THE ENERGY DISTRIBUTION OF NEUTRONS PRODUCED IN THE ARTIFICIAL DISINTEGRATION OF SEVERAL OF THE LIGHT ELEMENTS BY DEUTERONS

THESIS BY

WILSON MARCUS BRUBAKER

In Partial Fulfillment of the Requirements for the

Degree of

DOCTOR OF PHILOSOPHY

CALIFORNIA INSTITUTE OF TECHNOLOGY

PASADENA, CALIFORNIA

1936

INDEX

ILLUSTRATIONS

Bothe and Becker,[1] in 1930, found that several of the light elements, when bombarded by alpha particles of polonium, emit a penetrating radiation which appeared to be of the gamma ray type. The effect was greatest in the case of Be, but B, Li, F, Mg and Al gave evidence of the same type of radiation. Subsequent work of Bothe, Mme. Curie-Joliot and others[2] showed that the newly discovered radiation excited in Be posessed a penetrating power which was distinctly greater than that of any gamma ray known at that time.

Working with extremely strong sources, Mme Curie-Joliot and M. Joliot[3] discovered that the radiation from Be and B had the amazing property of being able to impart large amounts of energy to hydrogen nuclei. In their experiments the radiation from Be was passed through a thin window into an ionisation chamber which was connected to a Hoffman electrometer. When hydrogen containing substances, such as paraffin, cellophane, etc. were placed in front of the window, the ionisation was greatly increased; sometimes it was doubled. They showed that the protons ejected by the Be radiation had ranges in air as great as 26 cm, which corresponds to a velocity of $3x10^9$ cm/sec. The B radiation ejected protons with a range of about 8 cm. To explain this phenomenon they suggested a 'nuclear Compton process' in which the extremely hard gamma ray imparted energy to a nucleus in a manner similar to that in which ordinary gamma rays are known to project electrons. According to this, the quantum energy of the Be radiation was of the order of 50 MEV., while that of the B radiation was of the order of 35 MEV. It was difficult to account for the emission of this high quantity of energy in the disintegration of Be.

Chadwick[4] made some further experiments on the radiation from Be. Using a small ionisation chamber which was connected to an amplifier and an oscillograph, he searched for heavy particles which were projected into the chamber by the radiation. When he placed the elements Li, B, C and N in front of the chamber, an increased number of 'kicks' were recorded. Also, when the chamber was filled with the gases H_2, He, N_2, O_2 and A, deflections were observed which were attributed to the production of recoil atoms of the respective gases. The absorption in Al of the protons ejected from paraffin showed that they had a maximum range in air of about 40 cm. This corresponds to a velocity of 3.3×10^9 cm/sec., or to an energy of 5.7 MEV. From the size of the kicks observed when the chamber was filled with nitrogen, it was shown that the N recoil nuclei produced between 30,000 and 40,000 ion pairs. Assuming that the energy required to form each ion pair is 35 volts, this gives approximately 1 MEV. for the energy given to the nitrogen nuclei. This is in good agreement with the more accurate determination made by Feather.[5] By photographing the recoil nitrogen nuclei in a cloud chamber operated at reduced pressure, he showed that they had a maximum range of 3.5 mm in air at standard pressure. According to the range-velocity data of Blackett and Lees[6], a range of 3.5 mm corresponds to a velocity of 4.7×10^8 cm/sec., or to an energy of 1.2 MEV.

By the Compton process, the maximum energy which a quantum of energy $h\nu$ can impart to a particle of mass m is given by

$$E = \frac{2}{2 + mc^2/h\nu} h\nu$$

If we solve this equation for $h\nu$ and apply it to the observed energies in the case of nitrogen and hydrogen recoils, the energies of the quanta required to eject these nuclei are 90 MEV. and 55 MEV., respectively.

Chadwick suggested that this penetrating radiation was not of the gamma ray type, but that it consisted of a stream of particles of unit mass and zero charge. These particles were called neutrons. He showed that if one assumes the radiation to be neutrons instead of gamma rays, the discrepancies disappear. Neutrons were discussed by Rutherford[7] in his Bakerian Lecture of 1920, and various attempts to observe them had been made in vain. Chadwick showed that the mass of the neutron is approximately unity, as it would indeed be if it were a hydrogen atom in which the electron had fallen into the nucleus as Rutherford had suggested.
If we assume the conservation of energy and momentum in an elastic collision between two particles of masses m and M, the maximum velocity V which a particle of mass m and velocity v can impart to a particle of mass M is given by

$$V = \frac{2m}{m + M} v \qquad (1)$$

Thus the maximum velocity which a neutron of mass m can give to a hydrogen nucleus is

$$V_p = \frac{2m}{m + 1} v$$

and the maximum velocity which it can give to a nitrogen nucleus is

$$V_N = \frac{2m}{m + 14} v$$

By eliminating v from these two equations, solving for m, and using the experimentally determined values of 3.3×10^9 cm/sec and 4.7×10^8 cm/sec for the velocities of the hydrogen and nitrogen nuclei Chadwick was able to show that the mass of the neutron was approximately unity. The value obtained by these calculations was 1.15.

While this method of determining the mass of the neutron is sufficiently accurate to show the order of magnitude of its mass, it is vastly inferior to another method for obtaining the exact value. We will consider this better method in detail.

When Q, the kinetic energy released in the disintegration is known, a nuclear reaction equation which describes a disintegration is really a relation among the several masses involved in the reaction. The single relation between the masses and the energies of the particles can be expressed either as a relation between masses, or as a relation between energies by the use of the Einstein relation $E \quad m c^2$. When kinetic energy appears in the disintegration (Q is positive) the sum of the masses of the resultant particles is less than the sum of the masses of the incident particles, as this energy is released at the expense of the masses. By applying the conservation of energy and momentum in each individual disintegration, in the cases where only two particles share the kinetic energy after the disintegration, a knowledge of the energy of either, together with the knowledge of the energy of the incident particle, uniquely determine the energy released. This is shown in the following considerations: if we denote the mass and velocity of the incident particle by m_i and v_i, the mass and velocity of the neutron by m_n and v_n, and the mass and velocity of the resultant nucleus by m_r and v_r, the angle between the direction of the incident particle and the neutron by θ and the angle between the direction of the incident particle and the resultant nucleus by ϕ, then momentum considerations will yield the two equations

$$m_i v_i = m_n v_n \cos\theta + m_r v_r \cos\phi$$

$$0 = m_n v_n \sin\theta + m_r v_r \sin\phi$$

Energy considerations lead to

$$m_i v_i^2 + 2Q = m_n v_n^2 + m_r v_r^2$$

From these three equations we may eliminate ϕ and v_r and then we can solve for Q in terms of the masses, v_i, v_n and θ. When this is done we obtain:

$$Q = E_n(1 + m_n/m_r) - E_i(1 - m_i/m_r) - (m_n m_i/m_r)v_i v_n \cos\theta \quad (2)$$

This formula requires a knowledge of the mass of each of the nuclei involved in the reaction. Prior to mass spectrograph data, which followed Thomson's work on positive ray parabolas, the best information we had concerning nuclear masses was that obtained from chemical atomic masses. In fact, it was not known that the fractional values were due to mixtures of isotopes each of which had a mass which was almost exactly an integral multiple of the mass of hydrogen. Thomson found that neon, of chemical atomic mass 20.183

was composed of a large portion of Ne^{20} and a smaller portion of Ne^{22}. More recent work has shown the presence of Ne^{23}, also. The assemblage of mass spectograph data was a great aid to nuclear physicists in their early attempts to interpret their observed transmutations.

Having shown that the mass of the neutron to the first approximation was equal to that of the proton, Chadwick turned to this more exact method for a better determination of the neutron's mass. At that time, there was no mass spectrograph data on the mass of the Be nucleus, so he could not use the data from the disintegration of Be. Aston,[8] however, had determined the masses of B, He, and N and so Chadwick used the data from the disintegration of B, which he assumed to be according to the equation

$$_5B^{11} + {}_2He^4 \longrightarrow {}_7N^{14} + {}_0n^1 + Q_3 \qquad (3)$$

for the more precise determination. The energy of the neutrons was determined by absorbing the ejected protons in Al foil. As the energy of the polonium alpha particles was known, he was able to solve equation (2) for Q_3. Then he solved equation (3) for the mass of the neutron, and obtained 1.0067.

Many times the resultant nucleus is formed in an excited state and subsequently drops to the ground state with the emission of a gamma ray. In these cases the total energy released in the disintegration is not given by Q. Fortunately, it seems that a gamma ray quantum is not always given off. In these instances, the knowledge of the kinetic energy released in the disintegration gives one a relation between the masses of the nuclei involved.

Thus, in the investigations of the energies given to the disintegration products, one is particularly interested in the maximum energy with which the particles are at times given off, for these are the times when the resultant nucleus is formed in the ground state, and it is this maximum value of Q that is useful in determining the relations between the masses.

With the increasing amount of disintegration data which has been compiled in the past few years, it has become possible to arrange from it alone a table of isotopic masses for the lighter elements which is internally consistent to the precision with which the individual measurements are known.[9]

In the first reactions studied the energies of the charged disintegration particles were measured by various means. Usually the energies were determined from the ranges, which in turn were determined by absorption measurements, or directly from the lengths of tracks photographed in a cloud chamber. In most of the disintegrations in which neutrons are liberated the charged particle is quite heavy in comparison to the neutron, so that its range is so short that it is either impossible or impractical to determine Q from the energy of the charged particle. In these cases it becomes necessary to determine the energy of the neutron by some means. The neutron, as shown by the work of Curie-Joliot[10] and later by Dee,[11] very seldom disturbs the electron in its path; hence, it leaves no trail of ions as does a charged particle. The neutron loses energy by making intimate collisions with the nuclei of the material through which it passes. As it has no charge, the cross section for an intimate collision is of the same order of magnitude as the nucleus itself, and so it is a rare occurence, compared to the number of collisions which a charged particle makes under the same conditions. For this reason the probability of observing a recoil nucleus which has received its maximum amount of energy from a neutron is extremely small, unless there are many neutrons present. This makes the study of neutron energies a slow and tedious task.

Although means of investigating neutron energies other than those first used by Curie-Joliot, Chadwick, and Feather have been developed, the best methods known today are merely refinements of the original ones. Dunning, using a shallow ionisation chamber and a linear amplifier explored the energy spectrum of the neutrons emitted from a Be + Rn source.[12] Following Chadwick, he measured the absorption of the protons ejected from paraffin. Unfortunately, neutrons also eject nuclei of the gas in the ionisation chamber, thus producing a background, or a residual number of counts which are recorded even when the paraffin is not in front of the chamber. This is a serious objection when one is attempting to determine the maximum energy of the spectrum, as a weak group of high energy could not be observed in the presence of a strong group of lower energy by this means.

From equation (1) we see that an incident particle can lose all of its energy to another particle of the same mass. This is true of a neutron when it strikes a proton. Neutrons with energies of the order of 14 MEV. have been observed.[13] Protons of this energy have a range in air of nearly 2 meters, so one immediately sees the impossibility of determining the energy of such high energy neutrons by observing the maximum length of the tracks of recoil protons in an ordinary cloud chamber. If one knew the direction of the incident particle, the velocity and direction of the struck nucleus, and the values of all the masses involved in an elastic collision, he would have sufficient data from which to compute the velocity of the incident particle. Thus one could determine neutron energies from the observed lengths and directions of proton tracks in a cloud chamber if he knew the directions of the incident neutrons. He could measure high neutron energies in this manner by observing the protons which do not receive the maximum energy of the neutron and applying the formula

$$v_p = v_n \cos \alpha \tag{4}$$

where α is the angle between the directions of the paths of the neutron and proton. A few of the early investigators assumed that the neutron went straight from the source to the end of the proton track nearest the source and applied formula (4). However, as Dunning pointed out, one unfortunately has no way of knowing the direction of the incident neutron, as it could have been scattered through a large angle by a heavy nucleus (which is in the apparatus or the walls of the room) with a very small loss of energy; for this reason one is led to the wrong answer when he applies formula (4). If one uses helium or nitrogen in the cloud chamber part of this difficulty is overcome, as the energy given to the heavier nucleus is smaller than that given to a hydrogen nucleus, and its range for the same energy is smaller. These gases were used by Feather[14] and by Kurie[15] in the investigation of neutron energies. However, one must have in a cloud chamber not only a permanent gas, but also a condensable vapor. The vapors most commonly used are those of water and alcohol. Both of these contain hydrogen, so there will be a few hydrogen recoils in the chamber if neutrons traverse it. As it is impossible to distinguish the track of a proton from that of a heavier nucleus with certainty, this small amount of hydrogen present in the chamber will again give a background to any measurements made on the energy given to helium or nitrogen nuclei under those conditions. Bonner and Mott-Smith[16] removed this troublesome background by the use of a high pressure cloud chamber filled with either methane or hydrogen. With this arrangement, there can be no tracks longer than those due to the hydrogen recoils, and hence there will be no chance of ascribing more energy to the incident neutron than it actually had. With this apparatus they investigated the energy spectrum of the neutrons from Be, B, and F when bombarded by alpha particles from polonium.[17] This was an experimental chamber and had to be operated by hand.

APPARATUS

Dr. T. W. Bonner and I designed and constructed an automatic high pressure cloud chamber to be used in the study of neutron energies. The chamber has been operated successfully at a pressure of 20 atmospheres. Because of the high pressure at which the chamber was to be operated, special precautions were taken in its design and construction. The wall of the chamber was made of pyrex glass 1.3 cm thick; to increase its strength the glass was cemented into a brass cylinder with 0.5 cm walls. For the top glass we used a disk cut from 2.5 cm plate glass. Perhaps the greatest departure from the design of previous chambers was the manner in which the lower part of the chamber was sealed. Not only is the total pressure in the chamber very high, but the difference in the pressure before and after expansion is as high as 40 lbs/sq. in., even when alcohol is used to furnish the condensable vapor. (A smaller expansion ratio is required for alcohol vapor than for water vapor.) To take care of this large pressure difference, a modification of the sylphon type of chamber described by Dahl, Hafstad and Tuve[18] was used. As shown in the cut of the chamber in Fig. 1, the working volume V_1, which is the cloud chamber proper, is closed at the bottom by a close-fitting piston P. Alcohol in the space between the piston and the sylphon S_1 serves two purposes: it furnishes vapor for V_1, and it lowers the volume V_2 for the gas, so that V_2 will have the same expansion ratio as V_1. There will be no tendency for gas to blow past the piston and cause turbulence in V_1 when the expansion ratios of the two volumes are the same.[19]

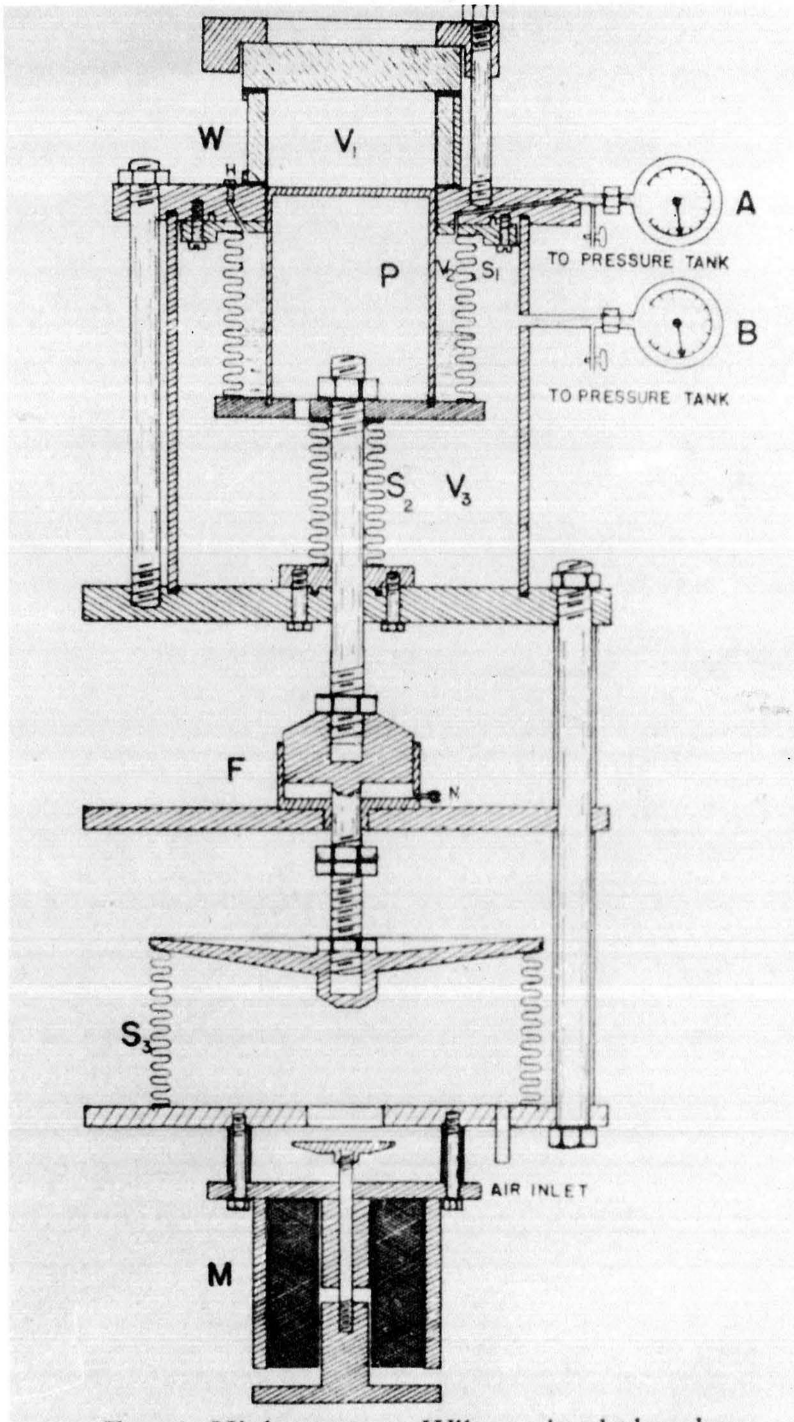

FIG. 1. High pressure Wilson cloud chamber.

The fact that the cross section of V_2 is an annular ring does not affect its expansion ratio. Thus, when the level of the alcohol is so adjusted that the axial length of V_2 is equal to the depth of V_1, the relation

$$dV_1/dV_2 = V_1/V_2$$

is satisfied for any finite movement of the piston assembly. This is exactly true to the extent that a sylphon can be considered a cylinder of constant diameter while its length changes. As $\Delta l/l$, where Δl is the distance the piston moves and l is the length of the sylphon, is always less than 1/10 it is readily seen that the error introduced by assuming the sylphon to have a constant diameter is negligible. Hence when the correct amount of alcohol is in the space between the piston and the sylphon there will be no tendency for the gas to blow past the piston and cause turbulence in the chamber at the time of expansion. In practice, we have not found the adjustment of the alcohol level to be very critical. The pressure in V_3 is made approximately the same as the pressure in V_2 after the expansion; thus the maximum pressure which S_1 experiences is only a little greater than the change in pressure in V_1 upon the expansion of the chamber. Leakage of gas from V_3 around the piston shaft is prevented by the sylphon S_2.

The chamber is illuminated by the light from a 2000-watt movie flood lamp. This has been a very satisfactory source of light for the photographing of proton and electron tracks in methane at pressures of several atmospheres or greater, and for proton tracks in hydrogen at half atmospheric pressure. Between expansions the voltage on the lamp is reduced to 10 volts, and $\frac{1}{2}$ second before the expansion it is raised to 110 volts. Besides being a most convenient and constant source of light, the lamp has been economical as well; our first lamp provided the illumination for nearly 150,000 pictures. A Sept movie camera equipped with an F. 3.5 lens has been used with 35 mm super-panchromatic film for taking the pictures. Two parallel, vertical mirrors above the chamber make it possible to take three images on the same frame, which makes stereoptical reprojection in the dark room possible.

We have used this cloud chamber in connection with the high potential tube developed by Lauritsen and Crane.[20] Using the voltage of the million volt (r. m. s.) cascade transformer set in the high voltage laboratory, this tube has been designed to accelerate positively charged particles with energies up to a million electron volts. When used with a cloud chamber, it is obviously desireable to have the positive ions strike the target only for a short time after the expansion. To accomplish this, relays at the potential of the ion source are actuated by solenoids at ground potential which are connected to the relays by non-conducting strings. The solenoids are energized by current from the contact system which controls the chamber. When the first relay is operated, $\frac{1}{2}$ second before the chamber expands, the following things happen to the ion source and its auxiliary equipement: a small amount of gas (usually deuterium) is allowed to enter the ion source, the low voltage fields of the high voltage generators are energised, and the filament in the ion source is raised to emitting temperature (between expansions it is burned at a much lower temperature). When the chamber is fully expanded, the other relay is operated, throwing the d. c. voltage of the generators on the ion source. Thus it is impossible for the chamber to have 'old' tracks in it. This last contact is for a very short time, (about 1/5 second). The camera shutter is opened 1/10 second after the chamber is expanded, and is closed 3/10 second after the expansion. Thus the chamber is not filled with tracks which come in too late to be recorded on the film. These extra, unphotographed tracks would cause more vapor to be condensed and thereby increase the time required between expansions for the chamber to come into equilibrium so that it may again be expanded. The time required for the chamber to come sufficiently into equilibrium when operated under these conditions at the highest pressures is of the order of 50 seconds.

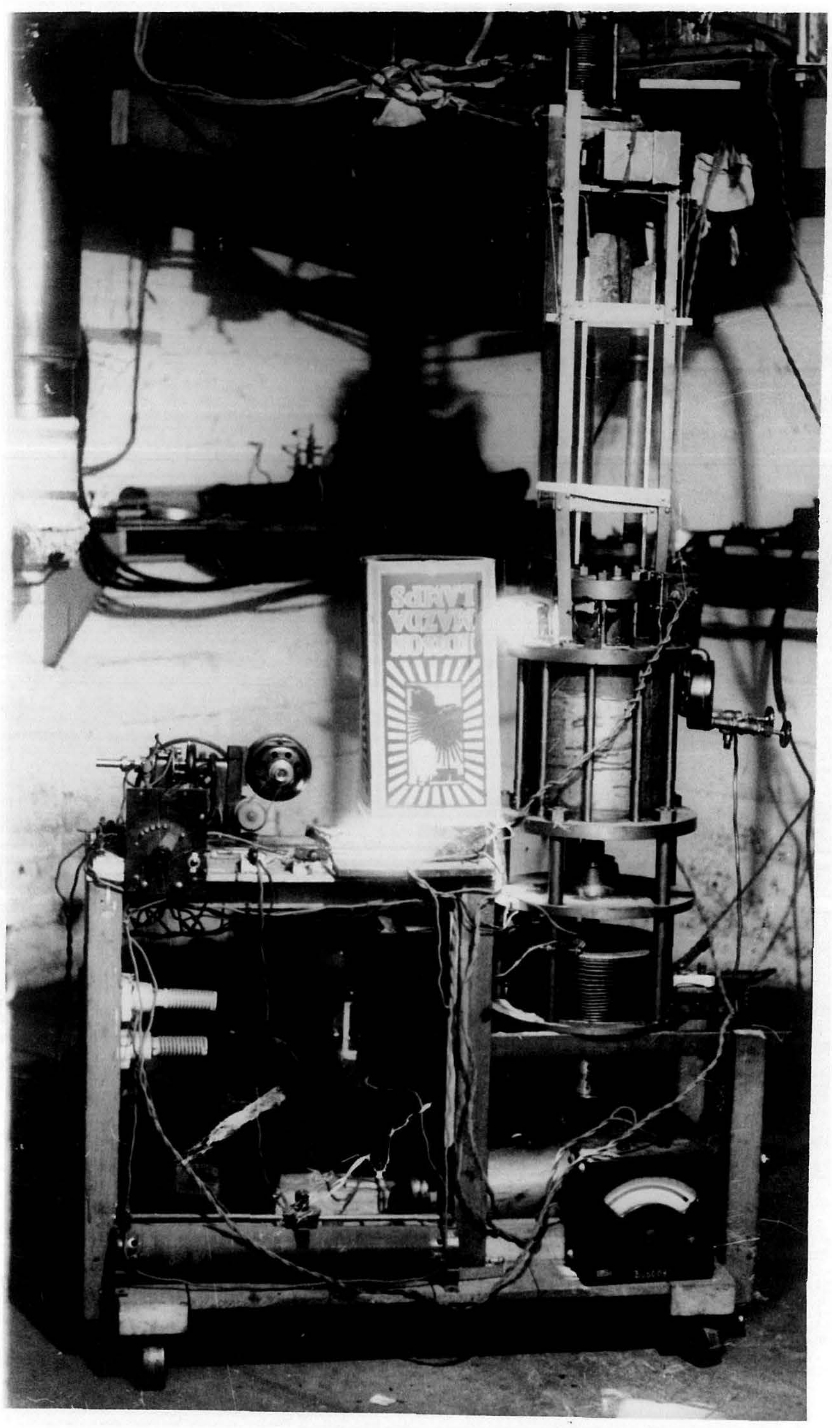

Fig. 2

EXPERIMENTAL PROCEDURE

With the apparatus just described, we have investigated the energies of the neutrons liberated in several disintegrations. In all of the work to be described in this thesis, the gas in the chamber was ordinary illuminating gas taken from the gas mains and pumped into suitable containers under pressure for us by Dr. B. H. Sage of the Chemical Engineering Laboratory. We found that the illuminating gas contained the same gases, and in almost exactly the same proportion, as the mixture which the Ohio Chemical Co. sold as 'methane' gas. The mixture was as follows: 85% CH_4, 14% C_2H_6, 0.8% N_2 and 0.2% CO_2. The chamber was also filled with the vapor of ethyl alcohol, in equilibrium with the liquid. This mixture of gases worked better in the chamber than a mixture considerably richer in C_2H_4. 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 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 was computed from data given by Phillipp.[21] The pressure of the gas in the chamber was adjusted so that the tracks of the protons were of a desirable length.

The direction of motion of the deuterons in the tube is downward, and the neutrons which enter the chamber directly from the target travel horizontally. Thus for these neutrons, θ is zero and equation (2) reduces to

$$Q = E_n(1 + m_n/m_r) - E_i(1 - m_i/m_r) \qquad (5)$$

Every target used has approximately 1/8" of brass directly below it. Neutrons are emitted with a distribution which is nearly spherically symetrical. Those emitted in the forward direction ($\theta = 0^\circ$) have a slightly greater energy than those emitted at 90°. A few of these higher energy neutrons can be scattered through 90° by the brass in such a manner that they may enter the chamber with greater energy than those which are emitted at 90°. We attribute the few tracks of energy higher than the value we chose for the maximum to be used in formula (5) to neutrons which have been scattered in this manner. For a given energy of disintegration all the neutrons emitted at 90° do not have the same energy. This is due to the fact that deuterons of all energies up to the maximum impinge on the targets and may produce a disintegration. Thick targets produce the same effect. However, for all the disintegrations studied except that of deuterium by deuterons , the excitation curve is so steep that the probability of a disintegration being produced by a deuteron of energy appreciably less than the maximum is so small that the spread in neutron energies from this cause is negligible.

For reprojecting the tracks, the entire assembly of camera and mirrors is removed from the chamber and taken to the dark room. A screw cover is removed from the back of the camera, and a lamp with suitable condensing lenses is placed back of the film. Thus it is possible to use the identical optical system for viewing the tracks as is used for taking the pictures. Any two of the three images can be combined to determine the position of the track in space. When the position and direction of the track have been determined, only one of the images is used to determine its length; greater contrast on the graduated probe is obtained in this manner. Only those tracks are measured which make angles of less than 8° with the lines drawn from the points of collision to the center of the target. However, because of the size of the source, some protons are measured which were projected at angles as large as 16°. The probability of measuring those which made angles greater than 8° with a neutron which came directly from the source is small, however. A proton projected at 8° gets 98.1% of the neutron's energy, and one projected at 16° gets 92.4%. Thus we should expect that a large proportion of the measured recoil-protons received between 98% and 100% of the energy of the neutrons, and that a rapidly diminishing number received from 98% down to 92.4%. 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.

NEUTRONS FROM THE DISINTEGRATION OF BERYLLIUM BY DEUTERONS

The copious emission of neutrons from the bombardment of beryllium by high speed deuterons was first reported by Crane, Lauritsen and Soltan.(22) Indications of the energies of the neutrons produced in this disintegration have been obtained by Kurie,(23) Oliphant,(24) and Bjerge and Westcott.(25) From the disintegrations produced in nitrogen by the neutrons from beryllium which was bombarded with 2 MEV. deuterons, Kurie has inferred that their maximum energy is about 10 MEV. On the other hand, the results of Oliphant,(24) who used a helium-filled ionisation chamber and linear amplifier, suggest that there are not many neutrons with energies over 3 MEV. Bjerge and Westcott 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 those from beryllium + alpha-particles. This indicates that the deuteron-beryllium neutrons are of low energy.

We have investigated the energy spectrum of the neutrons emitted from beryllium when it is bombarded by 0.9 MEV. deuterons. Test runs were made in which the deuterons were replaced by protons, and in which the deuterons were allowed to impinge on a brass target instead of the beryllium; in neither case were more than 1/1000 as many neutrons observed as when the deuterons bombarded the beryllium. Thus we felt justified in attributing the observed neutrons to the reaction

$$_4Be^9 + {_1H^2} \longrightarrow {_5B^{10}} + {_0n^1} + Q_6 \qquad (6)$$

Approximately 3,500 sets of stereoscopic pictures were taken when a beryllium metal target was bombarded by 0.9 MEV. deuterons. From these, 580 recoil proton tracks were measured. The energy distribution, plotted in 0.2 MEV. intervals, is given in Fig. 3. If these same data were plotted in 0.1 MEV. intervals, several more humps would appear in the curve. However, our previous work(26) in which we plotted the data in alternate 0.1 MEV. intervals shows that these extra humps are not entirely consistent and reproducible when different runs are made at different pressures. An energy interval of 0.1 MEV. corresponds to a range interval so short that small systematic errors in the measurement of the tracks would tend to throw tracks either into or out of the interval in which they really belong. A small error δ in the measurement of the track length would make an error of $P\delta$ in the range of the particle where P is the pressure of the gas in the chambers in atmospheres. The pressure used in this experiment was 7.2 atmospheres.

The different energy groups indicated are attributed to disintegrations with different Q_6's. The maximum value of Q_6, Q_{6a}, which corresponds to a neutron energy of 4.52 MEV., is observed when the resultant ${}_5B^{10}$ nucleus is formed in the ground state. When it is formed in an excited state, all of the energy released in the disintegration does not appear as kinetic energy; the energy with which the ${}_5B^{10}$ is excited is subsequently emitted as one or perhaps several gamma ray quanta. The work of Crane, Delsasso, Fowler and Lauritsen(27) indicates that the spectrum of the gamma

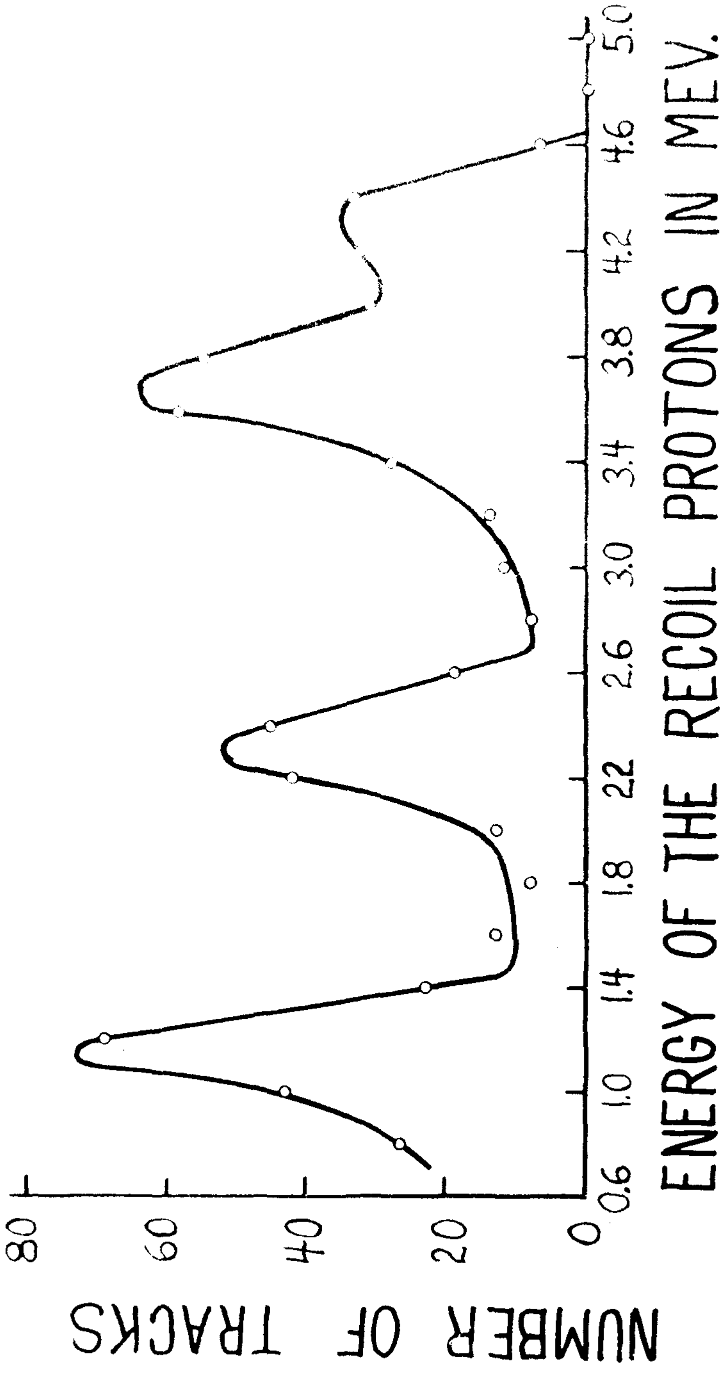
NUMBER OF TRACKS
0
20
40
60
80
0.6
1.0
1.4
1.8
2.2
2.6
3.0
3.4
3.8
4.2
4.6
5.0
ENERGY OF THE RECOIL PROTONS IN MEV.

Fig. 3

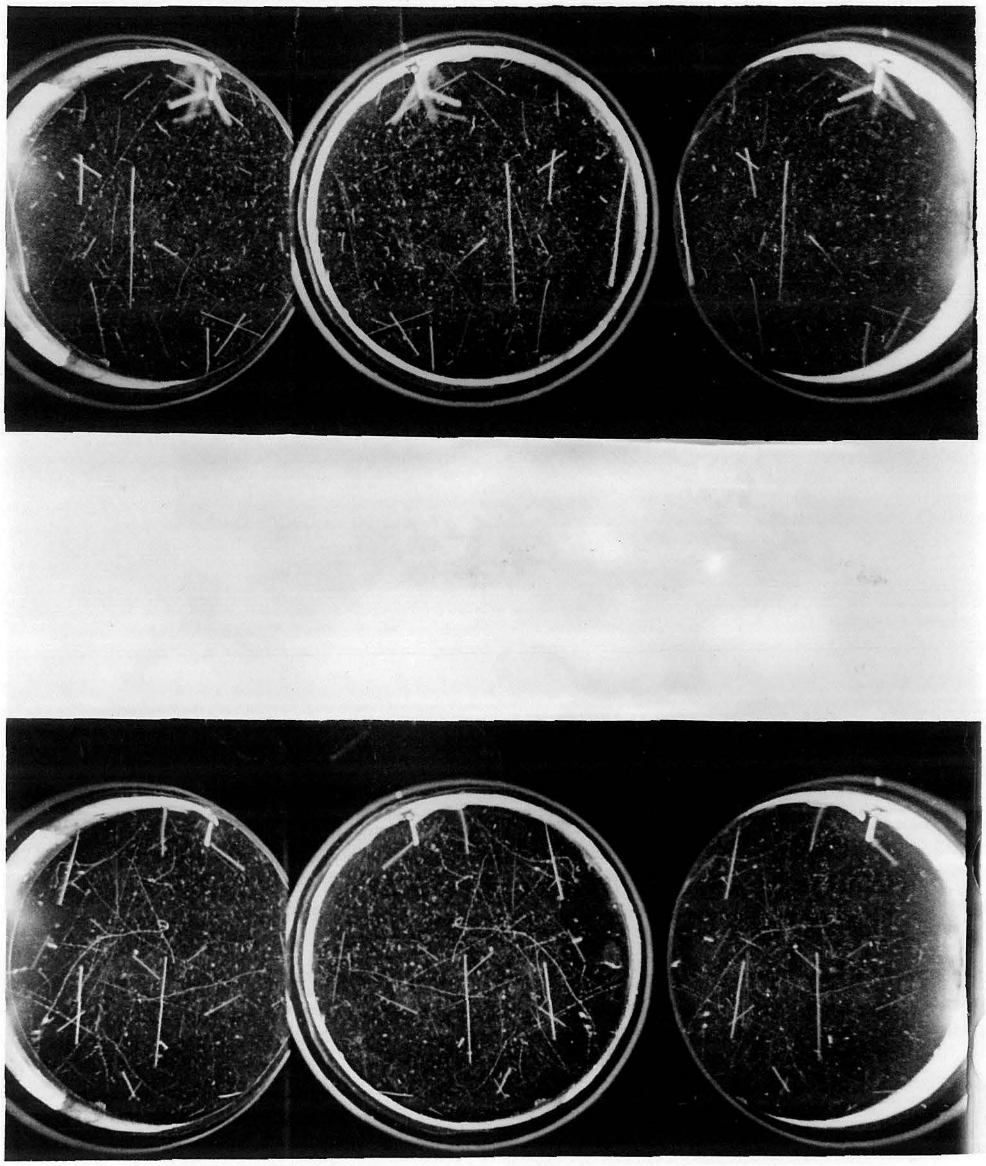

Fig. 4

rays emitted when beryllium is bombarded by deuterons is complex. Several reactions take place when beryllium is bombarded by deuterons. In these, several different resultant nuclei are formed, and the gamma rays may be due to any of these several nuclei. The extrapolated maximum energies of the neutron groups, as shown in Fig. 3 are 4.52 MEV., 4.0 MEV., 2.6 MEV. and 1.4 MEV. The corresponding Q_6's are:

Q_{6a} = 4.25 MEV. Q_{6c} = 2.1 MEV.

Q_{6b} = 3.7 MEV. Q_{6d} = 0.8 MEV.

The latter three values of Q_6 are observed when the ${}_5B^{10}$ nucleus is excited to levels of 0.55 MEV., 2.15 MEV., and 3.45 MEV. It is conceivable that gamma ray quanta whose energies correspond to the differences of these excited states are emitted. Thus we might expect some of the following gamma ray energies to be observed. In the second column is given the energy of some of the lines observed by Crane, Delsasso, Fowler and Lauritsen.

Transition	Energy Observed
$Q_{6a} - Q_{6b}$ = 0.55 MEV	0.6 MEV.
$Q_{6a} - Q_{6c}$ = 2.15 MEV.	2.0 MEV.
$Q_{6a} - Q_{6d}$ = 3.45 MEV.	3.3 MEV.
$Q_{6b} - Q_{6c}$ = 1.6 MEV.	
$Q_{6b} - Q_{6d}$ = 2.9 MEV.	2.9 MEV.
$Q_{6c} - Q_{6d}$ = 1.3 MEV.	1.3 MEV.

While this agreement is fair, it should be realized that it is not much better than that which might be obtained with any six values picked at random over the rather small energy interval of 3 MEV. This attempted correlation serves more as an illustration of our ideas about the energy levels in nuclei than as an agreement between the neutron and gamma ray energy spectra. The main comparison to be made between the two spectra at this time is that the maximum of the gamma ray spectrum corresponds to the greatest energy difference in the neutron spectrum. When the gamma ray spectrum, as well as the kinetic energies released when beryllium is bombarded with deuterons have been determined more accurately, entire agreement between them is expected to be found. Thus 'nuclear physics' may in time become 'nuclear spectroscopy'.

When we first determined the energy released in reaction (6) there was a disagreement of practically 3 MEV. between our experimentally determined Q_6 and the one computed from the mass spectrograph values of the masses involved in the reaction. In fact, there was disagreement of the same kind in most of the other reactions into which the beryllium nucleus entered. The mass-spectrographic value of the mass of $_4Be^9$ was greater than that of two alpha particles and a neutron, into which it theoretically should spontaneously disintegrate. Theoretical papers were written in attempts to explain how a nucleus which was known to be stable could be heavier than the sum of the masses of the more elementary particles into which it could disintegrate with the emission of energy. Order was regained when Oliphant[28] showed that all such difficulties could be alleviated if one assumed a slightly different value for the oxygen-helium ratio than the one determined by Aston, and re-arranged the masses of the elements of atomic number less then oxygen accordingly. Since then the masses have been further revised to bring them into better agreement with disnitegration data, so that there now is very good agreement in most cases between the experimentally determined values of the Q's of the reactions involving the light elements and the values computed from the masses of the nuclei involved. We have seen that the experimental value of Q_6 is 4.25 MEV. Oliphant's latest masses[29] give $Q_6 = 4.19$ MEV., which is seen to be in excellent agreement with our experimentally determined value.

NEUTRONS FROM THE DISINTEGRATION OF DEUTERIUM BY DEUTERONS

The emission of neutrons in large numbers from the bombardment of deuterium by deuterons was first reported by Oliphant, Harteck and Rutherford.[30] They attributed the neutrons to the reaction

$$_1H^2 + _1H^2 \rightarrow _2He^3 + _0n^1 + Q_7 \qquad (7)$$

They used a helium-filled ionisation chamber connected to an amplifier and oscillograph to measure the maximum energy of the neutrons. From the maximum oscillograph deflection they estimated that the neutrons have a maximum energy of 2.2 MEV. From the ranges of 30 recoil-helium tracks in a cloud chamber Dee[31] has inferred that the neutrons are homogeneous and have a maximum energy of 1.8 MEV.

We have studied the energy spectrum of the neutrons liberated when an H_3PO_4 target was bombarded by 0.5 MEV. deuterons. In this experiment the pressure of the methane in the chamber was 2.7 atmospheres. In a series of runs in which approximately 1200 recoil protons were photographed, 110 met our requirements for measurements which have been described previously. The energy distribution of these protons is given in the lower curve of Fig. 5. The upper curve shows data taken from an experiment on yields and described in the next section. In that experiment the chamber was placed very near the target, causing the direction of the neutrons not to be well defined. For this reason we could not investigate the entire energy distribution, but by measuring the long tracks we were able to get an independent value of the maximum energy of

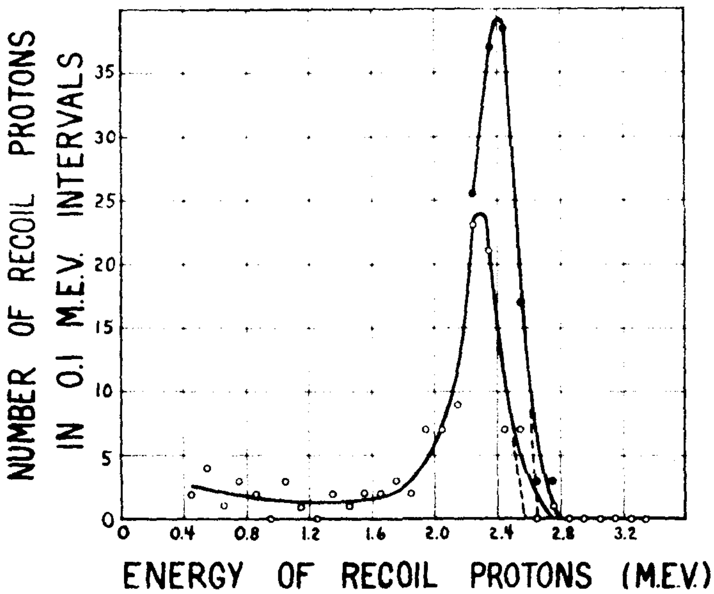
NUMBER OF RECOIL PROTONS
IN 0.1 M.E.V. INTERVALS
35
30
25
20
15
10
5
0
0
0.4
0.8
1.2
1.6
2.0
2.4
2.8
3.2
ENERGY OF RECOIL PROTONS (M.E.V.)

Fig. 5

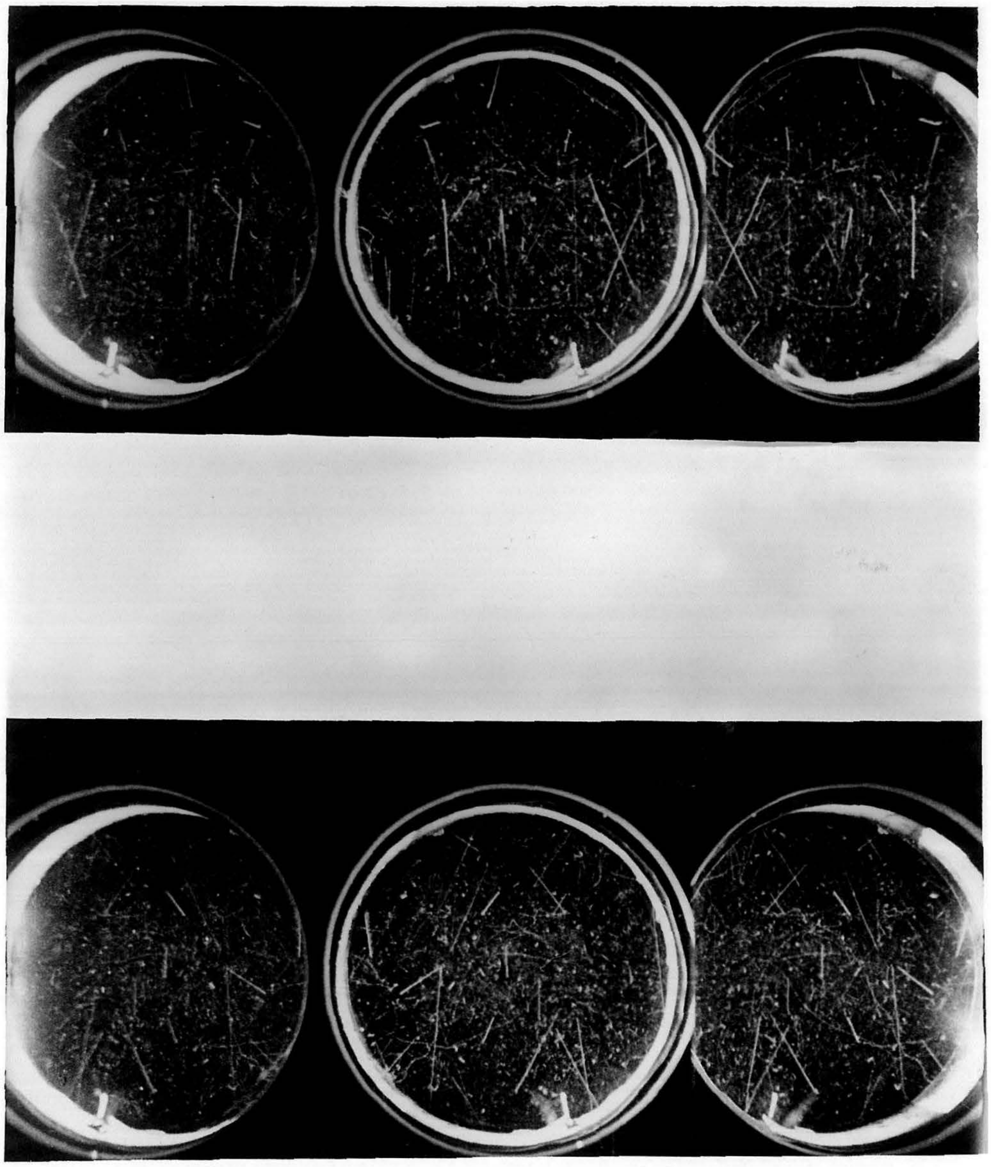

Fig. 6

the neutrons. The lower curve of Fig. 5 indicates that the neutrons are nearly homogeneous in energy with a maximum of 2.55 ± 0.10 MEV. We do not believe that the long tail on the low energy side necessarily means that neutrons of this energy come from the source; it is at least partly due to scattered neutrons which made large angle collisions with protons and projected them in a direction such that they were measured.

If one solves equation (5) for the energy of the neutron E_n he obtains

$$E_n = 3/4\ Q + 1/4\ E_i$$

where E_i is the energy of the deuteron which produced the disintegration. When our bombarding potential was 0.5 MEV., a maximum of 0.125 MEV. of this energy appeared in the kinetic energy of the neutrons emitted at right angles. Because we used a thick target and alternating current, disintegrations were effected by deuterons of all energies below the maximum. This gave the neutrons an energy spread of 0.125 MEV., with Q constant. A few neutrons which were emitted in a direction parallel to that of the incident deuteron beam made elastic collisions with little loss of energy in the 3 mm of brass which is directly below the target and so may have been scattered into the chamber. Such neutrons received a maximum of 0.9 MEV. more energy than those emitted at right angles and so may have been responsible for a few tracks with energies greater than 2.55 MEV.

The maximum energy of the neutrons as obtained from the lower curve is 2.55 $\pm$ 0.10 MEV. and from the upper curve is 2.62 $\pm$ 0.10 MEV. The corresponding Q's are 3.19 $\pm$ 0.13 MEV. and 3.23 $\pm$ 0.10 MEV. Dee and Gilbert(32) have obtained the energy of the short range $_2He^3$ particles which are produced in the same disintegration and from this energy have calculated that Q_7 is 2.8 $\pm$ 0.2 MEV.

From the energy released in this disintegration, one can calculate the mass of $_2He^3$. Using the value Q = 3.2 MEV., and Oliphant's latest values of the other masses(29), $_1H^2$ = 2.0147 and $_0n^1$ = 1.0090, we obtain

$$_2He^3 = 3.0170$$

This is in excellent agreement with Oliphant's value of 3.0171 which was computed from the disintegration of lithium by protons according to

$$_3Li^6 + {}_1H^1 \longrightarrow {}_2He^4 + {}_2He^3 + Q_8 \qquad (8)$$

EXCITATION CURVES FOR THE EMISSION OF NEUTRONS FROM DEUTERIUM AND BERYLLIUM

When Oliphant, Harteck and Rutherford[30] reported the emission of neutrons from the bombardment of deuterium by deuterons, they reported an equivalent yield of one neutron per 10^6 deuterons incident on a pure deuterium target at 0.1 MEV. This means an actual yield of about 1 in 10^7 from targets such as can be used conveniently. This yield from deuterium at 0.1 MEV. is comparable to the yield from a beryllium target at 0.8 MEV. reported by Crane, Lauritsen and Soltan.[33] However, other experiments in this laboratory as well as at Berkeley indicate that at high voltages the yield of neutrons from beryllium is considerably greater than that from deuterium.

We have compared the excitation functions for the emission of neutrons from Be and H_3PO_4 targets when bombarded by deuterons with energies between 0.5 MEV. and 0.9 MEV. by counting the number of recoil protons photographed in the chamber. We placed the chamber close to the target so that a large number of recoil protons could be observed. All observed tracks were counted, regardless of their orientation. The data taken in this manner have been reduced to an absolute yield and plotted as shown in Fig. 7. From 1000 to 2000 tracks were counted to determine each point on the curve. The relative yields are much more accurate than the absolute ones; the latter may be in error by as much as a factor of 5 or possibly 10.

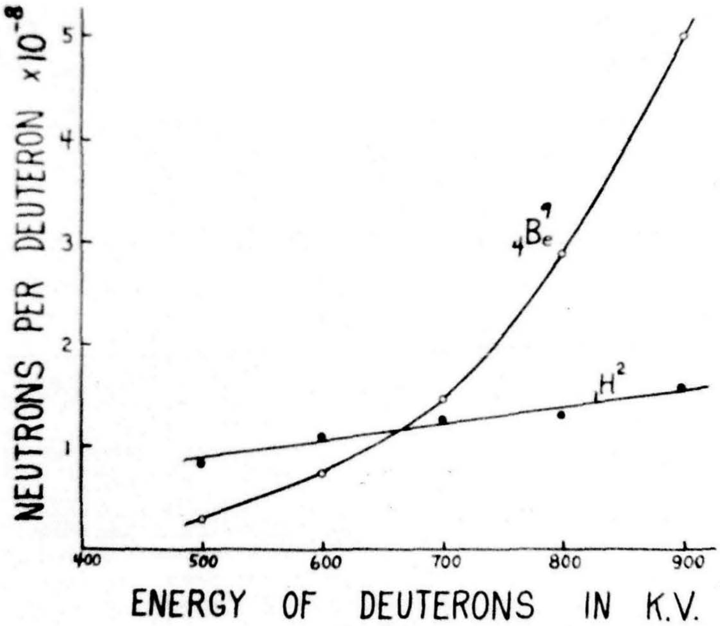
NEUTRONS PER DEUTERON ×10⁻⁸
5
4
3
2
1
400
500
600
700
800
900
ENERGY OF DEUTERONS IN K.V.
₄Be⁹
₁H²

Fig. 7

When the voltage was increased from 0.5 MEV. to 0.9 MEV. the average number of tracks per expansion increased from 2.7 to 42 with the Be target and from 7.1 to 13.4 with the H_3PO_4 target.

Examination of Fig. 7 shows that the yields from the two are equal at 0.68 MEV. Since the hydrogen in the H_3PO_4 molecule is responsible for only 1/8 of the molecular stopping power, one should multiply the experimental yield by 8 to get the yield from a pure deuterium target. From the curves we see that this would make the yield of neutrons from a pure deuterium target much greater than the yield obtained from a Be target when bombarded by deuterons with energies in the interval investigated in this experiment. It is impossible to use a target of pure deuterium, but it might be possible to use one of heavy water. If one were to freeze a thin layer of heavy water on to a brass target and keep it sufficiently cool to keep the ice on it when it is placed in a vacuum and bombarded by deuterons, he would have a target superior to the one we used. The fractional stopping power of the hydrogen in the water molecule is 28%. Thus there would be a gain of more than a factor of two if one used a target of heavy water instead of H_3PO_4.

The beryllium excitation curve agrees quite well with the one obtained by Crane, Lauritsen and Soltan(33) who used a paraffin-lined ionisation chamber to detect the neutrons. The curve is roughly exponential, doubling every 0.1 MEV. The deuterium curve appears linear in the interval between 0.5 MEV. and 0.9 MEV., increasing about 75% in the entire range. Since the height of the potential barrier for deuterons on deuterium is only about 0.1 MEV., this increase cannot be due to a greater probability of penetrating the potential barrier, but to the increased range of the deuterons in the target. The range of a 0.9 MEV. deuteron is approximately 90% greater than that of a 0.5 MEV. deuteron, so the agreement is fairly good.

If we extrapolate these curves down to 0.2 MEV. we may obtain an idea of the relative yields of the two targets at this bombarding potential. Upon doing this, we find that the ratio of the yield to be expected from Be to that from H_3PO_4 is 1/20. Thus it is apparent that, at potentials of the order of 0.2 MEV., deuterium contamination on targets may be responsible for an appreciable portion of the observed neutrons.

If one is interested in a source of neutrons with energies of the order of 2.5 MEV. it is seen that exceedingly high voltages are not necessary. In fact, over the range between 0.5 MEV. and 0.9 MEV., and probably at any voltage over 0.2 MEV., it would be more desirable to increase the yield by the use of targets richer in deuterium than H_3PO_4 , and by employing intense beams of bombarding particles than to use apparatus designed for higher voltages. This is particularly true if one were building an apparatus for the production of neutrons.

DISINTEGRATION OF LITHIUM BY DEUTERONS

When lithium is bombarded by deuterons, the following reactions are known to occur:

$$_3Li^6 + {}_1H^2 \longrightarrow 2\,{}_2He^4 + Q_9 \qquad (9)$$

$$_3Li^6 + {}_1H^2 \longrightarrow {}_3Li^7 + {}_1H^1 + Q_{10} \qquad (10)$$

$$_3Li^7 + {}_1H^2 \longrightarrow 2\,{}_2He^4 + {}_0n^1 + Q_{11} \qquad (11)$$

The first two of these reactions have been investigated by several people.[(34)] The emission of neutrons when lithium is bombarded by deuterons was first reported by Crane, Lauritsen and Soltan.[(35)] Experiments done with the separated isotopes of lithium by Oliphant, Shire and Crowther[(36)] have shown that the disintegration products had been attributed to the proper isotope. Oliphant, Kempton and Rutherford[(37)] have determined the energies of the alpha particles liberated in reaction (11). We investigated the energy distribution[(38)] of the neutrons liberated in the disintegration of lithium by 0.85 MEV. deuterons. In particular, we were interested in determining the maximum energy of the neutrons, and in investigating the probability of the transformation of $_3Li^7$ into $_4Be^8$ according to

$$_3Li^7 + {}_1H^2 \longrightarrow {}_4Be^8 + {}_0n^1 + Q_{12} \qquad (12)$$

Because of the very long ranges (over 190 cm in air) of the protons projected by neutrons released in the disintegration of lithium, we found it desirable to deviate slightly from the method described earlier in this thesis. The longest track which we can measure in our chamber is 8.8 cm long, and as the chamber is circular, the probability of observing a track of that length is very small. Furthermore, the chamber is not designed to withstand a pressure great enough that such an energetic proton would be stopped in 8.8 cm of methane. To overcome this difficulty we placed a sheet of mica of 114 cm air equivalent across the center of the chamber in a plane perpendicular to a line drawn to the target. Thus, with an expanded pressure of 14.7 atmospheres in the chamber we were able to investigate the range interval of 125 cm to 240 cm, or the energy interval of 10.5 MEV. to 15.3 MEV. With a sheet of mica of 58 cm air equivalent we investigated the energy interval of 8.4 MEV. to 11.2 MEV., and with no mica in the chamber we covered the interval of 2.2 MEV. to 8.4 MEV. Because the tracks of the lower energy protons were too short to be observed at a pressure of 14.7 atmospheres, two more series of runs were made. In one of these we used hydrogen at a pressure of 0.5 atmospheres, and in the other we used methane at a pressure of 2.67 atmospheres. The stopping power of the mica was computed in the usual manner, using the value 1.43 mg. per sq. cm equivalent to one cm of air.

The ranges of the recoil protons were computed from the track lengths and the stopping power of the gas and the mica sheet. These proton ranges were then converted into proton energies by the range-velocity curve of Mano.[39] A correction has been applied to the data of each run to compensate for the unequal probabilities of observing tracks of different lengths in the chamber. This was particularly important when the mica sheet was used.

The effect of the small amount of proton contamination in the deuteron beam was examined by making a control run in which the bombarding ions were protons. There were less than 1/200 as many recoil protons photographed as when deuterons were used, which indicates that the proton impurity could not have been responsible for more than 1/2,000 of the observed neutrons. In test runs which were made when the lithium chloride target was replaced by a brass one, less than 1/200 as many recoil protons were photographed.

From approximately 60,000 protons which were observed on 19,600 stereoscopic photographs, 1,550 met our requirements for measurement. Examples of pictures taken when the mica sheet was placed across the chamber are shown on page 40. The energy distribution of these recoil protons is given in Fig. 8. The curve includes data from the five overlapping series of runs which were fitted together as shown. In the lower energy portion of the curve, the number of tracks observed in a given 0.4 MEV. interval was only about half the number indicated.

The upper curve of Fig. 8 gives the distribution of recoil protons but not necessarily the distribution of the primary neutrons. A variation in the neutron-proton collision area with energy would make the neutron distribution curve differ from the proton curve. It is known that the collision area increases as the energy of the neutrons decreases. In order to obtain the neutron distribution curve, we have taken into account the experimental variation of collision area with neutron energy as found by Bonner[40] and by Dunning.[41]

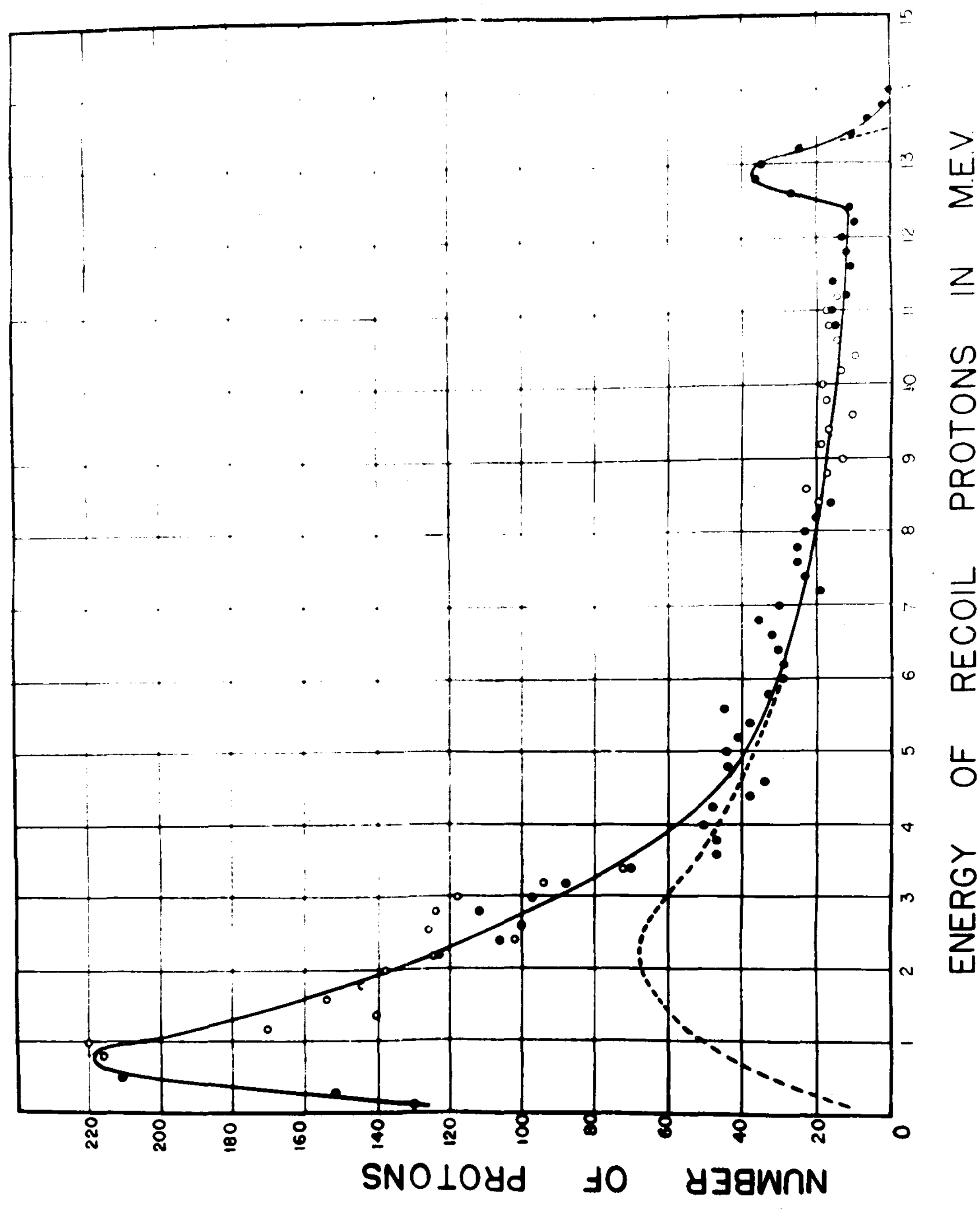
ENERGY OF RECOIL PROTONS IN M.E.V
NUMBER OF PROTONS
0 20 40 60 80 100 120 140 160 180 200 220
0 1 2 3 4 5 6 7 8 9 10 11 12 13 15

Fig. 8

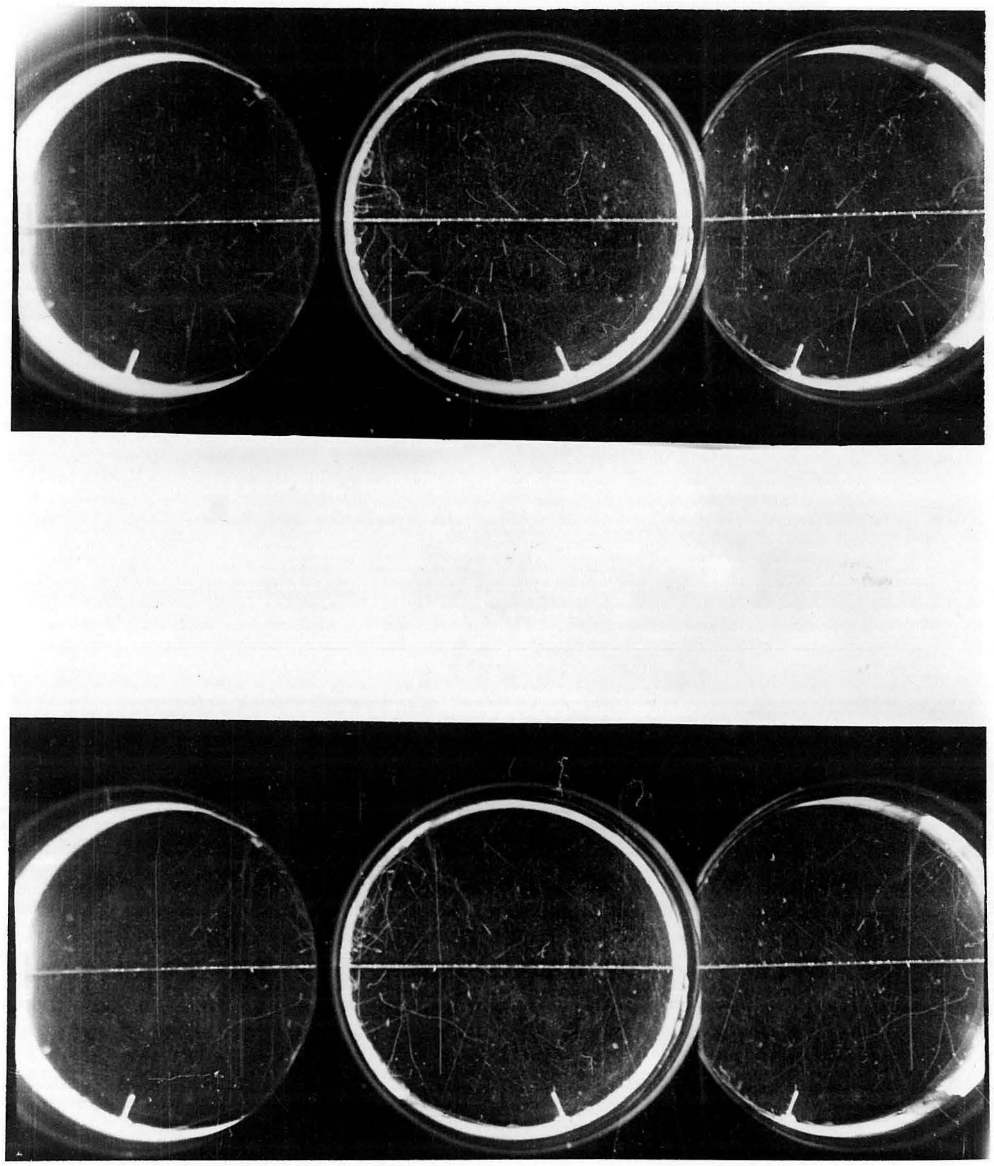

Fig. 9

The collision areas used were: $E \approx 0$, $\sigma = 31 \times 10^{-24}$; $E = 1.2$ MEV., $\sigma = 5.8 \times 10^{-24}$; $E = 2.1$ MEV., $\sigma = 3.2 \times 10^{-24}$; $E = 5$ MEV., $\sigma = 1.68 \times 10^{-24}$. Thus we get the dotted curve of Fig. 8 , which we believe to be the approximate form of the neutron distribution curve. It shows a pronounced hump near 13 MEV., which we have interpreted as being due to the transformation of ${}_3Li^7$ into ${}_4Be^8$ and a neutron as postulated in reaction (12). The area under the hump is approximately 5% of the entire area under the curve; this indicates that reaction (12) is 1/20 as probable as the reaction (11) in which two alpha particles and a neutron are formed. This probability may be a function of the bombarding potential.

${}_4\underline{Be}^8$

Evidence of the existence of ${}_4Be^8$ was first presented by Kirchner[42] in his study of the disintegration of boron by protons. He proposed the reaction

$$ {}_5B^{11} + {}_1H^1 \rightarrow {}_4Be^8 + {}_2He^4 + Q_{13} \tag{13} $$

to explain the small homogeneous group of alpha particles of 4.4 cm range at the tail of the continuous distribution of particles due to the reaction

$$ {}_5B^{11} + {}_1H^1 \longrightarrow 3\,{}_2He^4 + Q_{14} \tag{14} $$

Oliphant, Kempton and Rutherford[43] found that ${}_4Be^9$ could be disintegrated to form $_4Be^8$ by either protons or by deuterons:

$$_4Be^9 + {_1H^1} \rightarrow {_4Be^8} + {_1H^2} + Q_{15} \tag{15}$$

$$_4Be^9 + {_1H^2} \rightarrow {_4Be^8} + {_1H^3} + Q_{16} \tag{16}$$

They also studied the energies of the particles emitted when boron is bombarded by protons. In order to determine Q_{14} they used the average energy of the three alpha particles. These considerations led them to

$$Q_{13} - Q_{14} = {_4Be^8} - 2{_2He^4} = 0.1 \text{ MEV.}$$

The value for the mass of $_4Be^8$ which they found to give the greatest consistency in all of their reactions in which it is involved is

$$_4Be^8 = 2{_2He^4} + 0.2 \text{ MEV.}$$

Dee and Gilbert[44] have recently re-examined the ranges of the alpha particles emitted when boron is bombarded by protons. After a careful and detailed study of the mode of disintegration into three alpha particles, they arrived at the conclusion that

$$_4Be^8 = 2{_2He^4}$$

within the limits of the accuracy of their measurements. They also found evidence that $_4Be^8$ is sometimes formed in an excited state, 3 MEV. above the ground state. In this case, its life can not be longer than about 10^{-17} seconds.

Cockroft and Lewis[45] found that $_4Be^8$ is formed when $_5B^{10}$ is bombarded with deuterons

$$_5B^{10} + {}_1H^2 \rightarrow {}_4Be^8 + {}_2He^4 + Q_{17} \qquad (17)$$

Their evidence was again a small homogeneous group at the tail of the continuous distribution of alpha particles arising from the reaction

$$_5B^{10} + {}_1H^2 \longrightarrow 3\,{}_2He^4 + Q_{18} \qquad (18)$$

By combining their results with those of other well known reactions and Bainbridge's[46] value of the difference

$$2\,{}_1H^2 - {}_2He^4$$

they obtained

$$_4Be^8 = 2\,{}_2He^4 + 0.3 \text{ MEV}$$

From the energy of the apparently homogeneous group of neutrons at the tail of the neutron distribution curve we may compute the kinetic energy released in reaction (12). Equation (5) becomes, for this case,

$$Q_{12} = 9/8\ E_n - 3/4\ E_i$$

The extrapolated maximum energy is 13.6 ± 0.5 MEV. Because Mano's range-velocity curve is for mean and not extrapolated ranges, 0.1 MEV. should be subtracted from our extrapolated neutron energy. Using the value 13.5 MEV. for E_n and 0.85 MEV.

for E_i we obtain

$$Q_{12} = 14.5 \pm 0.5 \text{ MEV.}$$

The rather broad limits on the neutron energy are given for several reasons. The shape of the distribution curve is such that the extrapolated energy is not clearly defined. The range-velocity curve for protons of this energy has never been investigated experimentally, nor is it known that the stopping power of the mica remains constant for all velocities up to those observed in this experiment; there is evidence to the contrary. The value of Q_{12} can be inserted in equation (12) and one may then solve for the mass of ${}_4Be^8$ in terms of the other masses appearing in the same equation. Using Oliphant's[29] latest values this leads to

$${}_4Be^8 = 2\,{}_2He^4 + 0.28 \text{ MEV.}$$

A more direct method of determining the mass of ${}_4Be^8$ would be given by knowing the energy released in the alternative mode of disintegration in which two alpha particles and a neutron are formed, as in equation (11).

$${}_3Li^7 + {}_1H^2 \longrightarrow 2\,{}_2He^4 + {}_0n^1 + Q_{11} \qquad (11)$$

Oliphant, Kempton and Rutherford[47] have investigated the energies of the alpha particles liberated in this reaction, and find that they have a maximum range of 7.7 cm. It is not known just how the kinetic energy released in the disintegration is shared among the three particles. However, they assumed that this maximum range of the alpha particles corresponds to the mode in which the greatest possible energy is given to the alpha particle; i. e., when the other alpha particle and the neutron escape in the opposite direction, parallel to one another, and with the same velocity. When this happens, the first alpha particle receives 5/9 of Q_{11}. For any other division of the energy, the most energetic alpha particle would get less than 5/9 of Q_{11}. It is improbable that the alpha particle and the neutron should come off parallel to each other and with the same velocity. Just how nearly this may happen will remain a matter of conjecture until the energy released in reaction (11) is known accurately, from the masses or some other means; then one may compute the angle of separation of the two particles from Q_{11} and the maximum alpha particle energy. By assuming that the two particles come off in directions so nearly opposite that of the high energy alpha particle that the cosines of the angles are approximately unity, Oliphant, Kempton and Rutherford were able to set a lower limit to the value of Q_{11}. The value they obtained in this manner is 14.6 $\pm$ 0.25 MEV. The value to be expected from Oliphant's masses is 14.8 MEV. While the value obtained by Oliphant, Kempton and Rutherford agrees with the one computed from the masses, within the probable error, it is probable that part of the discrepancy is due to the fact that the mode of disintegration which is most favorable for a high alpha particle energy is not obtained in reality.

Because of the uncertainties involved in determining the energy released in a disintegration when it is shared by three particles, it is perhaps better to use the value of Q_{11} given by the masses than the one determined by Oliphant, Kempton and Rutherford. Combining this value with our experimentally determined value of Q_{12} we find

$$Q_{12} - Q_{11} = {}_4Be^8 - 2\,{}_2He^4 = 0.3 \text{ MEV.}$$

or $${}_4Be^8 = 2\,{}_2He^4 + 0.3 \text{ MEV.}$$

Thus it is seen that there is great consistency in the values of the mass of ${}_4Be^8$ which are computed in several ways. It seems evident that ${}_4Be^8$ is slightly heavier than two alpha particles. This makes it unstable and explains why it is not found in nature.

SUMMARY

A brief history of the discovery and identification of the neutron is given. It is shown how disintegration data give relations between the masses of the nuclei involved, and how one may obtain Q, the kinetic energy released in the disintegration, by observing the direction and velocity of one of the disintegration particles, in the cases where this energy is shared by only two particles. When a neutron is one of the disintegration particles, the determination of Q is more difficult. Means of determining neutron energies by observing recoil protons in a high pressure cloud chamber is explained in detail, including the design of a chamber for this work.

The energy distribution curves of the neutrons emitted by beryllium, deuterium and lithium when bombarded by deuterons, as well as the excitation curves for the emission of neutrons by beryllium and deuterium are given. It is shown that the mass values obtained by this means agree very well with those obtained by other means.

ACKNOWLEDGEMENTS

The author wishes to take this opportunity to express his sincere thanks to Dr. T. W. Bonner, who collaborated in all the work described in this thesis, and to Professor C. C. Lauritsen, under whose supervision the work has been done. The helpful suggestions of Mr. Julius Pearson in the design of the chamber were greatly appreciated. He is also grateful to the Seeley W. Mudd Fund for the financial support of this project.

REFERENCES

(1) Bothe and Becker: Zeits. f. Physik 66, 289; 1930

(2) Bothe: Zeits. f. Physik 76, 241

Mme. Curie-Joliot: Comptes Rendus 193, 1412 and 194, 708

Webster: Proc. Roy. Soc. A 136, 428; 1932

(3) Curie and Joliot: Comptes Rendus 194, 273; 1932

(4) J. Chadwick: Nature 129, 312; 1932

Proc. Roy. Soc. A 142, 1; 1932

(5) N. Feather: Proc. Roy. Soc. A 136, 709; 1932

(6) Blackett and Lees: Proc. Roy. Soc. A 134, 658

(7) Rutherford: Proc. Roy. Soc. 97, 374; 1920

(8) Aston: "Mass Spectra and Isotopes"

(9) H. Bethe, Phys. Rev. 47, 633

Oliphant, Kempton and Rutherford: Proc. Roy. Soc. A 150, 241

Bonner and Brubaker: to be published in the Physical Rev.

(10) Curie and Joliot: Comptes Rendus 194, 876; 1932

(11) P. I. Dee: Proc. Roy. Soc. A 136, 727; 1932

(12) Dunning; Phys. Rev. 45, 568; 1934

(13) Bonner and Brubaker: Phys. Rev. 47, 973; 1935

(14) N. Feather: Proc. Roy. Soc. A 136, 709; 1932

(15) F. N. D. Kurie: Phys. Rev. 47, 97; 1935

(16) L. M. Mott-Smith: Rev. Sci. Inst. 5, 346; 1934

(17) T. W. Bonner and L. M. Mott-Smith: Phys. Rev. 46, 258; 1934

(18) Dahl, Hafstad, and Tuve: Rev. Sci. Inst. 4, 373

(19) Brubaker and Bonner: Rev. Sci. Inst. 5, 143; 1935

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

(21) K. Phillipp: Zeits. f. Physik 17, 23; 1923

(22) Crane, Lauritsen and Soltan: Phys. Rev. 44 , 692; 1933

(23) F. N. D. Kurie: Phys. Rev. 47, 97; 1935

(24) Oliphant: Int. Conf. on Phys., London, October, 1934

(25) Bjerge and Westcott: Nature 134 177; 1934

(26) Bonner and Brubaker: Phys. Rev. 47, 910; 1935

(27) Crane, Delsasso, Fowler and Lauritsen: Phys. Rev. 47, 782

(28) Oliphant: Science, March 22, 1935

(29) Oliphant: Nature 137, 396; 1936

(30) Oliphant, Harteck and Rutherford: Proc. Roy. Soc. A 144, 692

(31) P. I. Dee: Proc. Roy. Soc. A 148, 623; 1935

(32) Crane, Lauritsen and Soltan: Phys. Rev. 44, 692; 1933

(33) Dee and Gilbert: Proc. Roy. Soc. A 149, 200; 1935

(34) Lawrence: Phys. Rev. 44, 55; 1933

Dee and Walton: Proc. Roy. Soc. A 141, 733; 1933

Oliphant, Kinsey and Rutherford: Proc. Roy. Soc. A 141, 722

Cockroft and Walton: Proc. Roy. Soc. A 144, 704; 1934

(35) Crane, Lauritsen and Soltan: Phys. Rev. 44, 692; 1933

(36) Oliphant, Shire and Crowther: Nature 133, 377; 1934

(37) Oliphant, Kempton and Rutherford: Proc. Roy. Soc. A 149, 406

(38) Bonner and Brubaker: Phys. Rev. 48, 742; 1935

(39) G. Mano: J. de Phys. et Rad. 5, 628; 1934

(40) T. W. Bonner: Phys. Rev. 45, 601; 1934

(41) J. R. Dunning: Phys. Rev. 45, 586; 1934

(42) Kirehner: Naturwiss. 21, 473

(43) Oliphant, Kempton and Rutherford: Proc. Roy. Soc. A 150, 241

(44) Dee and Gilbert: Proc. Roy. Soc. A __154__, 279; 1936

(45) Cockroft and Lewis: Proc. Roy. Soc. A __154__, 246; 1936

(46) Bainbridge: Phys. Rev. __41__, 115; 1932

(47) Oliphant, Kempton and Rutherford: Proc. Roy. Soc. A. __149__, 406