, and we provisionally assume that when one or the other disintegration occurs, no $\gamma$-ray is emitted. The possible influence of an *alternative* process of $\gamma$-ray emission must be left open at the moment.

According to current ideas on the dynamics of disintegration processes, it is convenient to consider that they occur through a transient intermediary stage of an excited "compound" nucleus so that we write them as

$$_5B^{11}+{}_1H^1\rightarrow{}_6C^{12*}\rightarrow 3\,{}_2He^4, \qquad (1')$$

$$\rightarrow{}_6C^{12**}\rightarrow{}_4Be^8+{}_2He^4. \qquad (2')$$

It is of interest to decide, if possible, whether the two levels of the excited $C^{12}$ nucleus implied in (1′) and (2′) are the same. Save for a possible influence of the resonance phenomenon itself in producing a shift in the levels,[14] if two different levels are involved they should differ in energy merely by the binding energy of $_4Be^8$. At the present time this is an uncertain quantity, so that it is not possible to come to any conclusion on this basis. Considered as excited levels of $_6C^{12}$ they lie well within the continuum of energy levels above the first "dissociation potential"

$$_6C^{12}+(\sim 7.5\text{ Mev})\rightarrow 3\,{}_2He^4.$$

The "resonance levels" referred to might better be spoken of as "pre-dissociation levels" lying at about 16.1 Mev above the normal state of $_6C^{12}$.

From our experimental results it seems most probable that the two excited levels involved in (1′) and (2′) are distinct from each other, and that (1′) and (2′) represent independent modes of capture and disintegration rather than alternative disintegrations from one single resonance level. The reason for supposing this is as follows: Suppose that (1′) and (2′) both went through the same excited level of $_6C^{12}$. Let $\gamma_0$ be the contribution to the width of the intermediate level due to transitions from the initial proton state, and $\gamma_1$ and $\gamma_2$ be the half-widths of the transitions out of this state, while $\gamma=\gamma_0+\gamma_1+\gamma_2$. Then the corresponding cross sections in the immediate neighborhood of the resonance energy may be written on the resonance theory in the approximate forms[15]

$$\sigma_1\sim A_1\Lambda^2\frac{\gamma_0\gamma_1}{(V-V_r)^2+\gamma^2},$$

$$\sigma_2\sim A_2\Lambda^2\frac{\gamma_0\gamma_2}{(V-V_r)^2+\gamma^2},$$

where $A_1$ and $A_2$ are nearly equal and vary only slowly with $V$ close to the resonance potential $V_r$. From these formulas one would expect that *both* processes should show the resonance phenom-

[11] Breit and Wigner, Phys. Rev. **49**, 519 (1936). Cf. also Dirac, *Quantum Mechanics*, Second Edition, p. 203.

[12] Crane, Delsasso, Fowler and Lauritsen, Phys. Rev. **48**, 102 (1935).

[13] It would be interesting to extend the disintegration measurements to this region to look for further resonance effects.

[14] Breit and Wigner, reference 11, p. 526.

[15] Cf. Breit and Wigner, reference 11, Eq. (14) for the analogous case of neutron scattering or capture with $\gamma$-ray emission. In the formulas in the text we have not considered the effect of the variation in the Gamow penetration factor over the width of the resonance level. Its inclusion should hardly affect the general conclusion.

enon, and that their corresponding cross sections should be roughly in the ratio of their corresponding half-widths; i.e., the ratio of the corresponding yields. Since (1′) is a much more prolific reaction than (2′), one would then expect to find a large resonance in the main group of $\alpha$-particles. While this might be somewhat masked by the apparent exponential increase in the yield which is observed, yet the absence of any observable resonance in (1′) leads us to consider that the dynamics of the two disintegration processes probably involve two different modes of "capture" of the proton.

We can estimate roughly the relative probabilities of "capture" into the two excited levels as follows: We find, in agreement with Kirchner and Neuert[2] that about 100 times as many $\alpha$-particles are observed in the main group as in the small high energy group. From (2′) we would expect to be able to observe only one $\alpha$-particle per disintegration even if the $Be^8$ nucleus should be unstable and disintegrate, since the resulting $\alpha$-particles would have very small energies. It has further been shown by Dee and Gilbert[10] that the most probable disintegration from (1′) is such that one $\alpha$-particle receives very little energy, the other two dividing the energy roughly evenly. From such a break-up there are then two particles available for measurement. This gives for the relative number of disintegrations from (1′) and (2′) about 50 to 1. If we neglect the probabilities of other modes of passage out of the excited levels (or better, assume that they are equally important for both) then we can use this figure as a rough measure of the probabilities of "capture" into the two levels.[16] The most important correction to this seems likely to come from the possible influence of $\gamma$-ray emission, mentioned above.

This ratio suggests that the two processes (1′) and (2′) may result from interactions of $s$ and $p$ protons, respectively, with the $B^{11}$ nucleus, the gross difference being due primarily to the influence of the angular momentum of the $p$ protons in keeping them away from the nucleus. The resonance would then be a resonance of the $p$ protons. Check calculations on the potential well model are being made to test this hypothesis, but without definite results to date.

While no detailed theory can be given at the moment, a suggestion may be made from the observed value of the width of the resonance region on the nature of the mechanism of the disintegration. The observed value of about 11 kv for the half-width indicates a mean lifetime of the excited state involved in (2′) of about $10^{-18}$ or $10^{-19}$ sec. If the initial state of the nucleus is represented by one particle wave functions say as in a Hartree model, without any more tendency towards the formation of specific groups than is implied in the use of a self-consistent field and a shell structure modeled after that of the external electrons, it would seem that the probability for the formation of the structures actually observed in the disintegration would be much too low. Particularly as in the present case where there must be the formation of three $\alpha$-particles which must then distribute the available kinetic energy among themselves in a manner distinctly different from that to be expected *a priori*.[10] The inference is that it would be advantageous to allow in the theory for a predisposition for the preformation of the group structures which make their appearance on disintegration.[17] It is hoped to return to this problem in a more definite way in a later communication.

We wish to express our sincere thanks to Mr. W. G. Shepherd and Mr. R. O. Haxby for invaluable assistance with the recording apparatus. This research was supported by a grant from the Graduate School of the University of Minnesota.

[16] This statement is only of tentative and approximate significance since the mathematical theory of the disintegration through a resonance level does not provide that the probability of disintegration is equal to the product of a probability for capture and a probability for disintegration after capture. Instead the total probability is determined by a formula of the general type

$$(\alpha/\hbar^2)\left|\sum_k \frac{(a|H'|k)(k|H'|b)}{(E-E_k)+i\beta}\right|^2,$$

where $a$ and $b$ refer to the initial and final states; i.e., before and after disintegration, and $k$ refers to the intermediate states within the resonance band. $\alpha$ and $\beta$ are constants. This allows for the possibility of an interference between the different modes of resonance capture within the resonance band. It is only under special circumstances in which this interference is unimportant that the above expression can be reduced to the form

$$g(E_0)\,\frac{|(a|H'|k)|^2|(k|H'|b)|^2}{(E-E_0)^2+\beta^2},$$

where $E_0$ is the energy at the maximum of the resonance band and $g(E_0)$ is a weighting factor.

[17] Wells and Hill, Phys. Rev. **49**, 858 (1936).