scattered beam passed through the second set of slits into the ionization chamber and produced a definite deflection of the galvanometer. The magnetic field was now switched on and careful observation made to see whether the deflection changed. Then the field was switched off, the shutter closed, and the galvanometer zero checked again. In no case could any effect of the magnetic field be detected. Tests were made at 1° intervals for both curves of Fig. 2, a field of 2700 gauss being used. An effect as large as two percent could have been detected in the case of the largest deflections.

Discussion of Results

The diffraction of x-rays by Na-K alloys has been investigated previously by K. Banerjee,[5] who used the Mo $K\alpha$ radiation and a photographic method. Banerjee finds a maximum at 11° 28′. In the present work the maximum is at about 9.5°. The scattering of the points at the maximum in Fig. 2 appears to be rather too large for high accuracy; however, repeated trials indicated a definitely smaller angle for the maximum than was found by Banerjee. The reason for the discrepancy is not evident. It may be mentioned, however, that thin, flattened, glass tubes, such as Banerjee used to contain his alloy, could not be used in the present work because their scattering was comparable to that of the alloy. Using the Bragg formula the spacing of diffracting centers in the liquid turns out to be 4.3 Angstrom units, according to the present data, instead of 3.5 as given by Banerjee.

The absence of any effect of a magnetic field indicates that no appreciable modification of molecular groupings is produced. Hence the magnetoresistance of the alloy cannot be explained on these grounds. The possibility remains that certain structural changes may occur which are too small to be detected by the x-ray method. Ferromagnetic crystals when magnetized give an unchanged x-ray spectrum although definite structural changes occur, as is evidenced by the presence of magnetostriction.

An attempt was made to detect magnetostriction in the Na-K alloy. A quantity of the material under oil in a glass bulb was placed bebetween the poles of an electromagnet and subjected to a field of 7800 gauss. The oil meniscus in a fine capillary tube connected to the bulb was observed under a microscope. It was estimated that if any magnetostriction occurred the volume change per unit volume must have been less than 3×10^{-7}, the limit of accuracy of the experiment. This is a smaller volume change than is found to exist in ferromagnetic materials.

The conclusion appears to be that in this alloy a magnetic field does not produce a resistance change by modification of any molecular groupings or spacings in the liquid. The main cause of magnetoresistance is thus to be sought in the Lorentz forces which modify the electron free paths.

[5] K. Banerjee, Ind. J. Phys. 3, 399 (1928).

SEPTEMBER 15, 1935 PHYSICAL REVIEW VOLUME 48

The Transmutation Functions for Some Cases of Deuteron-Induced Radioactivity[1]

Ernest O. Lawrence, Edwin McMillan and R. L. Thornton, *Radiation Laboratory, Department of Physics, University of California, Berkeley*

(Received July 1, 1935)

When nuclei are bombarded with deuterons, a commonly observed type of reaction is that resulting in proton emission and the conversion of the nuclei into isotopes of mass number one unit greater. Many such reactions give beta-radioactive products. The variation of the transmutation cross section with deuteron energy has been studied for the radioactivity thus produced in Na, Al, Si and Cu, with deuteron energies ranging from 0 to 3.6 MV. In all these cases it is found that the excitation curve is too flat to be explained by the Gamow theory, while it is fitted very well by a theoretical curve derived by Oppenheimer and Phillips. This is based on the idea that the nucleus can capture the neutron from the deuteron without requiring the penetration of the deuteron through the nuclear Coulomb barrier. The form of the theoretical curve depends on the binding energy of the deuteron; a value between 2.0 and 2.4 MV is required by the experimental results.

Introduction

IN THE original investigations of the radioactivity induced in sodium[2] and aluminum[3] by deuteron bombardment, observations of the voltage excitation curves up to a deuteron energy of 1.9 MV were made. In this range the experimental curves can be fitted reasonably well by the Gamow[4] nuclear penetration function, which has been found to describe so well many other nuclear reactions produced by α-particle and proton bombardment. It was noticed, however, in the case of aluminum, for which the experimental data were more detailed, that the experimental points corresponding to the lowest deuteron energies lie above the theoretical curve when it is made to fit the high energy points. The true significance of this was not realized until the experiment was repeated with a deuteron beam of much greater energy, extending the excitation curve for aluminum up to 3.4 MV.

It was then found that the differential excitation function for aluminum beyond 2 MV, instead of rising with a rapidly increasing slope as predicted by the Gamow theory, goes up at a much more modest rate. The part of the curve between 2 and 3.3 MV is in fact a straight line when plotted against the range of the deuterons. Curves of similar shape were found for the sodium reaction, and some others that will be described later. (See Figs. 2–5.)

These observations indicated that some new description of the mechanism of these reactions was necessary. If one should attempt to explain the experimental results while retaining the usual picture of a simple penetration of the bombarding particle through the nuclear potential barrier, it would be necessary to suppose either that a conglomeration of unresolved resonance levels happened to give this particular shape to the curve, or else that the deuterons were going over the top of the barrier at a remarkably low energy. The first of these suppositions is made highly improbable by the facts that the curves are smooth and monotonic, and are of similar shape for several different reactions. The second would require an abnormally large nuclear radius. Duncanson and Miller[5] find 9 MV for the height of the Al potential barrier to α-particles; one would expect the height for deuterons to be half as great, and therefore beyond the energy range covered in these experiments.

At this point Professor Oppenheimer became interested in the problem from a theoretical standpoint, and found that the experimental results are not at all mysterious, but are just what must be expected for reactions of the type investigated when the small stability of the deuteron is taken into account. A full account of the theory is given by Professor Oppenheimer and M. Phillips in the paper immediately following this one. We shall return to a discussion of the mechanism of reaction involved and its application in this case after devoting some attention to the experiments.

Reactions Studied

The formation of radioactive bodies from sodium and aluminum by deuteron bombardment has been shown[2, 3] to occur almost certainly according to the reactions:

$$Na^{23}+H^{2}\rightarrow Na^{24}+H^{1}, \quad (1)$$

$$Al^{27}+H^{2}\rightarrow Al^{28}+H^{1}. \quad (2)$$

Recently H. W. Newson,[6] working in this laboratory, has found that an active product of 2.8 hours half-life, isotopic with silicon, is made from silicon under deuteron bombardment. The reaction concerned is presumably:

$$Si^{30}+H^{2}\rightarrow Si^{31}+H^{1}. \quad (3)$$

Finally, we have observed that copper with deuterons gives an activity of about 12 hours half-life, which is probably the same substance as the active copper isotope produced by neutron bombardment, whose half-life is given as 10 hours by Amaldi *et al.*[7] We also found a shorter

[1] This work was first reported at the Washington meeting of the National Academy of Sciences. Abstract in Science **81**, 421 (1935).

[2] Ernest O. Lawrence, Phys. Rev. **47**, 17 (1935).

[3] Edwin McMillan and Ernest O. Lawrence, Phys. Rev. **47**, 343 (1935).

[4] Gamow, *Atomic Nuclei and Radioactivity* (Oxford University Press, 1931). This is based on the wave-mechanical idea of the "diffraction" of particle waves through potential barriers, which was first applied to a nuclear problem (α-radioactivity) by Gurney and Condon and independently by Gamow.

[5] W. E. Duncanson and H. Miller, Proc. Roy. Soc. **A146**, 413 (1934).

[6] H. W. Newson, Bull. Am. Phys. Soc. **10**, No. 4, p. 8 (1935).

[7] E. Amaldi, O. D'Agostino, E. Fermi, B. Pontecorvo, F. Rasetti and E. Segrè, Proc. Roy. Soc. **A149**, 522 (1935).

period, but cannot be sure that it arises from copper without further work, taking greater care to eliminate the ubiquitous carbon and nitrogen contamination effects. Only the long period activity will be considered in this paper. It is weak compared to that of sodium; after equal exposure to a 3.6-MV deuteron beam a copper target shows about 1/200 the activity of a sodium target. Nevertheless it is very much larger than one would expect for an element of such high atomic number (29) without some modification of the ordinary theory of nuclear penetration. The reaction of formation is probably:

$$Cu^n+H^2\rightarrow Cu^{n+1}+H^1, \qquad (4)$$

where n may be 63 or 65 depending on which of the two stable copper isotopes is the parent substance.

It will be noticed that all these reactions are of the same type, in which a deuteron is captured and a proton emitted, converting the bombarded nucleus into its next higher isotope. This sort of process can also be described by saying that the nucleus snatches a neutron away from the deuteron, leaving the proton free to escape, and it is in terms of this description that the theory of Oppenheimer and Phillips is to be understood. Many such reactions with radioactive products are now known. The four listed above[8] were chosen for the present study on purely mechanical grounds, in that the substances concerned can be obtained in the form of very thin uniform foils, as required by the experimental technique used.

Experimental Method

In order to obtain a voltage-yield curve for a reaction giving a radioactive product, one measures the intensity of activation of a number of samples exposed to bombardment by particles of different energies. The relative bombarding current and exposure time must be accurately known for each sample, a requirement which is most easily and satisfactorily met by activating them simultaneously. This was done by using as a target a stack of thin foils of the substance being investigated, through which the activating deuteron beam was sent. The energy of the deuterons traversing any particular foil is then determined by their initial energy and the stopping power of the preceding foils, and the measured activities give directly the differential excitation curve.

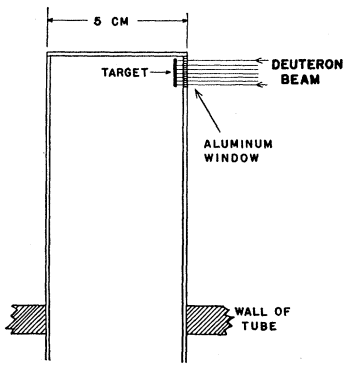

FIG. 1. Arrangement for bombarding targets.

An apparatus of the type developed by Lawrence and Livingston[9] was used to produce a beam of high speed deuterons.[10] The beam was allowed to emerge from the vacuum through a thin aluminum window (8 mm air equivalent stopping power), mounted on a brass grid near the end of a tube built into the side of the apparatus, as shown in Fig. 1. The target was placed next to the window, and the space between them was evacuated during the bombardment. Deuteron currents between 1 and 2 microamperes and exposure times from 5 minutes to 1.5 hours were used.

Measurements

The initial energy of the deuteron beam was deduced from its range in air, determined visually

[8] One other case of particular interest has recently been examined by M. C. Henderson (Bull. Am. Phys. Soc. **10**, No. 4, p. 6 (1935)). Magnesium with deuterons gives two active bodies, by the reactions:

$$Mg^{26}+H^2\rightarrow Mg^{27}+H^1, \qquad (5)$$

$$Mg^{26}+H^2\rightarrow Na^{24}+He^4. \qquad (6)$$

Making use of the widely different decay periods, he obtained the separate excitation curves of the two reactions, and found that reaction (5) follows a curve of the type described in this paper, while reaction (6) follows a Gamow curve. Theoretically one expects just this sort of behavior, since in reaction (6) the deuteron as a whole must penetrate into the Mg^{26} nucleus.

[9] Ernest O. Lawrence and M. Stanley Livingston, Phys. Rev. **45**, 608 (1934).

[10] Since we shall have many occasions in the future to refer to this apparatus, we feel that it should have a name. The term "magnetic resonance accelerator" is suggested. In this, the last two words imply the essential principle of operation, while the first word is added to distinguish it from the apparatus of Sloan and Lawrence (Phys. Rev. **38**, 2021 (1931)), which can be called a "linear resonance accelerator." The word "cyclotron," of obvious derivation, has come to be used as a sort of laboratory slang for the magnetic device.

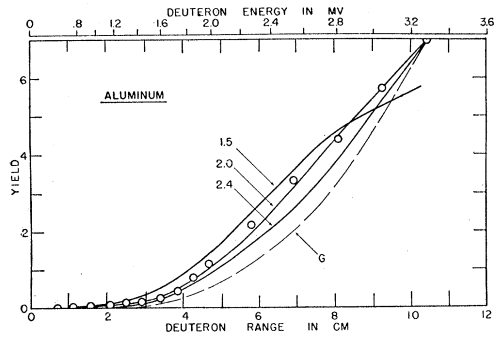

FIG. 2. Differential excitation curve of the radioactivity induced in aluminum ($Z=13$) by deuteron bombardment. Circles, experimental points. Solid lines, Oppenheimer-Phillips functions with the values of I given by the numbers, in MV. Dashed line, Gamow function.

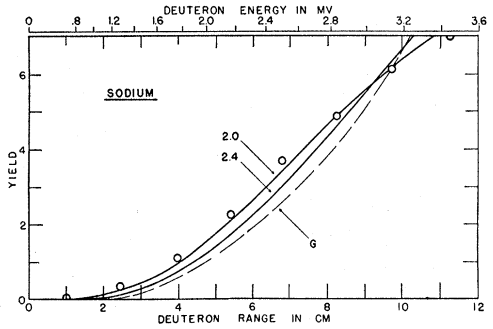

FIG. 3. Differential excitation curve of the sodium radioactivity ($Z=11$). Notation same as in Fig. 2. The ordinate of the highest energy experimental point is probably too low.

by observing the end of the streak of blue luminescence that it produces. Since the maximum air path available (see Fig. 1) was less than the range of the beam, aluminum foils were put next to the window, of such a thickness as to reduce the range to less than 4.5 cm. The stopping power of these foils was determined by weighing. The error in the range measurements made by this method was certainly not greater than 5 mm.

The stopping powers of the foils which were to be activated were determined by means of a polonium source mounted on a micrometer screw and a Wynn-Williams counter, the displacement of the counts-against-distance curve on interposing a foil being taken as its stopping power. An error of about 0.2 mm is possible in these measurements.

The activities of the foils were observed by a quartz-fiber electroscope in an ionization chamber provided with a thin aluminum window to admit β-particles. All the activities were large compared to the natural background, and these determinations should be precise to within one or two percent. The time of making each reading was recorded, making it possible to correct for the decay of the active products. In plotting the results, points with ordinates proportional to the corrected activities are put at abscissas corresponding to the centers of the foils. This method of plotting would be precise only if the curves were straight lines, but it is easy to see that the error introduced by the curvature is negligible with the spacing of points used.

Details of the various cases investigated are given below:

Aluminum (Fig. 2)

Range of deuteron beam in air (at 20°C) = 11 cm. Stopping power of individual foils (pure aluminum) = 11.5 mm. Since the active product has a half-life of about 156 sec., it decayed by a factor of about 7 in the 7 min. needed to measure the activities of all the foils, but the half-life is well enough known that this can be corrected for with very little error. The part of the curve below 4.5 cm deuteron range is taken from the results of reference 3, which were obtained with a shorter initial range, the ordinate scales being adjusted to make the two curves fit at 4.5 cm. The abscissas of the low-range points taken in this way are obviously more precise than those obtained by the passage of a long-range beam through a great thickness of foils.

Sodium and silicon (Figs. 3 and 4)

Range of beam = 12 cm. Stopping power of foils = 14.5 mm. The foils used were of mica, whose composition is given by the formula H_2 (K, Na) Al_3 Si_3 O_{12}. This substance after exposure to deuterons contains several active bodies; there are some short periods that practically vanish within an hour, as well as the 2.8-hour silicon product, and the 15.5- and 13.5-hour sodium and potassium products. Of the latter two, the sodium activity is much the stronger, even though the amount of sodium is less than that of potassium in ordinary micas (Na/K ~ 10–30 percent). A subsidiary experiment shows this. Targets of NaCl and KCl were given equal exposures (checked by the equality of the 40 min. chlorine activities induced), and observed 20 hours later.

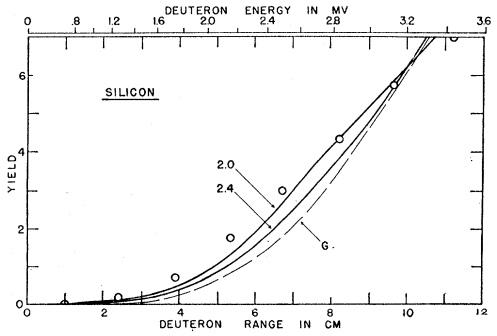

FIG. 4. Differential excitation curve of the silicon radioactivity ($Z=14$). Notation same as in Fig. 2. The ordinate of the highest energy experimental point is probably too low.

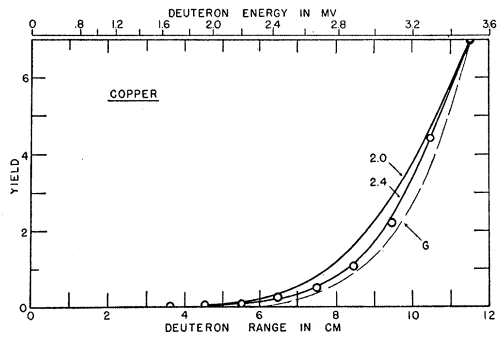

FIG. 5. Differential excitation curve of the long-period copper radioactivity ($Z=29$). Notation same as in Fig. 2.

The NaCl was found to have 70 times the activity of the KCl. Therefore in mica the greater susceptibility of the sodium to activation far outweighs its smaller abundance, and we can assume with little error that the whole long period activity arises from sodium.

The activities of the foils were measured 2 and 20 hours after activation, in order to disentangle the silicon and sodium effects. The total activities (sum of all foils) observed for silicon and sodium, corrected for decay back to the end of the activation (1.5 hours at 1 microampere) were 6 and 1.8 divisions/sec., respectively, corresponding to about 3 and 0.9 microcuries of active substances. The saturation activities after a very long exposure would be 8 and 13 microcuries.

The measured values of the activities of the highest energy foil are probably too low. This error arises from the forward recoil momentum imparted to the activated nuclei by the colliding deuterons, which, as shown in reference (3), drives the active material forward in the direction of the beam with an average range of the order of a millimeter air equivalent. As a result, an appreciable part of the activity of the first foil is transferred on to the second one. For the second and succeeding foils the loss in activity on one side is nearly compensated by the gain on the other from the preceding one. Aluminum is not subject to this error, since even the first foil is preceded by the aluminum window. Copper has such a heavy nucleus that the recoil range is small, and the error produced is negligible.

Copper (Fig. 5)

Range of beam = 10 cm and 12 cm. Stopping power of foils (pure copper) = 9.8 mm. This curve was obtained in two sections. The part from 0 to 10 cm was done at a time when the apparatus was not set to give a beam of the highest energy, and the extension up to 12 cm was made later, the two ordinate scales being adjusted to make the curves fit together at 9.5 cm.

The activities were measured 3 hours after bombardment, when only the long period copper activity remained. The total activity (all foils), expressed as that after a very long exposure to 1 microampere of 12 cm deuterons, was 14 divisions/sec. or about 7 microcuries.

Since the stopping power of copper relative to that of air varies with the velocity of the particles, the air equivalent thickness of the foils measured with polonium α-particles is slightly in error for some parts of the deuteron range. The necessary correction, which increases the effective stopping power for the highest energy and decreases it for the lowest, was made according to the values given by Mano.[11] The corresponding correction for aluminum and mica is negligible.

DISCUSSION OF THE THEORY AND ITS FIT WITH EXPERIMENT

The essence of the theoretical explanation of these results given by Oppenheimer and Phillips lies in the fact that reactions of the above type can occur without requiring the penetration of a charged particle through the nuclear Coulomb potential barrier which opposes the entry of the

[11] G. Mano, J. de phys. et rad. **5**, 628 (1934).

deuteron. The mechanism postulated can be described in the following way: Consider the deuteron as built of a proton and neutron, with the binding energy I. Because of the wave nature of the particles, this structure is not confined within a sharply limited volume, but there is a finite chance that the neutron or proton may be found some distance away from the center of mass. This chance decreases rapidly with the distance. When the deuteron is projected against a nucleus, the proton is held back by the Coulomb field. This distorts the probability distribution of the proton in such a way that for a given distance of the deuteron center of mass from the nucleus, the chance of finding it in the center of the nucleus is very much reduced. On the other hand, the neutron is immune to the action of the electrostatic field, and its probability distribution can overlap the center of the nucleus; this distribution is in fact distorted by the forces involved in the deceleration of the neutron, in such a way as to increase its density on the side toward the nucleus. Therefore the neutron has a relatively larger chance of being within the nucleus, and while there of undergoing a reaction in which it becomes bound, forming a new nucleus. The extension of the neutron distribution varies with I, becoming greater as I decreases. It is the relatively small value of I ($\sim$2 MV) that causes the slow energy variation of this type of reaction, by flattening out the neutron probability distribution.

The actual shape of the function giving the variation of the neutron-penetration with energy depends on the value of I. Since this most probably lies between 2.0 and 2.4 MV (see appendix), the curves for these two cases have been compared with the experimental values. They are plotted as solid lines on Figs. 2–5. On Fig. 2 (aluminum) the curve for $I=1.5$ MV is plotted also. The ordinates of the theoretical curves are adjusted to make them fit at the highest experimental points, except in the cases of sodium and silicon where the measured values of these are almost certainly too low because of recoil effects (see the special discussion of these cases).

The Gamow function:

$$(1/v^2)e^{-4\pi^2 Ze^2/hv}, \qquad (7)^{12}$$

where Z = atomic member, v = deuteron velocity, is also plotted on the figures for comparison. In this connection it should be emphasized that the power of v which multiplies the exponential, although usually given as $1/v^2$, is not definitely determinable without a rather detailed knowledge of the forces acting during the reaction. Depending on these, it may vary between 1 and $1/v^2$. We have used $1/v^2$, which gives the flattest curve, in order to show that even in this extreme case the function is too steep to fit the experimental results.

On the other hand, the results of Oppenheimer and Phillips show a very satisfactory agreement with the observed values. Consider first the case of aluminum. This is the most trustworthy experimentally; with pure aluminum foils the activity is very large compared to that of any possible contamination, and there is no error in the highest point caused by recoil. It is seen that the Oppenheimer-Phillips function with $I=2.0$ fits extremely well, while with $I=1.5$ and $I=2.4$ it is off by more than the experimental error.

The fit for sodium and silicon is also best for $I=2.0$. Here the possibility of experimental error is somewhat greater, and the apparent deviation in the case of silicon between 1.5 and 2.5 MV may not be real. The results for these two elements are of chief interest in showing that this type of excitation curve is not a characteristic of any particular reaction, but of a class of reactions. The comparative values for sodium and silicon show also that the steepness of the curves increases with Z, as it should.

For copper the fit seems to be best with $I=2.4$. Here, because the greatest variation of the function occurs in a narrower voltage range, the different theoretical curves are not as widely separated as in the other cases and the apparent better agreement with $I=2.4$ may not be real. We can give an explanation for it, which, however, we do not wish to emphasize unduly. Oppenheimer and Phillips point out that the theory is subject to small modifications whose evaluation would require an intimate knowledge of the nuclear structure, and which would be in such a direction as to increase the value of I giving the best fit; the magnitude of these modifications would be least for elements of large Z. The result of this would be to make the form of the theory

[12] Eq. (1), reference 3, which purports to give this function, contains a typographical error.

used here require a larger value of I for copper ($Z=29$) than for the other elements studied ($Z=11$, 13 and 14).

Such refinements are hardly justified at present. We can, however, make some conclusions that we feel are definitely beyond the possible uncertainties of both the experimental results and the theory. They are first, that the theory proposed by Oppenheimer and Phillips is adequate to explain the observed excitation curves while the Gamow theory is not, and second that the value of the deuteron binding energy consonant with this explanation is 2 MV or slightly larger.

The acceptance of this reaction mechanism as correct leads to another very important conclusion. Just as the variation of the transmutation yield with energy for a given atomic number is slower than expected, likewise the variation with atomic number for a given energy is slower. This has the consequence that it will be possible, with the available deuteron energies, to produce nuclear reactions much farther up the periodic table than one could have hoped before.

The interest and cooperation of Professor Oppenheimer and M. Phillips in this work has been of great value to us, and it is with real pleasure that we acknowledge it. We also express our appreciation of the helpful financial support given by the Research Corporation, the Chemical Foundation, and the Josiah Macy Junior Foundation.

Appendix on the Binding Energy of the Deuteron

The binding energy of the deuteron can in principle be calculated precisely from the disintegration energies of various reactions. Actually the results are subject to some uncertainty, because of possible errors in the values given for reaction energies and nuclear masses. In particular, there are intrinsic difficulties in measuring the energies of reactions involving neutrons. As an example of this sort of calculation we have chosen a set of reactions which can be combined so as to make most of the masses cancel out, and in which the direction of the uncertainty in the measurement of the energies is known, so that definite upper and lower limits can be set. These are:

$$Li^7+H^1\rightarrow 2He^4+17.06\pm 0.06 \text{ MV}, \quad (8)[13]$$
$$Li^6+H^2\rightarrow 2He^4+22.06\pm 0.07 \text{ MV}, \quad (9)[13]$$
$$H^2+H^2\rightarrow H^1+H^3+3.97\pm 0.02 \text{ MV}, \quad (10)[13]$$
$$Li^7+H^2\rightarrow 2He^4+n+14.60\pm 0.25 \text{ MV}, \quad (11)[13]$$
$$H^2+H^2\rightarrow He^3+n+2.8\pm 0.2 \text{ MV}, \quad (12)[14]$$
$$Li^6+H^1\rightarrow He^3+He^4+3.5\pm 0.3 \text{ MV}, \quad (13)[15]$$
$$Li^6+n\rightarrow H^3+He^4+4.6\pm 0.3 \text{ MV}. \quad (14)[16]$$

The energies of the particles emitted in reactions (8) to (11) have been measured with the greatest precision, and the reaction energies deduced from these are known with corresponding precision, except in the case of reaction (11). This is a three-body disintegration, and it was assumed that the most energetic α-particle comes off with the greatest energy allowed by the momentum laws. If this ideal limit is not actually attained, the reaction energy must be greater, and therefore the value given is a lower limit.

The energy given for reaction (14) was calculated from the observed H^3 range, using Mano's[11] range-energy relation. In a reaction of this type, involving the capture of a neutron, it is known, particularly from Kurie's[17] work, that some energy may be radiated during the capture; therefore the reaction energy given is a lower limit.

Since three of these reactions involve a neutron, three independent values of the deuteron binding energy can be obtained from them. The combinations giving the greatest cancelation of masses are:

$$(8)-(11), \text{ giving } H^1+n-H^2=2.46\pm 0.3,$$
$$(13)-(9)-(12), \text{ giving } H^1+n-H^2=2H^2-He^4-21.36\pm 0.4,$$
$$(14)-(9)-(10), \text{ giving } H^1+n-H^2=2H^2-He^4-21.43\pm 0.4.$$

H^1+n-H^2 is the binding energy sought. The only masses occurring on the other side of the equations are in the combination $2H^2-He^4$, which is equivalent to 23.8 ± 0.2 MV using the new values,[18] and to 23.4 ± 0.2 MV using the old ones. Putting the first of these into the equations, the three values obtained for the binding energy are:

$$(8)-(11),\ I=2.46\pm 0.3,$$
$$(13)-(9)-(12),\ I=2.44\pm 0.45,$$
$$(14)-(9)-(10),\ I=2.37\pm 0.45.$$

Recalling that the energies given for the reactions (11) and (14) are lower limits, one sees that the first value of I is an upper limit, and the third is a lower limit.

These values can be compared with that obtained by Chadwick and Goldhaber[19] from the process:

$$H^2+h\nu(2.6 \text{ MV})\rightarrow H^1+n+0.5 \text{ MV},$$

giving $I=2.1$ MV. The possible error in the measurement of the energy given to the ejected proton is uncertain, but may be some tenths of a million volts. The observed cross section for this reaction is smaller than that calculated from the theory of Bethe and Peierls,[20] using $I=2.1$; the value of I required by the theory to fit the observed cross section is 2.4.

[13] Oliphant, Kempton and Rutherford, Proc. Roy. Soc. **A149**, 406 (1935).
[14] Dee and Gilbert, Proc. Roy. Soc. **A149**, 200 (1935).
[15] Oliphant, Kinsey and Rutherford, Proc. Roy. Soc. **A141**, 722 (1933).
[16] Chadwick and Goldhaber, Nature **135**, 65 (1935); Taylor and Goldhaber, Nature **135**, 341 (1935).
[17] Kurie, Phys. Rev. **47**, 97 (1935).
[18] Aston, Nature **135**, 541 (1935).
[19] Chadwick and Goldhaber, Nature **134**, 237 (1934).
[20] Bethe and Peierls, Proc. Roy. Soc. **A148**, 146 (1935).