NEUTRONS FROM DEUTERON BOMBARDMENT OF BORON

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[*Manuscript received February 13, 1957*]

Summary

A natural boron target has been bombarded by 920 keV deuterons, and the emitted neutrons detected using nuclear emulsions. A new procedure for analysing measurements is described ; this procedure allows approximate corrections for errors in geometry in the plane of the emulsions. The dependence of resolution on various experimental factors has been studied, and the resolution achieved is indicated by peak widths of 245 ± 25 keV and 360 ± 50 keV at neutron energies of $9 \cdot 7$ MeV and $13 \cdot 9$ MeV respectively. The angular distributions of the neutrons from the $^{10}B(d,n)^{11}C$ reaction corresponding to the ground state of ^{11}C, and the neutrons from the $^{11}B(d,n)^{12}C$ reaction corresponding to the $7 \cdot 66$ MeV state in ^{12}C, have been determined ; both distributions may be attributed to compound nucleus formation. A search has been made for a neutron group corresponding to an excited state at about $5 \cdot 5$ MeV in ^{12}C suggested by Glassgold and Galonsky (1956) on the basis of the α-particle model. An upper limit for the intensity of any such group is set at 1 per cent. of the intensity of the group corresponding to the first excited state in ^{12}C.

I. Introduction

Little information is available on the resolution which may be achieved using nuclear emulsions to detect neutrons of energies from 10 to 15 MeV. The present paper describes some work carried out to determine this resolution. The apparatus and procedures described previously (Bird 1955) have been modified and used to study the neutrons emitted in the $^{11}B(d,n)^{12}C$ reaction. This reaction gives two well-defined neutron groups in the required energy range. The dependence of resolution on various experimental factors has been investigated.

As a secondary aim the angular distribution of the neutron group leading to the $7 \cdot 66$ MeV state in ^{12}C has been studied. The properties of this level are of astrophysical significance (Salpeter 1955), and, although the bombarding energy available (920 keV) was relatively low, it was hoped that the stripping process might make a sufficiently large contribution to the yield of the reaction to enable information to be obtained concerning the spin and parity of the level.

A search has also been made for neutrons corresponding to an excited state in ^{12}C at about $5 \cdot 5$ MeV. Such a state has been suggested by Glassgold and Galonsky (1956) from a theoretical investigation of the α-particle model for ^{12}C.

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II. Experimental Procedure

Because of the similarity of the neutron energies for the $^{10}B(d,n)^{11}C$ ground state group and the 7·66 MeV state group of the $^{11}B(d,n)^{12}C$ reaction, it was decided to use a natural boron target so as to enable simultaneous study of the two groups, and hence the accurate determination of the relative numbers of neutrons from each reaction. The target was prepared by evaporation *in vacuo* of amorphous boron from a tantalum strip onto a backing of 0·00025 in. electrolytic copper foil. The target thickness was estimated by counting interference fringes and from the energy of scattered protons as measured with a 180° magnetic analyser. Within the experimental errors both methods indicated a thickness of 60 keV. A $1\frac{1}{2}$ mm diameter beam of 920 keV deuterons was used to give an exposure of 32,000 μC.

Pairs of 1-in. square pieces of 200μ Ilford C2 nuclear emulsion plates were located at 15° intervals about the target, the camera and target arrangements being similar to those described previously (Bird 1955), except that the leading edges of the plates were in this case $7\frac{1}{2}$ cm from the target. Plates were vacuum dried for 16 hr prior to exposure, and kept in air dried by phosphorus pentoxide during exposure. Under these conditions the range-energy relation of Gibson, Prowse, and Rotblat (1954) may be used. Plates were developed for 1 hr using D19 diluted 6 : 1. This development was chosen to give optimum contrast between the beginnings of long tracks and background fog.

Measurements of the range and angle of recoil of proton tracks having an angle of recoil of less than 25° were made using a specially constructed microscope (Dunbar and Bower 1949). During preliminary measurements several methods of angle measurement were tested for accuracy by determining the width of the 10 MeV neutron group corresponding to the 4·43 MeV state of ^{12}C. For the determination of dip angle, two methods were considered : (i) measurement of the change in depth coordinate after moving a given distance in the assumed neutron direction (x-direction) from the beginning of the track, (ii) measurement of the length of track in focus at the beginning. Method (i) was found to be the more satisfactory. For the determination of lateral angle (in the plane of the emulsion), direct measurement with an eyepiece protractor was found to give more reliable results than measurement of the change in lateral (y) coordinate for a given change in x coordinate.

The total angle between the initial direction of each recoil proton and the assumed neutron direction was obtained using the chart illustrated in Figure 1. This represents the plane perpendicular to the assumed neutron direction at a fixed distance (0·002 in.) from the beginning of each track. Thus the y and z scales represent the change in lateral and dip coordinates respectively, and from the values measured for a particular track the total angle can be read from the circles, which in practice are drawn for every half degree. The y scale is also calibrated directly in degrees as read by the eyepiece protractor for the initial lateral angle, and a small correction (δ) for the change in neutron direction with variation of the position of each track on the plate is made by displacing the y scale an appropriate amount either to left or right. The value of δ is determined by plotting the position of the track on a map of the plate. In order to represent the dip in the emulsion prior to processing, the z scale units are enlarged by the shrinkage factor (taken to be $2 \cdot 30$).

The length of each track is taken as the distance between the first and last grains, and is found from the coordinates of these as recorded by the three micrometer movements of the microscope. The length of a track was generally

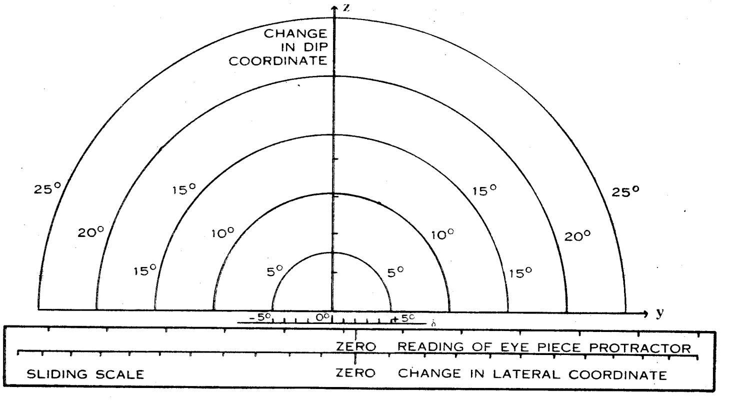

Fig. 1.—Chart for determination of total recoil angle.

reproducible by different observers to better than 1 micron. Where possible the various angles were recorded to the nearest $0 \cdot 1°$, and the chart of Figure 1 was designed to give the final angle correct to $0 \cdot 1°$, so that negligible error is introduced after the actual measurements are made.

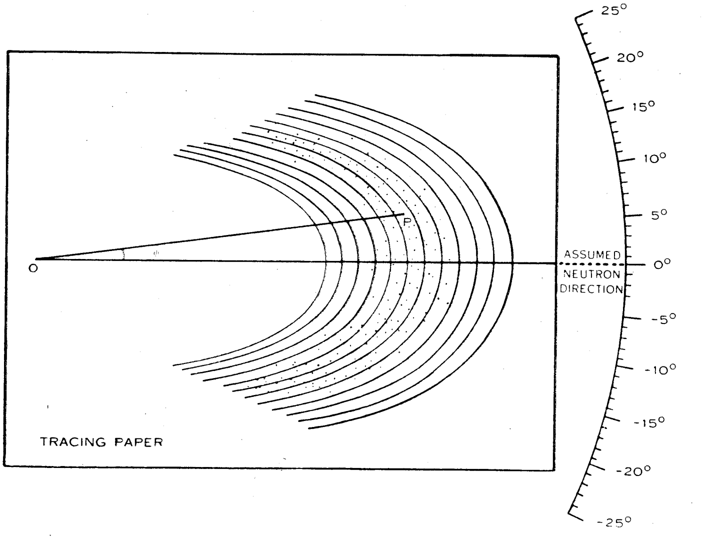

Fig. 2.—Determination of neutron energy spectrum.

In order to obtain an energy spectrum, the length and recoil angle for each track are plotted on tracing paper in a diagram similar to that of Figure 2. The radial distance OP is proportional to the track length, and the angle ψ is the recoil angle allotted a sign according to whether it fell to the right or left in

Figure 1. Each point on the diagram represents a track. The tracing paper is superimposed on a set of curves drawn to represent the variation in range of recoil protons with recoil angle for values of neutron energy in 100 keV steps. Thus the number of tracks occurring in each energy interval can be read directly. This procedure allows flexibility in the handling of data, so that the effects of various changes in selection criteria or methods of measurement can be readily tested.

Approximate corrections can be made for errors in the assumed neutron direction by rotating the tracing paper of Figure 2 by the appropriate amount about O as centre. A graph of the width of a given neutron peak versus angle of rotation of the tracing paper will pass through a minimum at the correct neutron direction. Errors in geometry can be detected in this way, and the energy spectrum determined with the tracing paper set at the correct orientation. This method will break down for tracks having a large dip angle combined with a small lateral angle, but is quite satisfactory for the ranges of values usually accepted for these angles.

III. Resolution

About 400 tracks longer than 170 μ were measured at each of the three angles 0, 15, and 75°. Approximately half of these tracks were from the 10 MeV neutron group corresponding to the $4 \cdot 43$ MeV level in ^{12}C. In Figure 3, the width at half height of the 10 MeV peak at 15° (assumed to be $2 \cdot 35$ times the calculated standard deviation) is plotted against the angle of rotation of the

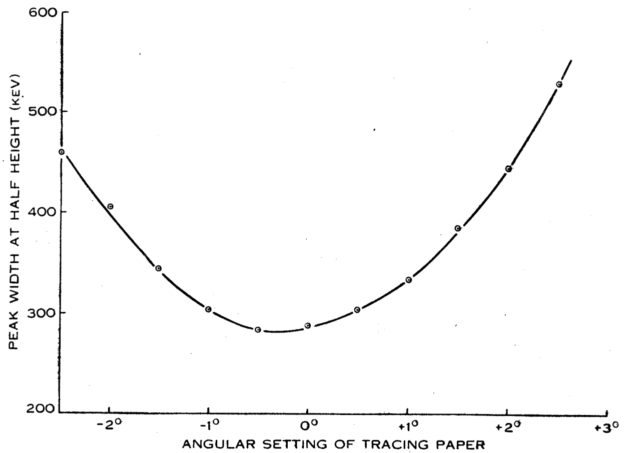

Fig. 3.—Variation of peak width with angle of rotation of tracing paper. Tracks from 10 MeV neutron group on 15° plate, with ψ up to 20° and dip angles in unprocessed emulsion less than 5°.

tracing paper of Figure 2. The points define a curve which passes through a minimum at $-0 \cdot 3°$, indicating that this error was made (in the plane of the emulsion) in the assumed neutron direction. Figure 3 also shows that an error of more than half a degree in the assumed neutron direction will have a significant effect on the observed resolution, and an error of 3° will approximately double the peak widths. The correct neutron direction was found to be at $+0\cdot1°$ for the $0°$ plate, and at $-2\cdot7°$ for the $75°$ plate; the latter error would, if not rectified, have a serious effect on the resolution achieved.

Errors in the measurement of recoil angles will have a greater effect on the resolution when the angle of recoil is large. This is illustrated in Figure 4, where the peak width at half height for the 10 MeV group is plotted against the maximum value of recoil angle accepted. An approximately linear increase in width is observed, amounting to about 50 per cent. of the lowest value when angles up to $25°$ are included. The experimental points in Figure 4 were obtained for tracks with angles of dip of less than $5°$ in unprocessed emulsion; if angles of dip up to $10°$ are included, the points are raised by about 10 per cent. due to the poorer accuracy achieved in the measurement of dip angles. These effects are quite sufficient to explain the wide variations in peak widths observed in the analysis of resolution by Bird and Spear (1955).

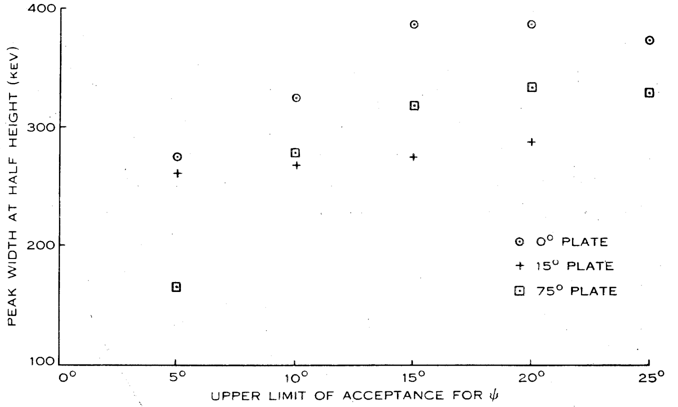

Fig. 4.—Variation of peak width with maximum value of acceptance of ψ (10 MeV neutron group, dip angles in unprocessed emulsion less than $5°$).

The best value of peak width for the 10 MeV group was obtained by considering only tracks with recoil angles less than $5°$. In order to obtain a statistically reliable estimate the results for the three plates were combined, allowance being made for the small differences in mean neutron energies at the three angles concerned. The peak so obtained gave a value of 250 ± 25 keV for the half width at a neutron energy of $9\cdot7$ MeV. After correcting for target thickness the value of 245 ± 25 keV was obtained. Applying a similar analysis to the neutron group corresponding to the ^{12}C ground state gave a peak width of 360 ± 50 keV for a mean neutron energy of $13\cdot9$ MeV.

The peak width at $9\cdot7$ MeV lies close to an extrapolation of the best values obtained in other experiments at lower energies (see curve II of Figure 2, Bird and Spear 1955). This suggests that possible effects due to variations in emulsion shrinkage or density are small, and that this value is close to the optimum resolution at this energy.

The best statistically reliable values for peak width at 14 MeV obtained from published spectra for various studies of the reactions $^{11}B(d,n)^{12}C$ and $^{7}Li(d,n)^{8}Be$ appear to be those of Trumpy, Grotdal, and Graue (1952) and Gibson and Prowse (1955). The widths obtained for these spectra, assuming the peak width at half height to be $2 \cdot 35$ times the calculated standard deviation, are 460 and 410 keV, respectively. This would indicate that the value 360 ± 50 keV is close to the optimum resolution to be expected at this energy, so that the present results may be used to obtain a curve indicating the optimum resolution for emulsion measurement of fast neutron energies up to 14 MeV.

IV. Angular Distributions

Tracks between 130 and 350 μ long were measured at angles of 0, 15, 30, 45, 75, 105, and 135° to the direction of the incident deuterons, and an energy spectrum drawn in each case for those tracks with dip less than 10° and ψ less than 20°. Tracks with single scattering of more than 10° were neglected. At each angle two peaks were observed, of approximately equal height in most cases. Although the peaks were not completely separate, there was no difficulty in deciding the numbers of tracks to be allocated to the reactions involving

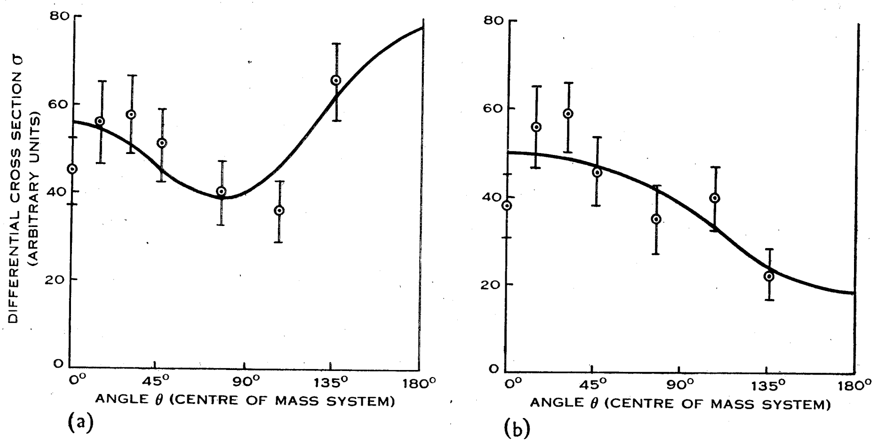

Fig. 5.—Angular distributions of neutrons emitted in deuteron bombardment of boron at 920 keV.

(*a*) $^{11}B(d,n)^{12}C$, $7 \cdot 66$ MeV state group. Full curve represents
$$\sigma(\theta) = 40 - 11 \cos\theta + 27 \cos^2\theta.$$

(*b*) $^{10}B(d,n)^{11}C$, ground state group. Full curve represents
$$\sigma(\theta) = 39 + 16 \cos\theta - 5 \cos^2\theta.$$

the $7 \cdot 66$ MeV level of ^{12}C and the ground state of ^{11}C. These numbers were corrected for loss of tracks through the surfaces of the emulsion, variation with energy of the neutron-proton scattering cross section, relative areas scanned on each plate, thickness of emulsion, and distance from target. The results obtained after conversion to centre of mass coordinates are shown in Figure 5. The errors indicated are statistical.

Graue (1954) has made the only previous measurement of the angular distribution of neutrons from $^{11}B(d,n)^{12}C$ to the $7 \cdot 66$ MeV excited state in ^{12}C.

His results, obtained using 850 keV deuterons, suffered from large statistical errors, but showed no deviation from spherical symmetry of greater than 25 per cent. In the present case the distribution was fitted by the method of least squares to a polynomial in cos θ. The curve shown in Figure 5 (*a*) is that for

$$\sigma(\theta)=40-11\cos\theta+27\cos^2\theta.$$

The fact that this gives a satisfactory fit to the experimental points indicates that the reaction leading to the 7·66 MeV level in ^{12}C can be explained in terms of compound nucleus formation. The asymmetry represented by the cos θ term suggests the presence of interference due to the participation of several levels in the compound nucleus. However, the stripping curve for $l_p=1$, calculated from the theory of Bhatia *et al.* (1952), is similar to a $\cos^2\theta$ curve, so that the possibility of some contribution from stripping at forward angles cannot be ruled out. The stripping curve for $l_p=0$ has a narrow peak at 0°, and that for $l_p=2$ is peaked at about 60°, so that these could only be involved to an even smaller extent. Thus no conclusive evidence can be obtained concerning the properties of the 7·66 MeV level of ^{12}C, although the results are consistent with the usual assumption of even parity and zero spin.

The distribution shown in Figure 5 (*b*) for the ground state group of the $^{10}B(d,n)^{11}C$ reaction is similar to that observed by Paris and Endt (1954) for 600 keV deuterons, and can be fitted by the curve

$$\sigma(\theta)=39+16\cos\theta-5\cos^2\theta.$$

The distribution is definitely asymmetric about 90°, which may be explained either by the occurrence of stripping of type $l_p=1$, or by compound nucleus formation with interference occurring between several levels of the compound nucleus.

V. ^{12}C Level Scheme

The *Q*-values obtained for the various neutron groups from the $^{11}B(d,n)^{12}C$ reaction are shown in Table 1. (After allowing for target thickness and the effects of surface contamination, the mean deuteron energy was taken as 885 keV.)

Table 1

Observed *Q*-values for neutron groups from $^{11}B(d,n)^{12}C$ reaction

All energies in MeV

Angle	Ground State Group	Group to First Excited State	Group to Second Excited State
0°	13·61	9·24	6·04
15°	13·64	9·23	6·05
75°	13·65	9·27	6·09
Mean	13·63±0·05	9·25±0·04	6·06±0·09

The probable error for the second excited state group is relatively large because of incomplete separation from the $^{10}B(d,n)^{11}C$ ground state group. The *Q*-value for the ground state group is significantly lower than the value calculated using the atomic masses (13·724 MeV); this discrepancy may be due to a difference between the densities of the emulsions used in the present work and those used by Gibson, Prowse, and Rotblat (1954) in determining the range-energy relation. From the observed Q-values, values of $4 \cdot 38 \pm 0 \cdot 08$ and $7 \cdot 57 \pm 0 \cdot 11$ MeV are obtained for the excitation energies of the first and second excited states of ^{12}C relative to the ground state. The latter value is in reasonable agreement with the value of $7 \cdot 658 \pm 0 \cdot 027$ MeV obtained by Ahnlund (1956) from magnetic analysis of the $^{14}N(d,\alpha)^{12}C$ reaction.

In an analysis of the α-particle model for ^{12}C, Glassgold and Galonsky (1956) have suggested an excited state at 5·53 MeV. Moak and Galonsky (1956) studied the reaction $^{10}B(^{3}He,p)^{12}C$, and found no evidence for such a level, concluding that if it exists then some selection rule suppresses its participation in the reaction. Since such a selection rule would not prevent the level participating in the $^{11}B(d,n)^{12}C$ reaction, a search has been made for neutrons with appropriate energy on the plates (0, 15, and 75°) on which long tracks were measured. For neutron energies corresponding to excitation energies in the range 5·1–6·6 MeV in ^{12}C, a total of 5 tracks was found on the three plates. At the same time 156 tracks were observed in the ground state group and 505 in the first excited state group. Thus, after making corrections for the variation with energy of the neutron-proton scattering cross section and the loss of tracks through the surfaces of the emulsion, an upper limit for the intensity of any group corresponding to an excited state at about 5·5 MeV in ^{12}C may be set at 1 per cent. of the intensity of the first excited state group, or 2 per cent. of the intensity of the ground state group. In view of the negative results from these two experiments, the existence of the predicted level appears improbable.

VI. Acknowledgments

The authors are grateful to Professor Sir Leslie Martin and Dr. D. N. F. Dunbar for their helpful interest in this work. Thanks are also due to Mr. D. F. Hebbard for measuring the target thickness by magnetic analysis. One of the authors (R.H.S.) is indebted to Imperial Chemical Industries of Australia and New Zealand Ltd. for a Research Fellowship.

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