A Precise Determination of the Energy Released in the Production of Deuterium from Beryllium under Proton Bombardment

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The kinetic energy of the deuterons liberated in the reaction Be^9 (p, d) Be^8 has been measured by deflecting the deuterons in an accurately known electrostatic field. The technique of the use of the electrostatic deflector is discussed, and experimental arrangements appropriate to the determination are described. From measurements at proton energies of 258, 262, and 315 kv the energy released in the reaction is found to be 0.557 ± 0.006 Mev. The shift of the high energy limit of the deuterons with bombarding voltage establishes the masses of the particles involved. By combining the result with other energy data as known at present it is shown that (*a*) the threshold for the disintegration of Be^9 by gamma-rays is 1.62 ± 0.02 Mev. (*b*) Be^8 is stable with respect to disintegration into two alpha-particles by 0.174 ± 0.09 Mev. Revision of the present values of the mass-spectrographic bracket between deuterium molecules and helium, or the value of the energy released in the reaction Li^6 $(d, \alpha)He^4$ would necessitate revision of conclusion (*b*). The experimental evidence on the stability of Be^8 is briefly discussed.

INTRODUCTION

IN a previous communication[1] from this laboratory we have described an electrostatic analyzer, adapted to the precise measurement of the kinetic energies of slow particles released in certain nuclear reactions. In this first communication we reported the measurement of the energy of the alpha-particles emitted in the reaction Be^9 (p, α) Li^6. In a subsequent brief letter,[2] we announced the results of the determination of the deuteron energy in the concomitant reaction Be^9 (p, d) Be^8. The present paper will give some experimental details of this latter investigation and discuss the results.

EXPERIMENTAL PROCEDURE

No change in the electrostatic analyzer itself was made in the interim between the alpha-particle and the deuteron experiments, and the previous description[1] is adequate. The main features may be summarized as follows. Some of the disintegration particles, produced from a polished target of beryllium under proton bombardment, pass through an entrance slit 0.1 cm wide placed 2.3 cm from the target. This slit is 8.90 cm (the focal distance) from the edges of the cylindrical plates of the deflecting electrostatic field. These plates are spaced 0.635 cm apart and have an average radius of curvature of 25.400 cm. They subtend an angle of 90° at their center of curvature, and are 8.26 cm high, although the height of the beam going through them is only 1.5 cm.

The electrostatic analyzer was disassembled shortly after these experiments were completed and the dimensions of the plates re-measured. The separation of the plates at no point varied by more than one percent of the mean 0.635 cm separation. These small areas of variation occurred at isolated points along the plates, mostly near the edges and not in the path of the beam of particles being analyzed. They therefore introduced no appreciable error.

The arrangement of the ionization chamber in which the particles were counted after passing through the analyzer is shown in Fig. 1. The entrance slit of the chamber is 1.5 cm high and 0.3 cm wide. It is covered with perforated screen with holes 0.0216 cm in diameter, and has a transmission ratio of 0.321.[3] A collodion foil of 2 mm stopping power is placed on the inside of the ionization chamber over the screen. The parts of the foil not actually over the window are painted with colloidal carbon (Aquadag) to make a conducting surface. The distance from the collecting electrode to the screen of the chamber was 0.8 cm and a potential of 750 volts was applied to collect the ions. Since the ranges of both types of particles emitted from beryllium

[1] S. K. Allison, L. S. Skaggs and N. M. Smith, Jr., Phys. Rev. **54**, 171 (1938).
[2] S. K. Allison, E. R. Graves, L. S. Skaggs and N. M. Smith, Jr., Phys. Rev. **55**, 107 (1939).
[3] R. B. Bowersox, Phys. Rev. **55**, 323 (1939).

under proton bombardment are about 0.8 cm in air, this means that the paths actually ended in the air of the ionization chamber. Under these conditions the amplified pulses from the particles entering the chamber were shown to be about three-fourths the maximum height of alpha-particle pulses obtainable from a polonium source shooting particles into the same chamber. It was not possible, however, to make a satisfactory distinction between alpha-particle and deuteron pulses from their relative heights as has been done by other observers[4] in shallower chambers. The deuteron and alpha-particle limits were identified by another method, to be described later.

The deflecting voltages put on the plates of the analyzer ranged up to 38 kilovolts for the beryllium particles. The rectified high voltage current from a transformer-kenetron circuit with half-wave rectification was passed into a condenser of 0.1 microfarad capacity, and a metallized resistance of 2.9×10^8 ohms placed between this condenser and the electrostatic deflector, which was also directly connected to an electrostatic voltmeter of sensitivity 300 volts per scale division in the region 25–45 kilovolts. No appreciable current was drawn from the condenser during the deflection of the particles through the analyzer. After a run, the voltmeter scale was calibrated in several places by connecting the voltmeter directly to the condenser, and putting in parallel with it a 2.8×10^7 ohm wire-wound precision resistor which at 38 kv drew 1.4 ma from the condenser. The voltage drop when this current passed through a resistance of approximately 1000 ohms was measured in a potentiometer circuit. The constants in this circuit were recently re-checked by Mr. F. V. Stearns, and found accurate to 0.1 percent.

As explained in a previous paper,[1] the geometry of the electrostatic analyzer is such that if V is the deflecting voltage which causes a beam of particles of homogeneous energy to traverse the mean radius and give the maximum counting rate in the ionization chamber, a change dV will reduce the counts to zero, where $dV/V=0.8$ percent. This is a measure of the resolving power. From the voltage V at which a homogeneous particle group traverses the mean radius, the energy E in electron volts of the particles in the group may be computed from

$$E=20.00\,Vz,$$

where z is the charge on the particles in electron units.

The target was a disk of pure beryllium metal 1.6 cm in diameter, mounted and heated previous to each bombardment as described by Hatch.[4] The proton beam was limited to a diameter of 8 mm by circular apertures in front of the target. The magnetically analyzed proton beam currents were from one to two microamperes in intensity. The plane of the polished target face was at 45° to the proton beam, and the disintegration particles entering the analyzer made an angle of 90° with the proton beam.

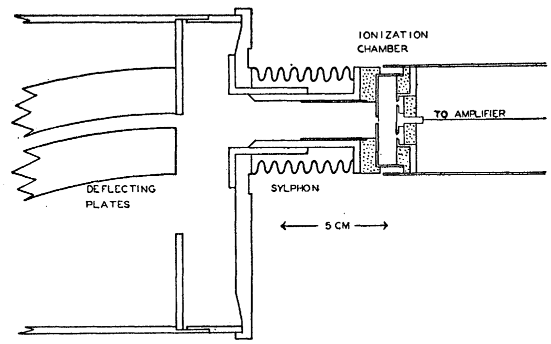

FIG. 1. Arrangement of the ionization chamber for detection of particles which have passed through the electrostatic analyzer. The front cap of the ionization chamber serves as part of the vacuum wall.

METHOD OF TAKING READINGS

The deflecting voltage was varied in steps of approximately 1000 volts through the region in which it was expected that the particles would traverse the proper radii through the analyzer. A cathode-ray oscilloscope was always connected to the output of the linear amplifier. If the counts did not exceed 2 to 3 per second, visual counting by two observers watching the oscilloscope was utilized. Frequent check counts with the proton beam off the target were made, especially at low counting rates. For higher counting rates (the 315- and 351-kv curves of

[4] M. L. E. Oliphant, A. E. Kempton and Lord Rutherford, Proc. Roy. Soc. Lond. **A150**, 241 (1935); J. S. Allen, Phys. Rev. **51**, 182 (1937); F. Kirchner and H. Neuert, Physik. Zeits. **38**, 969 (1937); G. T. Hatch, Phys. Rev. **54**, 165 (1938).

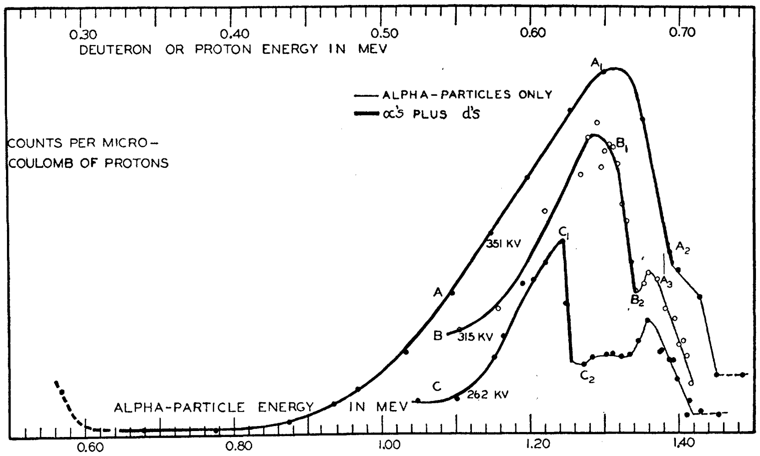

FIG. 2. The energy spectra of the particles emitted from beryllium under proton bombardment. For absolute values of the ordinates see Table I in the text.

Fig. 2), a scale-of-sixteen circuit with a mechanical counter was used, while an observer watched the oscilloscope for spurious disturbances. The elimination of such spurious counts has been one of the most difficult features of the work. Proton beam currents and readings of the current through the 7.5×10^9-ohm resistor measuring the bombarding voltage were taken at frequent intervals.

Discussion of Results

Figure 2 shows curves obtained at different bombarding energies. The total number of particles counted, the rate of counting and the method of counting (scale-of-sixteen with mechanical counter or visual observation of oscilloscope) are given in Table I for various points on the curves. Curve C of the figure shows the deuteron and alpha-particle limits well separated when the bombarding voltage was 262 kv. But when the bombarding voltage was raised to 351 kv the limits became practically coincident as is shown by curve A. It can be shown in the following way that the limit on the left of curve C is due to deuterons. The ordinary laws of mechanics give the following relation for the energy of the deuterons, ejected at 90° to the proton beam:

$$E_d=0.7E_p+0.8Q_1,$$

where E_p is the energy of the bombarding protons and Q_1 is the reaction energy. For the energy of the alpha-particles, the corresponding relation is:

$$E_\alpha=0.5E_p+0.6Q_2,$$

where Q_2 is the energy release in the reaction Be^9 (p, α) Li^6. If the bombarding energy is increased by 89 kv then the energy of the deuterons should be increased by 62 kv and the energy of the alpha-particles by 45 kv. If we assign the peak on the left of curve C to deuterons, then it indicates that the deuterons have an energy of 0.628 Mev at 262 kv bombarding energy. When the bombarding energy is raised to 351 kv the energy of the deuterons should be increased by 0.062 Mev. They should then have an energy of 0.690 Mev and the position of the limit at 351 kv bombarding energy should be as is shown by the point A_3 on curve A. If this were wrong and the limit on the left due to alpha-particles, their energies would be 1.256 Mev, which would be shifted to 1.301 Mev at 351 kv bombarding energy. The form of curve A clearly indicates that the original assumption of deuterons was correct. The shift of the limit on the high energy end of the entire curve is also consistent with the assumption that it is due to alpha-particles, the curves indicating a shift of about 40 kv and the calculations requiring 45 kv. Furthermore curve B, taken at an intermediate voltage, indicates the shifting of the limits to the right as the bombarding voltage is increased and the positions of its limits are in agreement with the conclusion just reached.

Because of the better resolution of the two limits when the bombarding energy is somewhat lower than 350 kv, we shall obtain our value of Q_1 entirely from curves taken in that region of bombarding energy. Table II shows the results of five trials. The correction of -0.005 Mev applied between columns 4 and 3 of Table II is arrived at as previously explained.[1] Due to the width of the beam of particles (0.1 cm) at the window of the ionization chamber, and the width of this window itself (0.3 cm), a homogeneous beam of particles will just reach zero counting rate when the deflecting voltage is raised 0.8 percent above that at which the particles traverse the mean radius. Thus a correction of -0.8 percent is applied to the high energy edges of the alpha-particle and deuteron groups.

In the vicinity of point B_1, the solid curve is drawn in a rather arbitrary manner through scattered points. If we follow the points consecutively, a curve is obtained which shows a fine structure of the deuteron energies. We have spent considerable time trying to establish the reality of such a fine structure. It appears on several curves, and is larger than the expected statistical error, but it does not appear with equal prominence on all the curves. At the present stage of our experiments, we do not wish to state categorically that such a fine structure is actually present. We are continuing investigation of this energy region. If such a structure is present, it would probably represent a very low excited state of Be^8, about 16 kv above the ground state. Another irregularity in the curve indicates such a state at 30–50 kv.

The formula used for calculating the reaction energy assumes an angle of 90° between the incident particle and the ejected particle. It can be shown that the variation in the value of Q with the angle θ between the incident and ejected particles is given by

$$dQ=2\left(\frac{M_1M_2}{M_3}E_1E_2\right)^{\frac{1}{2}}\sin\theta d\theta,$$

where the subscripts 1, 2 and 3 refer to the incident, the ejected and the residual nuclei, respectively, M is the mass of the nucleus and E its kinetic energy. The angle between the direction of the incident beam and the tangent to the circular deflection plates of the analyzer at the entrance of the field was measured and found to be $88°\,40'\pm 20'$. To this should be added the maximum allowable angle in the forward direction between the tangent to the deflection plates and the direction of a particle which can just pass through the analyzer. This is about $1°\,10'$. Therefore the most energetic particles which come through the analyzer were ejected at an angle of $89°\,50'\pm 20'$ with the bombarding protons. Since the measurements are made on the most energetic particles no appreciable error results from the assumption made in the calculations of a right angle between the two beams.

In the case of curve A of Fig. 2, the deflecting voltage on the electrostatic analyzer was lowered to the point where scattered protons could traverse the required path. The energies of such protons can be obtained from the equation[5]

$$E_s/E_p=\frac{[M\cos\theta\pm(m^2-M^2\sin^2\theta)^{\frac{1}{2}}]^2}{(M+m)^2},$$

where E_p is the bombarding energy, M is the proton mass, and m the beryllium mass. Taking θ as 90° we find $E_s=280$ kv if $E_p=351$ kv. No care was taken in observing these pulses but

TABLE I. *Number of particles counted in curves of Fig. 2.*

Point	Total No.	No. per sec.	Method of counting
A_1	744	18.6	Mechanical
A_2	400	10.0	Mechanical
B_1	675	11.2	Mechanical
B_2	270	4.5	Mechanical
C_1	246	2.36	Visual
C_2	90	1.05	Visual

TABLE II. *Energy liberated in the reaction* $Be^9\ (p, d)\ Be^8$.

Trial	Proton Energy kv	Deuteron Limit Mev	Deuteron Limit Corrected	Q_1 Mev	Q_1 Milli-mass-units
1	258	0.629	0.624	0.555	0.596
2	262	0.628	0.623	0.557	0.598
3	262	0.628	0.623	0.557	0.598
4	315	0.670	0.665	0.556	0.597
5	315	0.673	0.668	0.559	0.600

[5] C. G. Darwin, Phil. Mag. **27**, 499 (1914).

they were obviously present at the proper deflecting voltage of 14 kv.

Inspection of the relative heights of the limits in the 262-kv curve shows that the numbers of deuterons and alpha-particles are approximately equal. This is in agreement with observations of others by counting at different biases on the Thyratron scaling circuit and thus distinguishing between the intense alpha-particle pulses and the relatively weaker deuteron pulses.[4]

In view of the results of Table II, and of the previous paper from this laboratory,[1] we can now announce the energy releases in the following reactions:

$$Be^9+H^1=Be^8+D^2+Q_1;\quad Q_1=0.557\pm0.006 \text{ Mev} \tag{1}$$

$$Be^9+H^1=Li^6+He^4+Q_2;\quad Q_2=2.152\pm0.04 \text{ Mev.} \tag{2}$$

Deductions from the Energy Values

By adding the equation

$$D^2+h\nu=H^1+n^1+Q_4$$

to Eq. (1) above, we obtain

$$Be^9+h\nu=Be^8+n^1+Q_1+Q_4.$$

In a new determination of Q_4 by Rogers and Rogers,[6] the value -2.174 ± 0.02 Mev has been obtained. Less recently Stetter and Jentschke[7] found -2.189 ± 0.022 Mev. Taking the average of these as -2.18 ± 0.02 Mev, we obtain the value -1.62 ± 0.02 for the sum Q_1+Q_4. This numerical value represents the binding energy of the odd neutron in Be^9, and also is the photoelectric threshold for the photodisintegration of Be^9. Collins, Waldman and Polye[8] have reported that this reaction initiates with the x-rays from a high voltage tube when the voltage rises to about 1.65 Mev.

Our results also have some bearing on the problem of the stability of Be^8. If we use, in addition to the equations (1) and (2) representing our work, the equation

$$Li^6+D^2=2He^4+Q_3$$

we can obtain

$$Be^8-2He^4=-(2D^2-He^4)-Q_1+Q_2+Q_3.$$

The term $(2D^2-He^4)$ is a well-known mass-spectrographic doublet for which Bainbridge[9] finds the value 25.61 ± 0.04 mMU (thousandths of a mass unit). The value of Q_3 has been measured quite accurately by Oliphant, Kempton and Lord Rutherford,[10] who obtained the value 22.08 ± 0.07 Mev. From these values we find that the term Be^8-2He^4, which represents the stability of beryllium eight with respect to disintegration into two alpha-particles, to be -0.187 ± 0.10 mMU. This indicates that beryllium eight is stable by 0.174 ± 0.09 Mev.

Various other data may be used along with ours to calculate the stability of beryllium eight, although it seems[11] that the above is the most reliable. If Aston's value[12] of 25.51 ± 0.08 mMU for the deuterium-helium bracket is used instead of Bainbridge's, we get by the above scheme a Be^8 stable with respect to two alpha-particles by 0.087 ± 0.12 mMU. This is a result indecisive as to stability or instability.

If we discard the reaction Li^6 (d,α) He^4 as the source of the needed additional data, and use instead

$$Be^9\ (d,\alpha)\ Li^7;\quad Q_5=6.95\pm0.12 \text{ mMU,}^{13}$$

and $$Li^7\ (p,\alpha)\ He^4;\quad Q_6=17.13\pm0.006 \text{ mMU,}^{14}$$

we obtain (after the Q's are expressed in mass rather than energy units) the result

$$Be^8-2He^4=-(2D^2-He^4)-Q_1+Q_5+Q_6=-0.33\pm0.14 \text{ mMU}$$

with Bainbridge's value of the bracket. If Aston's value is used, the stability is 0.23 ± 0.16 mMU.

Thus the *present status* of the energy values definitely points to a *stable* Be^8, with the best value of the stability 0.174 ± 0.09 Mev.

Be^8 has not been found as a natural constituent of the earth's crust. Bleakney, Blewett,

[6] F. T. Rogers and M. M. Rogers, Phys. Rev. **55**, 263 (1939).

[7] G. Stetter and W. Jentschke, Zeits. f. Physik **110**, 214 (1939).

[8] G. B. Collins, B. Waldman and W. R. Polye, Phys. Rev. **55**, 412 (1939).

[9] K. T. Bainbridge and E. B. Jordan, Phys. Rev. **51**, 384 (1937).

[10] M. L. E. Oliphant, A. E. Kempton and Lord Rutherford, Proc. Roy. Soc. Lond. **A149**, 406 (1935); cf. S. K. Allison, Phys. Rev. **55**, 624 (1939).

[11] S. K. Allison, Phys. Rev. **55**, 624 (1939).

[12] F. W. Aston, Proc. Roy. Soc. Lond. **A163**, 391 (1937).

[13] J. H. Williams, R. O. Haxby and W. G. Shepherd, Phys. Rev. **52**, 1031 (1937).

[14] Oliphant, Kempton and Rutherford, reference 10.

Sherr and Smoluchowski[15] have examined the mass spectrum of beryllium under conditions in which doubly charged oxygen could not contribute a false mass eight spot, and found no Be^8 to one part in 10,000 of Be^9.

O. Laaff[16] placed an ionization chamber of effective depth 0.1 cm of air behind a window of 0.25 cm stopping power and amplified the pulses from alpha-particles produced in the boron-proton reactions. It is well known that there is a continuous distribution of ranges, culminating in a discrete group at 4.4 cm, supposed to arise from the reaction B^{11} (p, α) Be^8 in which the alpha-particle recoils from a complete Be^8 nucleus. The energy released is 8.55 Mev, so that the recoil energy of the Be^8 nucleus is 2.85 Mev, disregarding the 185 kv bombarding energy used by Laaff. Occasional pulses, more intense than those from alpha-particles, were observed in the chamber, and attributed to simultaneous entrance of two alpha-particles from the disintegration of the residual Be^8. From the effective solid angle for large pulses, which appeared to be less than the geometrical solid angle of the apparatus, Laaff estimated that the energy released in the disintegration of the Be^8 into two alpha-particles was smaller than 200 kv.

It seems difficult to ascribe the presence of intense pulses to two simultaneous alpha-particles without a discussion of pulse heights. The theory of ionization by moving positive charges predicts that, at the same velocity, the loss of energy per cm of path by a moving, quadruply charged, Be^8 nucleus is four times that of a single alpha-particle, and, of course, twice that of two alpha-particles. But if the presence of the two simultaneous alpha-particles be granted, it does not seem improbable that a Be^8 nucleus, stable by only 0.174 Mev, should be thrown into a low, oscillating, virtual quantum state from which it can decompose; particularly when the available recoil energy is 2.85 Mev. The recoil energy available for the Be^8 nucleus in the reaction Be^9 (p, d) Be^8, which we have studied here, is only 0.11 Mev.

Glückauf and Paneth[17] exposed a sample of beryllium metal to the gamma-radiation from RaB and RaC, dissolved the beryllium, and tested the evolved gases for traces of helium. They found that helium actually had been produced in the beryllium, to an amount of the order of magnitude of that to be expected from the yield of neutrons in the photodisintegration of Be^9. Thus they state that the end product of the photodisintegration is two alpha-particles and a neutron, and that Be^8, if produced in an intermediate stage of this reaction, is not stable.

The energy required to disintegrate Be^9 into two alpha-particles and a neutron according to our results is $1.62+0.17$ or 1.79 Mev. The two gamma-ray lines from RaB and RaC which have energy enough to disintegrate beryllium at all are 1.78 and 2.22 Mev. Thus they are also probably able to produce the complete disintegration into helium and neutrons.

The author wishes to thank Professor Samuel K. Allison for his interest and assistance in this work. Others who have given help are Mrs. E. R. Graves, Mr. Leonard Miller, Mr. Nicholas M. Smith, Jr., and Mr. Gilbert Perlow.

[15] W. Bleakney, J. P. Blewett, R. Sherr and R. Smoluchowski, Phys. Rev. **50**, 545 (1936).

[16] O. Laaff, Ann. d. Physik **32**, 743 (1938).

[17] E. Glückauf and F. A. Paneth, Proc. Roy. Soc. **165**, 229 (1938).