MEASUREMENT OF THE ENERGIES OF THE NEUTRONS FROM LITHIUM BOMBARDED WITH DEUTERONS

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ABSTRACT

The energy distribution of the neutrons resulting from the disintegration of lithium by 0.8 MV deuterons has been investigated by the observation of recoils in a high pressure cloud chamber. Both hydrogen and helium recoils have been observed at different pressures in the cloud chamber so as to cover the whole spectrum. It has been found that the reactions

$$Li^7 + D^2 \rightarrow Be^8 + n$$

$$Be^8 \rightarrow He^4 + He^4$$

$$Li^7 + D^2 \rightarrow He^5 + He^4$$

$$He^5 \rightarrow He^4 + n$$

account for most of the neutrons. The levels found in Be^8 and the ground state in He^5 have energies which agree with the values from other experiments. The low energy part of the spectrum may include neutrons from Li^6.

INTRODUCTION

Since their discovery in 1932 by Chadwick[1], neutrons have been interesting both because of their peculiar properties and because of the information they give about nuclei and their disintegrations.

In a number of transmutations, neutrons of homogeneous energy are emitted as one of the disintegration particles. The difference in energy between the highest energy neutron group (which leaves the nucleus in its ground state) and the lower energy neutron groups (which leave the nucleus in various excited states) give the energies of the excited states. The widths of the neutron groups also indicate the widths of the excited levels of the nucleus and their intensities give the relative probabilities of the various transitions. For these purposes, neutrons are often better than charged particles since the neutron has no barrier to cross in getting out of the nucleus. In three particle reactions, the energy distribution of the neutrons gives information as to the mechanism of the disintegration (whether the three particles come off simultaneously or the reaction occurs in two stages). Furthermore, a knowledge of the maximum energy of the neutrons emitted in a reaction enables the mass of one of the nuclei to be calculated in terms of the masses of the rest of the nuclei participating.

Since neutrons have no electric charge, no other long range interaction with electrons, and their wavelength is small compared to the wavelength of electrons, they rarely interact with electrons and so lose practically no energy in ionization. Their main interaction with matter (for medium fast neutrons) is in elastic collisions with nuclei. The recoil nuclei can then be observed by means of their ionization and the energy of the neutron before collision can be inferred. These recoil nuclei can be detected in ionization chambers, but the most unambiguous method of measuring their energy and direction is by the use of a cloud chamber. The cloud chamber is filled with a convenient gas whose atoms on being struck by neutrons, recoil and give observable tracks. This phenomenon was first observed by Curie and Joliot[2] even before it was known that neutrons caused recoils. Recoils of heavy gases such as nitrogen are so short (due to the small amount of energy imparted to them and to their high ionizing power) that accurate measurements of them are hard to make. On the other hand, hydrogen recoils are generally energetic enough to go all the way through a cloud chamber filled with one atmosphere of hydrogen. Hence Bonner and Mott-Smith[3] built a high pressure cloud chamber so that the recoil protons could be completely stopped in the cloud chamber. Further development by Bonner and Brubaker evolved a technique for getting reliable energy spectra of neutrons given off in nuclear disintegrations. They measured the energies of the neutrons resulting from the bombardment of deuterium, lithium, beryllium, boron and carbon by 0.8 MV deuterons[4]. The present work was begun in order to determine more accurately the energy of the high energy neutrons from lithium bombarded with deuterons. In the course of the investigation, the rest of the neutron spectrum was better resolved and gave evidence for a different interpretation of the mechanism of the disintegration.

The first section will describe the method of accelerating the deuterons, the second section will describe the methods used in measuring the neutron energies, and the third section will give the results found and their possible interpretation. Some of this material has already been published.[5][6][7]

METHOD OF ACCELERATING DEUTERONS

For much work in nuclear physics, neither homogeneous beams of bombarding particles nor extremely high energies are necessary. Especially in the study of neutron energies where the accuracy and resolving power are still not good (due to the indirect methods of measurement) all that is needed is medium high voltage, good currents, and an approximate knowledge of the maximum energies of the ions. Hence a vacuum tube designed for use with a million volts a.c. is quite satisfactory. Since the million volt transformer set at the Institute is available, it is a most practical voltage source. Indeed, Crane and Lauritsen have been very successful in making such a tube and using it in nuclear research.(8) Their vacuum tube had a relatively large distance between the ion source and the target. Furthermore, the voltages on different sections were fixed by being connected to the quarter points on the transformer set. With this arrangement it is impossible to vary the focussing of the ions very much. Hence it was thought that under these conditions, more current might be delivered to the target with a short ion path vacuum tube. Such a tube was built for one million volts with the distance between the ion source and the target as short as practical. The ion path is about half as long as that of the Crane and Lauritsen tube. The tube works quite well but does not give the hoped for increase in ion current. It does, however, provide a satisfactory source of high energy particles for producing nuclear disintegrations. Its main disadvantages compared to the Crane and Lauritsen tube are that it needs much more outgassing due to the increased area of metal exposed to strong electric fields and that it takes longer to pump out due to larger volume. The main disadvantages of both these tubes and voltage source are the fixed voltage taps (since it results in poor focussing which makes it impractical to use the magnetically analyzed beam for bombarding targets) and the presence of x-rays produced

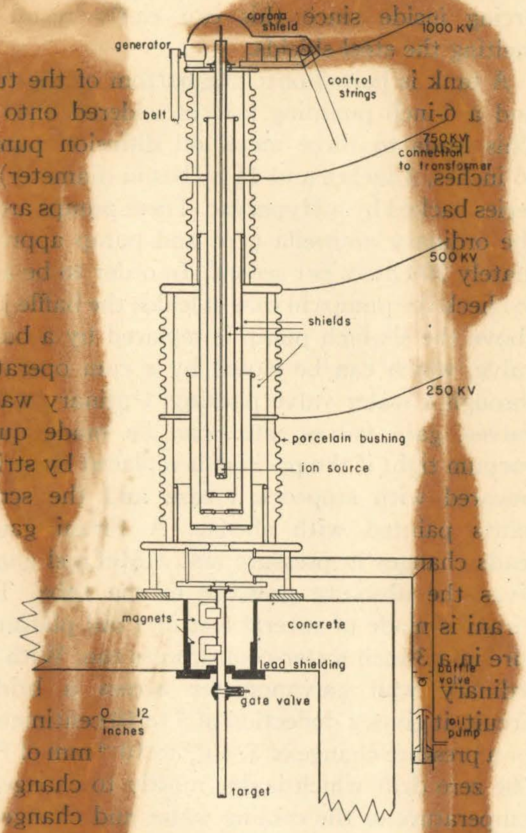

FIG. 1. Cross section of the tube.

near the target by electrons accelerated on the negative cycle of the a.c.

A magnetic analysis made on the ion beam after it had been passed through a slit showed that one-half of the ions had energies within 90% of the peak energy. This is what would be expected, since the transformers produce a good sine wave and the focussing gets better as the voltage is increased. This analysis also showed that the ratio of atomic to molecular ions was very roughly one. This is in contrast to the analysis of Roberts who used a similar ion source and found only 8% atomic ions compared to molecules[(9)]. Ions which had been formed in the accelerating gaps were present, but in very small numbers. Triatomic ions and negative ions of hydrogen and deuterium were also present to a small extent. Uncharged molecules and heavy charged molecules were appreciable but less in number than the hydrogen ions. It was found that when deuterium was used in the tube there still remained an appreciable number of protons. However, since protons of energy less than one million volts do not give neutrons, for our purposes the proton contamination of the deuteron beam does not matter.

The peak voltage on the tube is measured by a voltmeter across a special winding on the first of the four 250 Kv. transformers which are cascaded to make the million volt transformer set. This voltmeter was calibrated against a spark gap using 50 cm spheres up to 500 kv.[(10)] Above this voltage it was calibrated against a sparkless sphere gap voltmeter using 100 cm spheres.[(11)] This calibration was checked by measuring the excitation curve of the gamma ray from lithium bombarded by protons. It is known to have a sharp resonance at 440 kv.[(12)] A sharp rise in our excitation curve at 440 kv. indicated that the ions hitting the target have the maximum energy as indicated by the voltmeter.

The targets used in this work were metallic lithium. They soon became black, probably due to carbon deposited on them from the beam and possibly also due to the formation of Li_3N while they are exposed to air before being put into the tube. The carbon layer probably reduces the energy of the bombarding ions slightly and to make this effect small, the targets were renewed occasionally. We have investigated the neutrons resulting from nitrogen bombarded with deuterons and have found their yield to be very small(7). Bonner and Brubaker have likewise found the number of neutrons from C^{13} bombarded with deuterons to be very small compared to the number of C^{12} neutrons. These latter neutrons have 0.5 MV energy and were looked for in a test experiment with one atmosphere of hydrogen in the chamber while bombarding lithium with deuterons. None were found. Hence the contamination effect of C and N is very small since lithium is one of the most prolific neutron sources known. Deuterium contamination on the target due to absorption of the deuterium gas in the tube on the surface of the target and due to deuterium ions being driven into the target from the beam may give a few neutrons of 2.6 MV energy from the well known deuteron on deuterium reaction(4a).

METHOD OF MEASURING NEUTRON ENERGIES

The cloud chamber used was the one built by Brubaker and Bonner(13) and used by them to measure many neutron spectra. It is shown in section in Figure 2. Due to the use of a backing chamber V_3 to lessen the pressure difference on the large sylphon S_1, the expansion chamber V_1 can be used up to at least 18 atmospheres. At pressures higher than this it is hard to get good tracks if there is much radiation present (due to the ionization of electrons from Compton and photoelectric absorption). Also the sylphon S_1 can stand only pressure differences of 45 pounds. Hence, since the expansion ratio is 1.2, the difference in pressure before and after expansion in V_1 is 60 pounds (at 20 atmospheres pressure in V_1). As the pressure in V_3 is approximately constant (usually equal to the expanded pressure in V_1) this

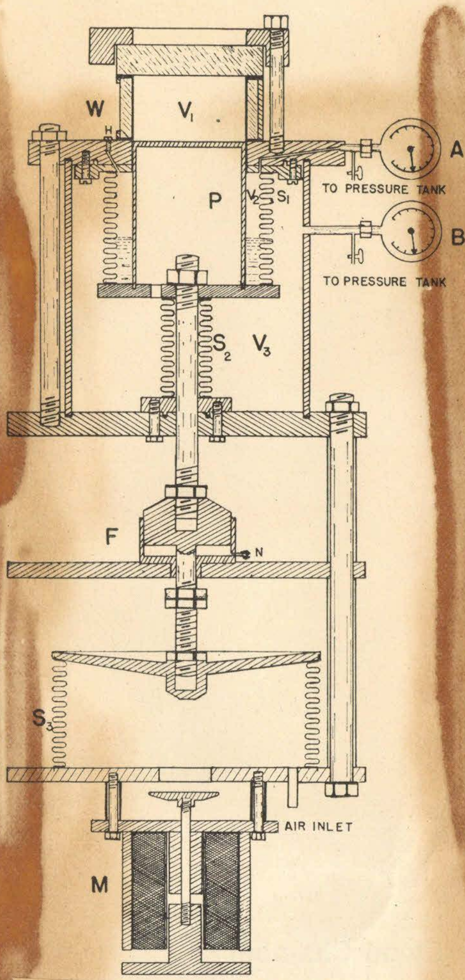

FIG. 2. High pressure Wilson cloud chamber.

excess pressure soon distorts and cracks the sylphon S_1. Stereoscopic pictures of the cloud chamber are taken at the time of expansion by a camera and set of mirrors not shown in the figure. These pictures are later reprojected and the tracks measured. A typical picture is shown in Figure 3.

The chamber is illuminated by a 2000 watt movie flood lamp through a cylindrical lens and a water absorption cell. The lamp is run steadily at about 20 volts and one-half second before the expansion takes place it is flashed to 110 volts. Under these conditions it can be used for as many as 60,000 expansions. With high pressures of methane, the density of the tracks is larger and the droplets do not fall very fast, so good photographs can be obtained with only 105 volts on the lamp with a corresponding increase in life. The timing mechanism is a set of cams run at about one revolution in three seconds and operating a set of microswitches which control the various operations of the cloud chamber, light, camera and ion source. The cycle time or time between expansions is determined by a delayed relay on the motor and the amount of delay can be varied by changing the resistance which charges up a condenser across the grid of a vacuum tube whose plate current actuates the relay. After one revolution of the cam shaft, one of the cams turns off the motor and resets the delay mechanism.

Of the gases which can be used in the cloud chamber the three which have been found important for neutron work are hydrogen, methane and helium. Since their cross sections for elastic collisions with neutrons are approximately the same, the important quantity for efficiency is the number of atoms per unit stopping power.

Gas	Atoms/ s.p.	S.p./atmosphere
H_2	9.5	0.21
CH_4	4.2	0.85
He	5.9	0.17

Figure 3. Helium recoils from the neutrons from lithium bombarded with deuterons. The stopping power of the helium was 2.6.

Hence hydrogen is most efficient, but its use is limited to neutron energies whose recoil protons can be stopped in the chamber. At 18 atmospheres of hydrogen, the stopping power of the chamber is 3.8, which is useful for neutrons up to about 3 MV. With methane, however, 18 atmospheres gives a stopping power of 18 which will stop recoils up to 8 MV. The addition of a mica sheet enables recoils up to at least 15 MV to be measured but with impaired geometrical conditions. Helium recoils since they receive only 16/25 of the neutron energy and since they lose energy faster than protons, cover more of the neutron spectrum at a given pressure, can extend to higher energies without mica, but have somewhat smaller resolving power. Since the geometrical corrections for the probability of seeing a track are quite uncertain, joining curves taken at different pressures is unreliable. Hence helium recoils have proven more satisfactory especially for high energies. A further advantage of helium is that with it in the chamber the stopping power can be calibrated with polonium (3.805 cm) or thorium C^{11} (8.533 cm) alpha particles. The stopping power of methane at high presures cannot be calibrated but must be calculated and hence is not very accurate. Since the energy of the neutrons from deuterons on deuterium has been measured quite accurately(14), they provide a nice means of calibrating stopping powers from 2 to 10. The best value of the Q for this reaction is 3.29 MV. Stopping powers above 10 must be calculated. The stopping powers relative to air for carbon and hydrogen are given by Bethe for different ranges of particles(15). Other stopping powers are given by Mano(16)..

The determination of the composition of the gas in the chamber is especially important in the case of methane since ordinary illuminating gas is used in the cloud chamber (since it is easy to obtain). Its initial composition as measured by the Southern California Gas Company was 81.2% CH_4, 17.6% C_2H_6, 1% N_2, 0.2% CO_2. However, the ethane is more soluble in the alcohol in the cloud chamber than the methane. Hence the composition in the cloud chamber is different. By measuring the specific gravity of a sample of the gas from the cloud chamber it is possible to calculate the new composition. In this case the percentage of methane was changed from 81% to 89%. When using stopping powers in the chamber of less than 2 it is very important to correct the stopping power for changes in temperature in addition to any leakage of gas from the chamber during the experiment. The approximate correction factor on the track length is

$$\frac{\Delta P}{P_o} \quad \frac{1.0661}{r} \quad - \quad \Delta t \quad C_{t_o} \quad - \quad \frac{1.0661}{r}$$

$$\Delta P = P - P_o$$
$$\Delta t = t - t_o$$
$$r = 1 + \alpha t$$

P pressure read on gauge

P_o pressure when stopping power of chamber was calibrated

t temperature of chamber

t_o temperature when chamber was calibrated

C_{t_o} variation of stopping power of vapor in chamber with temperature relative to total stopping power in chamber.

	Stopping Power	
t^oC	ethyl alcohol (5%water)	water
10	.065	.0085
15	.089	.012
20	.12	.016
25	.16	.022
30	.21	.030

The gauge which measures the pressure in the expansion chamber is calibrated at each filling of the cloud chamber against a standard gauge which is in turn calibrated against a standard oil balance. The impurities in the commercial hydrogen and helium used are known from the manufacturers. The hydrogen is about $99\frac{1}{2}\%$ H_2 with about 1/2% of oxygen. The helium is 96% He, about 3% N_2 and about 1% H_2. These compositions check with specific gravity measurements made on samples of the gas after they had been in the cloud chamber (corrected for alcohol vapor) so they are considered reliable. The commercial deuterium gas ~~which~~ is claimed to be 99.5% pure, but no check has been made on this.

If we apply the principles of conservation of energy and momentum to the collision of a neutron of energy E with a particle of mass M, we find that the energy E_r which the recoil particle gets is

$$E_r = \frac{4E\ M\ \cos^2 \varphi}{(1+M)^2}$$

where φ is the angle between the original direction of the neutron and the direction of the recoil particle. Hence, in principle, by assuming that the neutron comes directly from the center of the source we could calculate E from any recoil track after we measure φ and E_r. However, if we admit an error of 5° in measuring φ and calculate the percentage error made in calculating E for different angles φ we find

φ	0°	10°	20°	40°	50°	60°
error in E	1%	4%	9%	29%	63%	155%

Hence in practice it is best to limit the measured tracks to forward recoils only. Since our target usually subtends an angle of about 8° at the cloud chamber, we measure only tracks which point to the target. So most of the tracks give errors less than a few percent. For measurements of maximum energies of neutrons, this limitation is very important for another reason. Due to the large amount of material present (cloud chamber walls, etc) there are a large number of neutrons which have been scattered by heavy nucleii. On the average a neutron scattered by a copper nucleus loses only about 3% of its energy but its direction is radically altered. Hence it may then enter the cloud chamber and by a head-on collision give most of its energy to a proton whose apparent angle φ may be large. If this track were used to calculate E, the neutron energy would come out much too large. The energy distribution of recoil protons (even when limited to forward recoils) is distorted from the original neutron energy distribution by the fact that the angle error always decreases the energy, giving an asymmetrical error. Due to this asymmetry in proton recoil peaks, extrapolated values are more accurate than most probable values. For very accurate work these extrapolated values must be corrected for straggling, angle variation, thick target, etc. Bethe has given a formula for such corrections[17]. If the recoil particles are plotted in an integral number-range curve and extrapolated, then this extrapolated range must be corrected by subtracting X_{extr} S where

$$S^2 = s^2 + \gamma^2 + \frac{n^2}{48} R^2 \varphi_0^4 + n^2 \left(\frac{a}{b}\right)^2 R^2 \frac{M_1 M_2 E_1}{M^2 E_2}$$

s natural straggling of recoil particle

γ probable error in measuring track lengths times stopping power

n range exponent for recoil particle

$$n = 2 \frac{d(\log R)}{d(\log E)}$$ (reference 17 page 278)

R range of recoil particle in cm. of air at 15° C

φ_0 maximum angle of φ allowed in measuring recoils.

$\frac{a}{b}$ one-half the vertical angle subtended by the cloud chamber at the target

M_1, E_1 mass number and energy (MV) of particle used in bombarding target

M_2, E_2 for recoil particle

$M = M_1 + M_0$

M_0 mass number of nucleus used as target

M_3 mass number of residual nucleus left in target

X_{extr} is the thick target correction given by Bethe (reference 17, page 286) as a graphic function of β.

$$\beta = \frac{\left(z Z_1 \left(\frac{m_1}{E_1}\right)^{\frac{1}{2}} + 4\right) S E_2 M}{R E_1 (M_3 - M_1) m}$$

z atomic number of bombarding particle

Z_1 atomic number of target nucleus

The mean range obtained by this correction is then converted into energy using the range energy curves of Bethe (reference 17 page 268). To this energy is added $\frac{1}{2} E_2 \varphi_0{}^2$. The resultant energy is the energy of the neutrons at right angles to the bombarding beam for the bombarding energy E_1 used. To find the energy Q released in the reaction

$$M_o + M_1 \rightarrow M_3 + n + Q$$

we use the equation obtained from conservation of energy and momentum

$$Q = E_n \left(1 + \frac{1}{M_3}\right) - E_1 \left(1 - \frac{M_1}{M_3}\right)$$

where E_n is the above corrected energy of the neutrons at right angles to the beam. If instead of a two body reaction we have a three body reaction

$$M_o + M_1 \rightarrow M_2 + M_3 + Q_1$$

$$M_3 \rightarrow M_4 + n + Q_2$$

then the neutrons will have a continuum of energies between the limits of E^{max} and E_{min} where

$$E^{max}_{min\ 90^\circ} = \frac{\left(\sqrt{E_3{}^1 M_5} - \sqrt{Q_2 M_4}\right)^2}{M_3} - \frac{M_1 M_5 E_1}{M^2}$$

$$E_3{}^1 = \frac{Q_1}{M} + \frac{M_o E_1}{M^2}$$

All these formulae are based on the assumption that the incident particles have a monochromatic energy E_1. In our case the particles have a spread in energy due to the alternating voltage and molecular ions. However it has been calculated that the extrapolation method gives the correct result if the maximum energies (from the peak voltages) are used and if an appreciable fraction of the beam is atomic. The correction formula given above holds only for the case of good geometry where θ is small compared to θ_o.

$$\sin \theta = \frac{a}{b}$$

$$\cos \theta_o = \frac{n \sqrt{M_1 E_1}}{M \sqrt{E_2}}$$

If the chamber has been calibrated by particles of range R_c then this stopping power must be corrected to give the stopping power for recoils of different range R. Stopping power - range tables have been given both by Bethe(15) and by Mano(16). To change the neutron distribution from a range scale to an energy scale, the number of one-half mm. range intervals is calculated for equal energy intervals along the scale. The number of tracks occurring in each equal energy interval is then found by adding the number of tracks occurring in the included 1/2 mm. range intervals. This number is corrected for the discretness of the number of range intervals by dividing by the factor

$$\frac{\text{actual total range interval of nearest whole number of range intervals}}{\text{desired accurate range interval for equal energy intervals}}$$

There are two corrections that may be applied to the distribution in energy of the recoil particles to get a closer approximation to the original neutron distribution. One concerns the probability of a track of a given length R starting in the chamber and not hitting the wall. This geometrical correction can be easily calculated as $\pi r^2/P$ where

$$P = r^2 \cos^{-1}\left(\frac{-R}{2r}\right) - Rr\left(1 - \frac{R^2}{4r^2}\right)^{\frac{1}{2}} - r^2 \sin^{-1}\left(\frac{R\sqrt{1-\frac{R^2}{4r^2}}}{r}\right)$$

where r is the radius of the chamber. For track lengths up to three-fourths of the chamber diameter, this function can be closely approximated by a straight line and for our chamber (diameter 8.8 cm) this approximate correction factor on the number of tracks of length R is

$$\frac{7.5}{(7.5 - R)}$$

Ordinarily this factor varies from about 1.1 to 2 in the region of track lengths used. Another correction is for the variation with energy of the probability of a neutron colliding with a nucleus. The neutron-proton total scattering cross section has been calculated by Wigner(18) and E^1 adjusted to the experimental points.

$$\sigma_H = \frac{4\pi\hbar^2}{M}\left(\frac{1}{4}\frac{1}{|\epsilon'| + \frac{1}{2}E_0} + \frac{3}{4}\frac{1}{|\epsilon| + \frac{1}{2}E_0}\right)$$

$$= 5.15 \cdot 10^{-24}\left(\frac{1}{4(.04 + \frac{1}{2}E)} + \frac{3}{4(2.15 + \frac{1}{2}E)}\right)$$

where E is the energy of the neutron, ϵ^1 is the singlet level binding energy and ϵ is the triplet binding energy. The neutron helium cross section has been measured in comparison with the neutron-proton cross section by Bonner(19). He found that n-He scattering decreased slightly faster than the n-p scattering.

$\frac{\sigma_H}{\sigma_{He}}$	1.0	0.87	0.89
E	1.3 MV	2.2 MV	5 MV

The similarity between n-p and n-He scattering has been confirmed by work on the neutrons from boron bombarded with deuterons. The energy distribution of the neutrons has been measured by recoils of both hydrogen (4b) and helium(20). The relative intensities of the lines measured in He and H are nearly the same (within experimental errors). It must be remembered, though, that the σ's are total cross sections, whereas in cloud chamber work, use is made only of the forward scattered recoils (backward scattered neutrons). Hence a variation in the angular distribution of the recoils could complicate the situation. However, Dee and Gilbert (21) and Bonner(22) have shown that at least at 2.5 MV neutron energy the angular distribution of the n-p scattering is symmetrical in the center of gravity coordinates. This gives a $\sin\varphi\cos\varphi$ distribution in the laboratory coordinates independent of energy. Assuming only short range forces between the neutron and proton, Bethe has calculated that the neutron-proton scattering should not show deviations from this distribution up to 20 MV. If this is true then the experiments on He recoils indicate not much variation in its angular distribution with energy. These questions are still very uncertain and it is important to find experimentally the variation with energy and angle of neutron scattering. However, assuming the above cross sections to be right, the observed numbers of recoils can be corrected to give a better estimate of the number of original neutrons. This correction is most important in the low energy region

EXPERIMENTAL RESULTS AND THEIR INTERPRETATION

We have bombarded a lithium metal target with high energy deuterons and measured the energy distribution of the neutrons at 90° to the incident deuterons. Four runs were made with different gases and different pressures in order to get the complete spectrum. These runs were taken under the following conditions:

	Deuteron Energy	Pressure	Gas	Calibrated with	Stopping power	Number Pictures	Number Tracks	
(1)	0.93 MV	11.9 atm.	He	$ThC^{11}\alpha$	2.7	9000	1034	o
(2)	0.8 MV	6.0 atm	He	D+D,n	1.4	12000	746	▫
(3)	0.8 MV	11.0 atm.	CH_4	D + D,n	12.5	5000	1026	x
(4)	1.0 MV	12.5 atm	H_2	D + D,n	3.03	2500	714	•

The energy ranges covered in these runs were (1) 5 - 15 MV, (2) 2 - 9 MV, (3) 2 - 6 MV and (4) 1 - 4 MV. They all overlap and the various runs after being corrected as described above may be fitted together. The resulting neutron energy distribution is shown in Figure 4.

The possible reactions involving neutrons which can occur when lithium is bombarded with deuterons are:

1.0 $\quad Li^7 + D^2 \rightarrow {}^*Be^9 \rightarrow {}^*Be^8 + n + Q_{10}$

1.1 $\quad Li^7 + D^2 \rightarrow {}^*Be^9 \rightarrow {}^*Be^8 + n + Q_{11}$

1.2 $\quad Li^7 + D^2 \rightarrow {}^*Be^9 \rightarrow {}^{**}Be^8 + n + Q_{12}$

1.3 $\quad Li^7 + D^2 \rightarrow {}^*Be^9 \rightarrow {}^{***}Be^8 + n + Q_{13}$

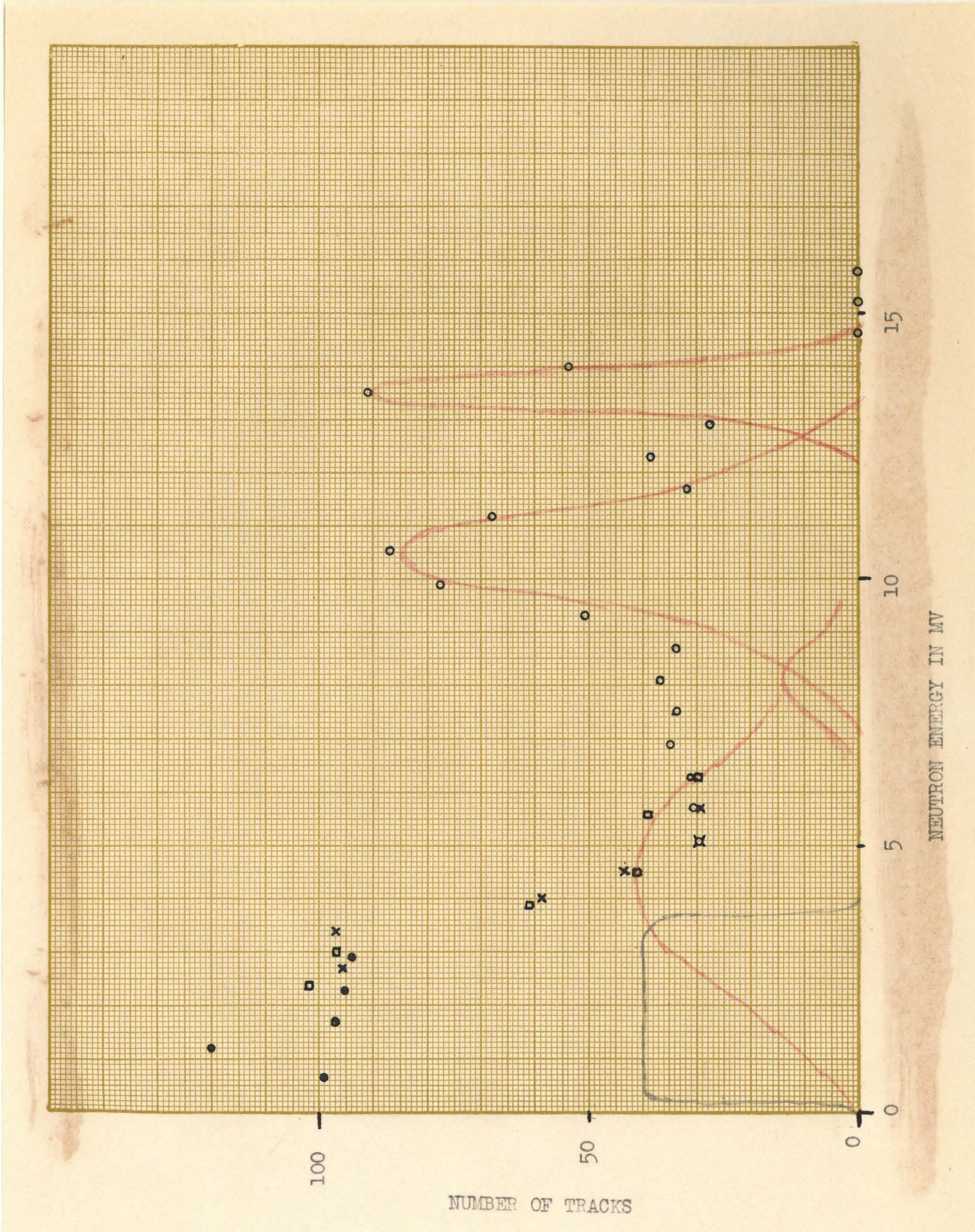

Figure 4

1.01 $Be^8 \rightarrow He^4 + He^4 + Q_{101}$

1.11 $*Be^8 \rightarrow He^4 + He^4 + Q_{111}$

1.21 $**Be^8 \rightarrow He^4 + He^4 + Q_{121}$

1.31 $***Be^8 \rightarrow He^4 + He^4 + Q_{131}$

2.0 $Li^7 + D^2 \rightarrow *Be^9 \rightarrow He^5 + He^4 + Q_{20}$

2.01 $He^5 \rightarrow He^4 + n + Q_{201}$

3 $Li^7 + D^2 \rightarrow *Be^9 \rightarrow He^4 + He^4 + n + Q_3$

4.0 $Li^6 + D^2 \rightarrow *Be^8 \rightarrow He^5 + He^3 + Q_{40}$

4.01 $He^5 \rightarrow He^3 + n + Q_{201}$

5.0 $Li^6 + D^2 \rightarrow *Be^8 \rightarrow Be^7 + n + Q_{50}$

6 $Li^6 + D^2 \rightarrow *Be^8 \rightarrow He^4 + He^3 + n + Q_6$

The work of Bonner and Brubaker[4b] showed a distinct group of neutrons with an energy of 13.4 to 13.8 MV giving a Q value of 14.3 to 14.7 MV. They attributed this peak to reaction (1.0) where Be^8 is left in its normal state. The normal state of Be^8 then cŏmes out unstable with respect to alpha particles. We have confirmed this peak and get a more accurate value of $Q_{10} = 15.05 \pm .2$ MV. From the mass spectroscopic masses of Li^7 and H^2 and the mass of the neutron given by Bethe[22], we can calculate that Be^8 is unstable by 0.04 MV ($Q_{101} = .04$ MV) with respect to two alpha particles. This estimate is subject to error mostly due to uncertainty in the stopping power of the gas in the chamber. The mass of Be^8 can also be calculated from the reactions where boron is bombarded with protons. Bethe[23] has calculated a value of 0.1 MV unstable from the corrected values of the reactions[24, 25]

$$B^{11} + H^1 \rightarrow Be^8 + He^4 + 8.60 \pm 0.11 \text{ MV}$$

$$B^{11} + H^1 \rightarrow *Be^8 + He^4 \rightarrow He^4 + He^4 + He^4 + 8.70 \pm 0.2 \text{ MV}$$

A recent experiment by Kirchner, Laaf and Neuert[26] claims to give conclusive evidence that Be^8 in its normal state is unstable. They bombard boron with protons which gives Be^8 (normal) plus an alpha particle and the recoil energy of the Be^8 is 2.9 MV. If the Be^8 is unstable, then when it splits up into two alpha particles, they will have an angle between them determined by the energy of disintegration of Be^8 and the direction between recoil and breakup. If this angle is small enough, the two break-up alpha particles will enter an ionization chamber simultaneously and give twice as much ionization as a single alpha particle (the same as a single Be^8 particle). Then by changing the aperture of the ionization chamber, the variation of the number of these coincidences with angle of aperture of the ionization chamber can be measured. If Be^8 is stable this curve will only increase linearly (for small angles where the 3 MV excited state of Be^8 does not contribute) linearly with the solid angle subtended by the ionization chamber at the target. If Be^8 is unstable, the increase with angle will be greater due to the increased angular divergence of the breakup alpha particles allowed to enter. This increase will continue up to an angle equal to the maximum angle possible between the alpha particles. From then on the increase will be less due only to the increase in solid angle. Presumably from this type of analysis Kirchner, etc. concluded that Be^8 is unstable by 0.04 to 0.12 MV.

Bonner and Brubaker's curve for the rest of the neutron spectrum was a smooth curve which increased toward lower energies with a broad maximum near 3 MV. They interpreted this as meaning that there was a large probability of reaction (3) in which the three particles break up simultaneously with conservation of the 15 MV energy and momentum. Thus the energies of the neutron will depend on how the particles come apart and will vary continuously to zero. This was even more striking since Be^8 was known to have a level at about 3 MV and the absence of a peak at 11 MV lead Bonner and Brubaker to their idea that reaction (1.1) was rare. We have obtained evidence that this is not the case. The distinct peak at 11 MV in our curve indicates that reaction (1.1) is even twice as strong as reaction (1.0). When the neutron comes off with this energy (11.1 MV corrected) it leaves Be^8 in a 3.3 MV excited state so that $Q_{11} = 11.8$ 0.4 MV and $Q_{111} = 3.3$ MV. The width at half maximum of the level can be estimated at 1.5 MV. Other evidence for this 3 MV level in Be^8 is found in the reaction (26,27)

$$B^{11} + H^1 \rightarrow Be^8 + He^4$$

and the reaction (28,29)

$$B^{10} + D^2 \rightarrow Be^8 + He^4$$

where the alpha particle energy distribution indicates a 2.8 MV level with a width at half maximum of 0.77 MV. Also the radioactive alpha particles from $Li^8 \rightarrow {}^*Be^8 + {}_{-}e$, ${}^*Be^8 \rightarrow 2He^4$, indicate a level with an energy between 4.7 MV and 2.6 MV and a width at half maximum of 1.4 MV to 1.0 MV (30,31). Since theoretical calculations (32) indicate a $^1D_2$ level in Be^8 at 1.9 MV this may correspond to the observed level. The fact that Bonner and Brubaker's curve does not show this group of neutrons may possibly be due to uncertainty in their corrections for the probability of a track of a given length going through the mica and starting and ending in the chamber. The correction they applied varies from about +150 percent at 8.4 MV to 0 percent at 9.9 MV to +150 percent at 11.2 MV and might well have obscured a peak in this region.

The neutrons between 6 MV and 9 MV are not well resolved in any of the runs. Hence until further work is done it cannot be said with certainty whether these neutrons are background, unresolved groups, tails on the observed groups at 11 MV and 4.5 MV, or a high probability of reaction (3). Since the width of the levels should increase (those disintegrating into two alpha particles) for higher excitation energies of Be^8 (due to the shorter half life for α disintegration according to the Geiger-Nuttall law) we should expect a large amount of tailing off of the high levels and a sort of overlapping between levels. However it may be emphasized that this overlapping is not the same as saying that reaction (3) occurs, since we still have the neutron coming off first, leaving an excited Be^8. There is no certain evidence for sharp levels in this region (levels which are forbidden to disintegrate into two alpha particles and hence last long enough to give γ rays) although the γ rays might be expected to reveal such levels. The radiative capture of protons by lithium gives two sharp states of Be^8 above 17 MV which seem only to have transitions to the wide 3 MV state and the ground state[33]. The experiments of Gaerttner and Crane[34] which seemed to show other sharp levels are suspected of being in error ~~due to deuteron contamination of the proton beam~~. There is some evidence for a wide level in Be^8 from the reaction [35,36]

$$B^{11} + D^2 \rightarrow Be^8 + He^4 .$$

This would give a neutron peak in our experiment with its center near 8 MV and the experimental points are consistent with a small yield of (1.2) together with a tailing off of the neighboring groups.

There seems to be a wide group with its center near 4 or 5 MV. This would leave Be^8 excited to 10 or 11 MV giving Q_{13} = 4 MV or 5 MV and Q_{131} = 10 MV or 11 MV. Other evidence for this level comes from Fowler and Lauritsen's radioactive alpha particle curve[31] (from Li^8). When they correct their observed energy distribution for the fact that the probability of the beta transition should increase at least as $(E_{max})^5$, then a very wide level seems to be present around 10 to 12 MV.

The sharp rise at 3.8 MV is attributed to the maximum energy neutrons from reaction (2.01). Reaction (2.0) was discovered by Williams, Sheperd and Haxby[37] who measured Q_{20} to be 14.3 MV. They found a monochromatic line of alpha particles which had more energy than could be accounted for by any other reaction. Using this Q value, the mass spectrographic masses of Li^7, He^4 and D^2 and the photodisintegration value of the mass of the neutron we can calculate He^5 to have a mass of 5.0137 and to be unstable against breaking up into a neutron and alpha particle by 0.82 MV (Q_{201}). We can then calculate that if the He^5 breaks up symmetrically in the center of gravity coordinates, then it will give a continuum of neutrons with energies equally distributed between 0.1 MV and 3.8 MV (for 0.8 MV bombarding energy). In order to make sure that this interpretation was right we have measured the relative yields of reaction (1) and (2) by comparing the alpha particle peak due to (2.0) with the continuum of particles due to (1) and (2.01). This was measured with an absorption cell - ionization chamber - linear amplifier - biased thyratron and counter set. Both a differential (high bias) and integral (low bias) number - range curve was measured. These were consistent in giving a relative number of disintegrations of (1) to (2) of four or five to one. This together with neutrons from (1.3) accounts for about two-thirds of the height of the experimental curve at 3.5 MV. The difference may be due either to neutrons from reaction (5.0) or to error in the relative intensities of the high and low energy parts of the spectrum due to uncertainty in the scattering cross section variation with energy. However, there seems to be more neutrons between 0 and 2 MV than can be accounted for by Li^7, and may be due to neutrons from Li^6.

It has been found that separated targets of Li^6 give relatively large numbers of neutrons, more than be accounted for by contamination[38]. Recently it has been shown that reaction (5.0) seems to occur.[39] We can calculate the energies of disintegration of the Li^6 reactions from the masses involved and we find Q_{40} 0.84 MV, Q_6 1.6 MV and Q_{201} 0.82 MV. From these values we can calculate the energies of the neutrons emitted at right angles to 0.8 MV deuterons. From (4.01) the neutron energies would have a continuum from 0.18 MV to 1.22 MV. Reaction (6) would give neutrons with a continuum of energies from 0 to 1.85 MV. Although Be^7 is not known we can estimate its mass within limits. It is known that Be^7 does not give detectable positrons[40]. Hence an upper limit on its mass can be estimated as a mass heavier than Li^7 by two electron masses plus 0.3 MV (minimum observable positron energy). A lower limit would be that Be^7 is just the same mass as Li^7, in which case it might disintegrate by K electron capture, a process very hard to detect. This gives limits on Q_{50} of 4.17 MV and 2.8 MV, the neutrons get about the same energies, and the neutron group would be presumably narrow. Hence these Li^6 reactions may well account for a lot of the low energy neutrons. This cannot be decided until a good neutron energy spectrum can be observed from a separated Li^6 target.

In Figure 4 we have drawn the expected distribution of neutrons for the Li^7 reactions with the relative intensities

(1.0): (1.1): (1.2): (1.2): (2.01) 1 : 3 : 1 : 2 : 2.

It can be calculated that the neutrons from Li^7 can be explained by the reactions (1) and (2) with approximately the above intensities and with the disintegration energies:

Q_{10} = 15.05 MV	Q_{101} = 0.04 MV
Q_{11} = 11.8 MV	Q_{111} = 3.3 MV
Q_{12} = 9 MV	Q_{121} = 6 MV
Q_{13} = 4 MV	Q_{131} = 11 MV
Q_{20} = 14.3 MV	Q_{201} = 0.82 MV

It also seems probable that neutrons from some Li^6 reaction are present.

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REFERENCES

(1) Chadwick, Proc. Roy. Soc. 136, 705 (1932)

(2) Curie and Joliot, Compt. Rendus 194, 273 (1932)

(3) Bonner and Mott-Smith, Phys. Rev. 46, 258 (1934)

(4) Bonner and Brubaker, Phys. Rev. 48, 742 (1935)

a - " " " " 49, 19 (1936)

b - " " " " 50, 308 (1936)

(5) Stephens, Phys. Rev. 53, 223 (1938)

(6) Stephens and Lauritsen, Rev. Sci. Inst. 9, 51 (1938)

(7) Stephens, Djanab and Bonner, Phys. Rev. 52, 1079 (1937)

(8) Crane and Lauritsen, Rev. Sci. Inst. 4, 118 (1933)

Crane, Lauritsen and Soltan, Phys. Rev. 45, 507 (1934)

(9) Roberts, Phys. Rev. 51, 810 (1937)

(10) Sphere gap standard, A. I. E. E. 55, 783 (1936)

(11) Sorenson and Ramo, A. I. E. E. 55, 444 (1936)

(12) Hafstad, Heydenburg and Tuve, Phys. Rev. 50, 504 (1936)

(13) Brubaker and Bonner, Rev. Sci. Inst. 6, 1943 (1935)

(14) Bonner, Phys. Rev. 53, 711 (1938)

(15) Livingston and Bethe, Rev. Mod. Phys. 9, 274 (1937)

(16) Mano, Jour. de Phys. et Rad. 5, 628 (1934)

(17) Livingston and Bethe, Rev. Mod. Phys. 9, 289 (1937)

(18) Bethe and Bacher, Rev. Mod. Phys. 8, 117 (1936)

(19) Bonner, Phys. Rev. 45, 601 (1934)

(20) Stephens and Bonner, Phys. Rev. 52, 527 (1937)

Staub and Stephens, Phys. Rev. 53, 212 (1938)

(21) Dee and Gilbert, Proc. Roy. Soc. 163, 265 (1937)

Bonner, Phys. Rev. 52, 685 (1937)

(22) Bethe, Phys. Rev. 53, 313 (1938)

(23) Livingston and Bethe, Rev. Mod. Phys. 9, 310 (1937)

(24) Kirchner and Neuert, Physik. Zeits 35, 292 (1934)

Oliphant, Kempton and Rutherford, Proc. Roy. Soc. 150, 241 (1935)

(25) Dee and Gilbert, Proc. Roy. Soc. 154, 279 (1936)

(26) Kirchner, Laaf and Neuert, Naturwiss. 25, 794 (1937)

(27) Dee and Gilbert, Proc. Roy. Soc. 154, 279 (1936)

(28) Cockcroft and Lewis, Proc. Roy. Soc. 154, 246 (1936)

(29) Wheeler (mentioned in Livingston and Bethe, Rev. Mod. Phys. 9, 320 (1937))

(30) Lewis, Burcham and Chang, Nature 139, 24 (1937)

(31) Fowler and Lauritsen, Phys. Rev. 51, 1103 (1937)

(32) Feenberg and Phillips, Rhys. Rev. 51, 597 (1937)

(33) Delsasso, Fowler and Lauritsen, Phys. Rev. 51, 391 (1937)

(34) Gaerttner and Crane, Phys. Rev. 52, 528 (1937)

(35) Cockcroft and Lewis, Proc. Roy. Soc. 154, 246 (1936)

(36) Wheeler (mentioned in Livingston and Bethe, Rev. Mod. Phys. 9, 320 (1937))

(37) Williams, Shepherd and Haxby, Phys. Rev. 51, 888 (1937)

Phys. Rev. 52, 390 (1937)

(38) Rumbaugh and Hafstad, Phys. Rev. 50, 681 (1936)

(39) Roberts and Heydenburg, Bulletin of the A. P. S. 13, NO. 2, Abstract 78 (1938)

(40) Crane, Delsasso, Fowler and Lauritsen, Phys. Rev. 47, 971 (1935)