# The Energy Spectrum of the Neutrons from the Disintegration of Beryllium by Deuterons*

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The energy distribution of the neutrons from the disintegration of beryllium by high speed deuterons has been investigated by the method of recoil-protons in a high pressure cloud chamber. The maximum neutron energies which were observed correspond to an energy of disintegration of 4.14 MEV. The mass of $Be^9$ calculated from these data, assuming the reaction ${}_4Be^9+{}_1H^2\rightarrow{}_5B^{10}+{}_0n^1$, is $9.0123\pm0.0008$. Several other neutron groups of lower energies were observed which indicate that the $B^{10}$ nucleus is left in one of several possible excited states. The excited $B^{10}$ nucleus presumably falls to the normal state by the emission of a $\gamma$-ray.

THE copious emission of neutrons from the bombardment of beryllium by high speed deuterons was first reported by Crane, Lauritsen and Soltan.[1] Indications of the energies of the neutrons produced in this disintegration have been obtained by Kurie,[2] Oliphant,[3] and Bjerge and Westcott.[4] From the disintegrations produced in nitrogen by the neutrons from beryllium which was bombarded with 2 M.E.V. deuterons, Kurie has inferred that their maximum energy is about 10 M.E.V. On the other hand, the results of Oliphant,[3] who used a helium-filled counting chamber and linear amplifier, suggest that there are not many neutrons with energies over 3 M.E.V. The energy of the bombarding deuterons in the latter experiment was only 0.3 M.E.V., but there still remains a considerable discrepancy in the two results. Bjerge and Westcott[4] have found that the deuteron-beryllium neutrons do not induce radioactivity in fluorine and silicon as do the high energy neutrons from lithium + deuterons and beryllium + alpha-particles. This suggests that the deuteron-beryllium neutrons are of low energy.

The purpose of the present experiment was to determine accurately the maximum energy of the deuteron-beryllium neutrons, and to study their energy distribution. This was done by measuring the ranges of the recoil-protons ejected from $CH_4$ in a high pressure cloud chamber, a method which has been described and used by Bonner and Mott-Smith.[5] In a high pressure cloud chamber, it is possible to stop a recoil-proton of high energy in a comparatively short distance, so that the entire track lies within the chamber.

The maximum energy of the neutrons cannot be determined definitely unless the velocity and mass of the recoil nucleus are known. Range-velocity curves are accurately known only for protons and $\alpha$-particles. At present it is impossible without the aid of a very strong magnetic field to distinguish unambiguously between the tracks left in a cloud chamber by these two particles. Because of the water or alcohol vapor used in an expansion chamber, there are always hydrogen atoms present. Thus we cannot determine the maximum energy of neutrons with a helium-filled chamber as the recoil H-particles have a longer range for the same energy. The above reasons force one to the use of recoil-protons for the cloud-chamber determinations of neutron energies. The presence of carbon or other atoms heavier than hydrogen does not interfere with this work, since such atoms have very much shorter ranges than recoil-protons of the same energy.

## APPARATUS

The automatic high pressure cloud chamber which was used in this experiment has been described previously.[6] It is 9 cm in diameter, and 3 cm deep. In use, its center was placed 20 cm from the center of the beryllium target which had a radius of 2.5 cm. The arrangement was such that the neutrons which entered the chamber

* A preliminary report of this work was given at the meeting of the American Physical Society, Los Angeles, December 1934. Phys. Rev. **47**, 254 (1935).
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[1] Crane, Lauritsen and Soltan, Phys. Rev. **44**, 692 (1933).
[2] F. N. D. Kurie, Phys. Rev. **47**, 97, 253A (1935).
[3] Oliphant, Int. Conf. of Physics, London, October, 1934.
[4] Bjerge and Westcott, Nature **134**, 177 (1934).
[5] Bonner and Mott-Smith, Phys. Rev. **46**, 258 (1934).
[6] Brubaker and Bonner, Rev. Sci. Inst. **6**, 143 (1935).

made an angle of approximately 90° with the incident beam of deuterons on the target. The deuterons were accelerated by the Crane and Lauritsen apparatus, which was operated in such a manner that the deuterons struck the target for only a fraction of a second following the expansion. Thus no neutrons entered the chamber until it was expanded. The cloud chamber was filled with gas from a cylinder which contained 85.1 percent $CH_4$, 13.5 percent $C_2H_6$, and 1.4 percent $N_2$. The pressure of the gas in the chamber before and after expansion was read from an ordinary pressure gauge which had been calibrated hydraulically. The stopping power of the gas relative to air was computed from the known pressure and the relative amounts of the gases contained in the chamber. The stopping powers used there were those determined by Bragg, and were 0.86 for $CH_4$, 1.52 for $C_2H_6$, and 0.99 for $N_2$. The stopping power of the alcohol vapor contained in the chamber was computed from data given by Phillipp.[7]

## Results

Approximately 3000 sets of stereoscopic photographs were taken when beryllium was bombarded by 0.9 M.E.V. deuterons. On the photographs, numerous recoil-protons were observed and the ranges of approximately 900 were measured. Test runs were made in which the beryllium target was replaced by a brass one; less than 1/1000 as many recoil-protons were observed. The effect of the small amount of proton contamination in the deuterons was examined by making a control run in which the bombarding ions were protons. The results indicated that the proton impurity in the deuteron gas could not have been responsible for more than 1/2000 of the observed neutrons.

Three series of runs were made in this experiment, in which the expanded pressures in the chamber were 10.5, 7.20 and 5.85 atmospheres. The ranges of the protons were measured by reprojecting the photographs through the camera lens system in the usual manner. These lengths were converted into cm of air-equivalent range from the calculated stopping-power of the gas. The energies of the protons were then computed from the range-velocity curve of Duncanson.[8]

In an elastic head-on collision, a neutron gives all of its energy to a proton. If, however, the neutron-proton collision is not head-on, only a portion of the kinetic energy of the neutron will be transferred to the proton. In general, the energy given to the proton will be $E_p = E_n \cos^2 \theta$ where $E_p$ is the energy of the proton, $E_n$ the energy of the neutron and $\theta$ the angle between the direction of motion of the incident neutron and the recoil-proton. Thus, to get the energy of the neutron from that of the proton, one must know the direction of the incident neutron. To assume that the neutron came directly from the source and to apply this equation would introduce serious error, because some neutrons are scattered into the chamber. These produce a small number of high energy recoil-proton tracks, which are sometimes at large angles to a line drawn to the source. Obviously the application of the above equation to these tracks would give neutron energies which are too high. In this experiment, we have eliminated this difficulty by measuring only those tracks which made angles less than 8° with the lines drawn from the points of collision to the center of the target. A proton projected at 8° gets 98.1 percent of the neutron's energy. However, because of the size of the source, some protons were measured which were projected at angles as large as 16° and so received only 92.4 percent of the neutron's energy. Thus we should expect that a large proportion of the measured recoil-protons received between 98.1 and 100 percent of the neutron energies, and that a rapidly diminishing number received from 98.1 down to 92.4 percent. Of course, a small number of protons which appeared to be in this angular range (0–8°) were actually protons which had been projected at large angles by scattered neutrons. This number is probably quite small and is effective only in giving a low energy background or tail to the energy distribution curve.

The curves given in Fig. 1 represent the energy distribution of the recoil-protons which have been measured in this manner. The three curves $A$, $B$ and $C$ refer to tracks obtained when the chamber was operated at expanded pressures of

[7] K. Phillipp, Zeits. f. Physik **17**, 23 (1923).

[8] W. E. Duncanson, Proc. Camb. Phil. Soc. **30**, 102 (1934).

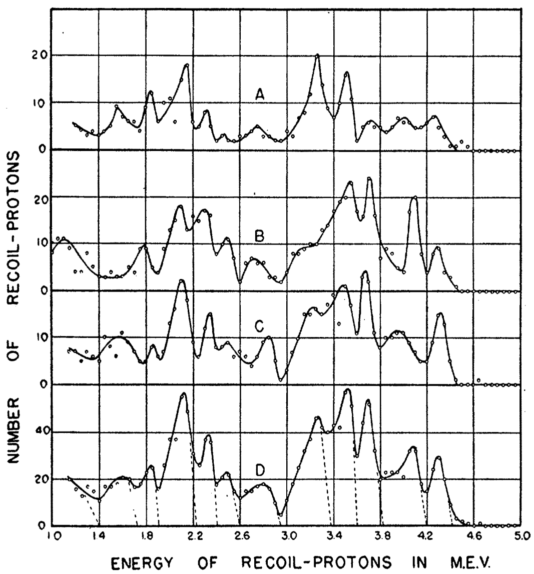


FIG. 1. Energy-distribution curves of recoil-protons projected in the forward direction. Curves $A$, $B$, $C$ include proton tracks which were obtained at expanded pressures of 10.5, 5.85 and 7.20 atmospheres, respectively. The ordinates of points on curve $D$ are equal to the sum of the ordinates of curves $A$, $B$ and $C$.

10.5, 5.85 and 7.20 atmospheres, respectively. Curve $D$ is the sum of these three curves. The four curves all give approximately the same maximum energy of the recoil-protons, and consequently the same maximum energy of 4.42 $\pm$0.27 M.E.V. for the neutrons. Recoil-protons of higher energy would have been observed, if present, since the length of the highest energy group of tracks photographed was less than a third of the diameter of the chamber.

The energy distribution curves show distinct maxima and minima which indicate that there are several energy groups. Essentially the same groups are indicated by the separate curves, although the heights of the peaks vary. Such variations are probably caused by statistical fluctuations. The agreement of the positions of the maxima and minima on the curves obtained at different pressures leads us to believe that most of the groups indicated are real, and are not due to statistical fluctuations.

## Theory of Results

The neutrons in this experiment are attributed to the reaction

$$_4Be^9 + {}_1H^2 \rightarrow {}_5B^{10} + {}_0n^1.$$

The energy of the disintegration can be computed from the well-known relation,

$$Q = \tfrac{1}{2}MV^2 - \tfrac{1}{2}M_hV_h^2 + (1/2M_n)(M^2V^2 - 2MM_hVV_h\cos\phi + M_h^2V_h^2) \quad (1)$$

where $Q$ is the energy of the disintegration, $M$ the mass of the neutron, $V$ the velocity of the neutron, $M_h$ the mass of the deuteron, $V_h$ the velocity of the deuteron, $\phi$ the angle between the incident deuteron and the neutron, and $M_n$ the mass of the resulting nucleus ($B^{10}$ in the present case). In this experiment $\phi$ was 90°, so the relation becomes

$$Q = 11E/10 - 4E_h/5,$$

where $E$ and $E_h$ are the energies of the neutron and deuteron.

With 4.42 M.E.V. as the energy of the neutrons, the above formula gives 4.14 M.E.V. as the energy of disintegration. Corresponding to this value of $Q$, a neutron ejected in the forward direction has an energy of 4.93 M.E.V. If a few of the neutrons which were ejected at angles less than 90° were scattered into the chamber by the brass beneath the beryllium target, we should find a few recoil-protons which had energies between 4.4 and 4.9 M.E.V. We attribute the small number of observed energies above 4.42 M.E.V. to such neutrons.

For a given energy of disintegration, all the neutrons emitted at a 90° angle do not have exactly the same energy. This is due to the fact that deuterons of all energies up to 0.9 M.E.V. produce disintegrations. However, the excitation curve of Crane, Lauritsen and Soltan[1] shows that the efficiency of disintegration increases very rapidly with deuteron energy, so that the number of neutrons produced by 0.8 M.E.V. deuterons is only about half that produced by 0.9 M.E.V. deuterons. Since at 90° $E_n = 10Q/11 + 8E_h/11$, we see that the change in energy of the neutron is only 8/11 that of the deuteron. Thus, we should expect to get a neutron line with a half-width of about 0.07 M.E.V.

The other neutron groups indicated by the curves of Fig. 1 probably correspond to cases where the entire energy of the reaction does not go into the kinetic energy of the neutron and recoil nucleus. The $B^{10}$ nucleus may be left in an excited state and then fall to the normal state with the emission of a $\gamma$-ray. The energies of disintegration (in M.E.V.) calculated from the various neutron groups are $Q_0=4.14$, $Q_1=3.89$, $Q_2=3.48$, $Q_3=3.25$, $Q_4=3.00$, $Q_5=2.51$, $Q_6=2.14$, $Q_7=1.93$, $Q_8=1.73$, $Q_9=1.39$, $Q_{10}=1.19$ and $Q_{11}=0.82$. The maximum difference in the $Q$'s might be expected to correspond to the highest energy $\gamma$-ray emitted by the excited $B^{10}$ nucleus. This value of 3.32 M.E.V. is in good agreement with the maximum energy of the $\gamma$-rays found in cloud chamber experiments by Crane, Delsasso, Fowler and Lauritsen.[9] We might also expect two intense $\gamma$-ray lines with energies equal to $Q_0-Q_2=0.66$, and $Q_0-Q_3=0.89$, which together probably correspond to the 0.8 M.E.V. $\gamma$-ray line they have reported. Another intense $\gamma$-ray line $Q_0-Q_8=2.41$ seems to correspond to their $\gamma$-ray line of 2.50 M.E.V.

It is seen that the neutron energy spectrum is considerably more complex than the $\gamma$-ray spectrum which supposedly arises from the same reaction. This is probably due to a difference in the resolving power of the two methods, more than one line being included in a single hump in the $\gamma$-ray spectrum. Exact correlation between the two spectra is therefore not possible.

The energy of the disintegration calculated from the masses of the isotopes ${}_4Be^9=9.0155$, $H^2=2.0136$, $B^{10}=10.0135$, and $n^1=1.0080$ is 7.1 M.E.V. which differs by 3 M.E.V. from our experimental value of 4.14 M.E.V. The limit of error in this experiment is much smaller than this difference. Assuming a maximum uncertainty in the stopping power of the gas in the cloud chamber of as much as 10 percent, the uncertainty in the maximum energy of the neutrons is only 0.27 M.E.V. The possibility that this 3 M.E.V. of energy is always given off as a $\gamma$-ray seems very unlikely on the basis of the known $\gamma$-ray spectrum. If this were the case, we should expect to find an intense $\gamma$-ray with an energy of 3 M.E.V. and also $\gamma$-rays with energies up to 6.32 M.E.V. On the basis of the neutron energy spectrum there should be at least 11 possible transitions giving $\gamma$-ray energies between 3 and 6.32 M.E.V. It would be strange if none of these were permitted. Crane, Delsasso, Fowler and Lauritsen find only a $\gamma$-ray with an energy of 3.3 and possibly a weak one at 4.0 M.E.V. and no $\gamma$-rays with an energy greater than this.

Thus it seems as if at least one of the masses listed above is in error. It appears most likely that this error is in the mass of $Be^9$, as there is considerable evidence from other disintegrations that its mass should be lower by approximately 3.0 M.E.V. A number of the disintegrations which give a lower mass for $Be^9$ have been pointed out by Kirchner and Neuert,[10] Ridenour, Shinohara and Yost,[11] and Crane and Lauritsen.[12]

A summary of the disintegrations and the computed mass of $Be^9$ is given below.

$${}_4Be^9+{}_1H^1\rightarrow{}_3Li^6+{}_2He^4 \text{ (Kirchner and Neuert—}Be^9=9.0110\pm0.0006), \quad (2)$$
$${}_4Be^9+h\nu\rightarrow2{}_2He^4+{}_0n^1 \text{ (Ridenour, Shinohara and Yost—}Be^9=9.0114\pm0.0011), \quad (3)$$
$${}_3Li^6+{}_2He^4\rightarrow{}_5B^9+{}_0n^1\rightarrow{}_4Be^9+e^++{}_0n^1 \text{ (Meitner—}Be^9=9.0110\pm0.0006), \quad (4)$$
$${}_4Be^9+{}_1H^1\rightarrow2{}_2He^4+{}_1H^2 \text{ (Oliphant—}Be^9=9.0110), \quad (5)$$
$${}_4Be^9+{}_1H^2\rightarrow{}_4Be^{10}+H^1 \text{ (Crane and Lauritsen—}Be^9=9.0125), \quad (6)$$
$${}_4Be^9+{}_1H^2\rightarrow{}_5B^{10}+{}_0n^1 \text{ (Bonner and Brubaker—}Be^9=9.0123\pm0.0008). \quad (7)$$

There seems to be a considerable body of evidence which indicates that the mass of beryllium should be between three and four million volts lower than Bainbridge's value of 9.0155. This would just make $Be^9$ stable against disintegration into two $\alpha$-particles and a neutron.[13]

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[9] Crane, Delsasso, Fowler and Lauritsen, Phys. Rev. **47**, 782 (1935).

[10] Kirchner and Neuert, Physik. Zeits. **36**, 54 (1935).

[11] Ridenour, Shinohara and Yost, Phys. Rev. **47**, 318 (1935).

[12] Crane and Lauritsen, Phys. Rev. **47**, 420 (1935).

[13] *Note added in proof:* If we use a revised set of isotopic masses as recently suggested by Oliphant and Rutherford, Bethe and Aston, we get a different computed mass of beryllium. If we use the masses given by Bethe we get the following consistent set of masses for ${}_4Be^9$ from the above reactions (2) 9.0139, (3) 9.0143, (4) 9.0133, (5) 9.0137, (6) 9.0133, (7) 9.0133. Beryllium then will be stable by 1.5 M.E.V. against disintegration into two alpha-particles and a neutron.