NEUTRONS EMITTED IN THE DISINTEGRATION OF BERYLLIUM BY DEUTERONS

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Summary

Neutrons obtained by bombarding a thick beryllium target with 600 keV. deuterons were studied by the photographic plate technique at angles of emission of 0, 90, and 150°. Five previously reported neutron groups were confirmed giving energy levels of B^{10} at 0·73, 1·75, 2·20, and 3·64 MeV. An additional group corresponding to an energy level of 2·85 MeV. was observed and the evidence for regarding these as genuine beryllium neutrons is discussed. The Q-value for the ground state transition is found to be $4 \cdot 35 \pm 0 \cdot 02$ MeV. which agrees with the value $4 \cdot 36 \pm 0 \cdot 04$ deduced from the most recent masses.

I. INTRODUCTION

The energy spectrum of the neutrons obtained from deuteron bombardment of beryllium was first investigated with cloud chambers by Bonner and Brubaker (1936) and Staub and Stephens (1939), and their results indicated the presence of energy levels in B^{10} at 0·7, 2·2, and 3·6 MeV. An early demonstration of the photographic plate technique for neutron detection gave similar results (Powell 1943). Whitehead and Mandeville (1950) using Ilford C_2 emulsions showed the presence of a further level at 5·1 MeV.

Using a bombarding energy of 3·4 MeV. and a thin beryllium target, Ajzenburg (1951) demonstrated that neutrons hitherto attributed to the D–D reaction were in fact a genuine beryllium group, and reported levels at 4·8 MeV. and higher energies. Pruitt, Hanna, and Swartz (1952) obtained similar results.

A study of the reaction $Li^7(\alpha,n)B^{10}$ by Haxel and Stuhlinger (1939) indicated levels at 0·8, 1·3, and 2·1 MeV.

The γ-radiation from the excited B^{10} nucleus, has been studied by Rasmussen, Hornyak, and Lauritsen (1949) who suggested levels at 0·412, 0·713, 1·017, 1·42, 2·14, 2·86, 3·58, and 5·16 MeV. and commented on the possible existence of an equally spaced set of levels 0·713 MeV. apart. Not all of these levels, however, are necessary to explain the observed γ-radiation.

The purpose of the present experiment was to investigate further the possibilities of weak neutron groups from this reaction and verify the existence of the 1·79 MeV. level reported by Ajzenburg.

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II. Experimental Technique

A thick target of beryllium metal 2 mm. in diameter mounted on a thin copper disc was bombarded for 100 μAh. by a 600 keV. deuteron beam. Preliminary investigations using a thin evaporated target gave insufficient yield for the detection of weak neutron groups.

Quarter sections of 50μ Ilford C_2 plates were placed at various angles to the incident deuteron beam and with the surface of the emulsion in the direction of the neutron flux. The plates were supported by fine wires inside a thin-walled brass doughnut at a distance of 12 cm. from the target. The two straight edges of each quarter section were used to locate the plates to within $0 \cdot 5°$ of the required angles.

Prior to use the plates were vacuum dried overnight and a phosphorus pentoxide drying agent was used to prevent absorption of moisture by the emulsion during the exposure period.

III. Measurements

Measurements were made on plates exposed at 0, 90, and 150° to the deuteron beam over areas subtending $\pm 1°$ at the target. The range distribution of the proton recoil tracks was measured at two magnifications covering the energy intervals 0–3 and 2–5 MeV. respectively. Proton recoils were selected which made an angle of not more than 5° with the neutron direction. This was effected by accepting tracks whose initial direction lay within 5° lines marked on an eyepiece graticule, and whose angle of dip in the unprocessed emulsion was less than 5°. Taking into account the known depth of focus of the objectives used and the emulsion shrinkage factor (Martin 1949) the restriction on the angle of dip requires that the beginning of the tracks be in focus for 10 and 20μ at high and low magnification respectively.

The eyepiece scales used for range measurements were calibrated against a Grayson ruling, which had been checked with a Hilger travelling microscope, and all range determinations are considered to be accurate to within $0 \cdot 3$ per cent.

A total of 4200 tracks which had their whole length within the emulsion was recorded.

The observations were plotted as energy distributions in intervals of 100 keV. using a range-energy curve deduced from the work of El-Bedewi (1951), Rotblat (1951), and Dyer (1952).

These distributions were then corrected for the variation with energy of the neutron-proton scattering cross section (Bailey *et al.* 1946 ; Lampi, Freier, and Williams 1950) and the loss of tracks from the emulsion (Richards 1941).

At each angle the observations for the two magnifications were then normalized using the overlapping regions. The angular distribution of the low energy peak was measured separately under constant conditions of observation and used to adjust the ordinate scale of the three curves to express the actual variation of neutron intensity (Fig. 1).

IV. Analysis of Results

In order to obtain the " mean thin target " energy for each neutron group it was necessary to make a thick target correction and the results for each peak

RAIN FROM NON-FREEZING CLOUDS

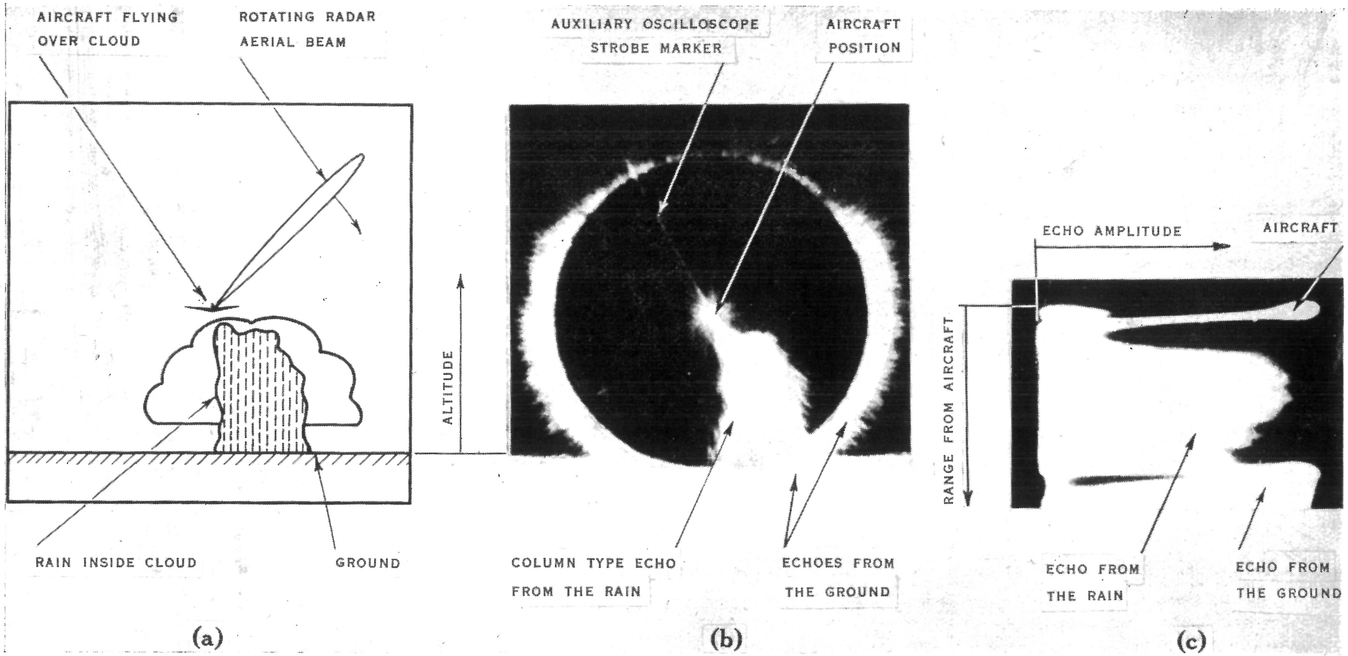
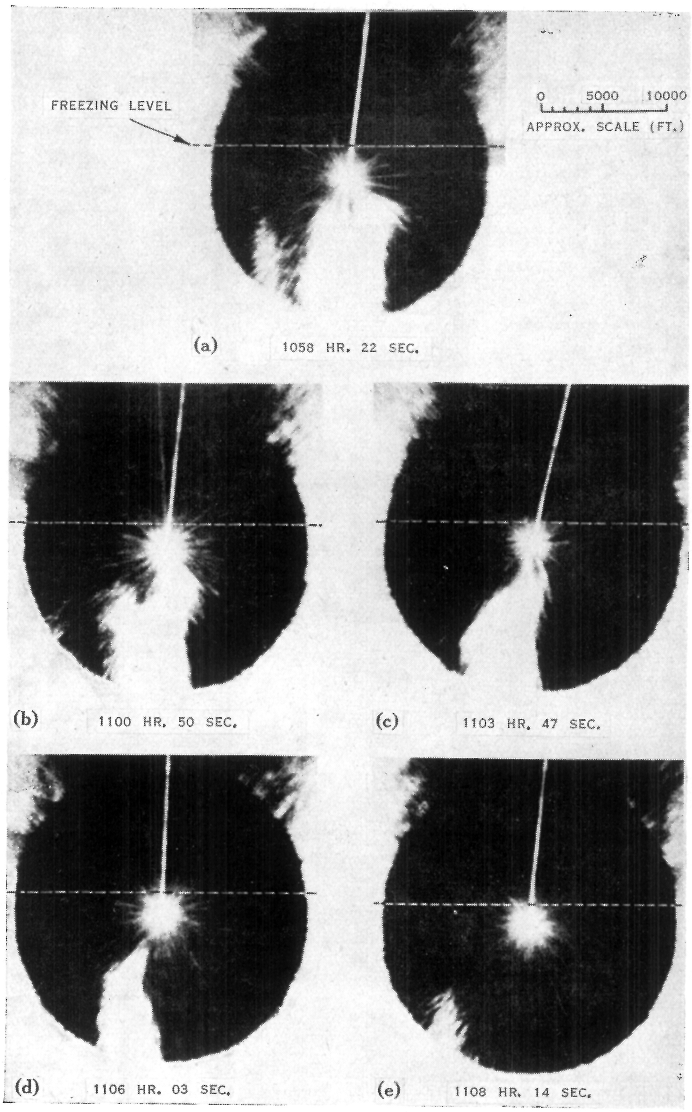


Diagram illustrating the principle of the airborne radar display.

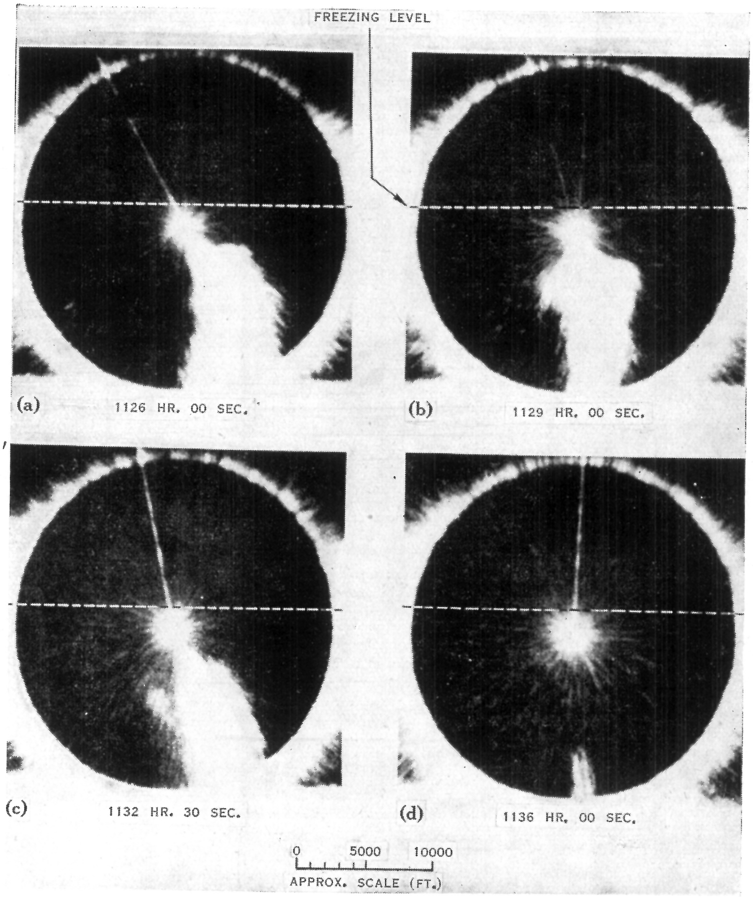
(*a*) Aircraft fitted with the radar set is depicted flying above a raining cloud.
(*b*) The corresponding display of the radar echoes from the rain on a position indicator oscilloscope.
(*c*) The corresponding radar echo intensity down through the rain displayed on an amplitude-range oscilloscope.

RAIN FROM NON-FREEZING CLOUDS



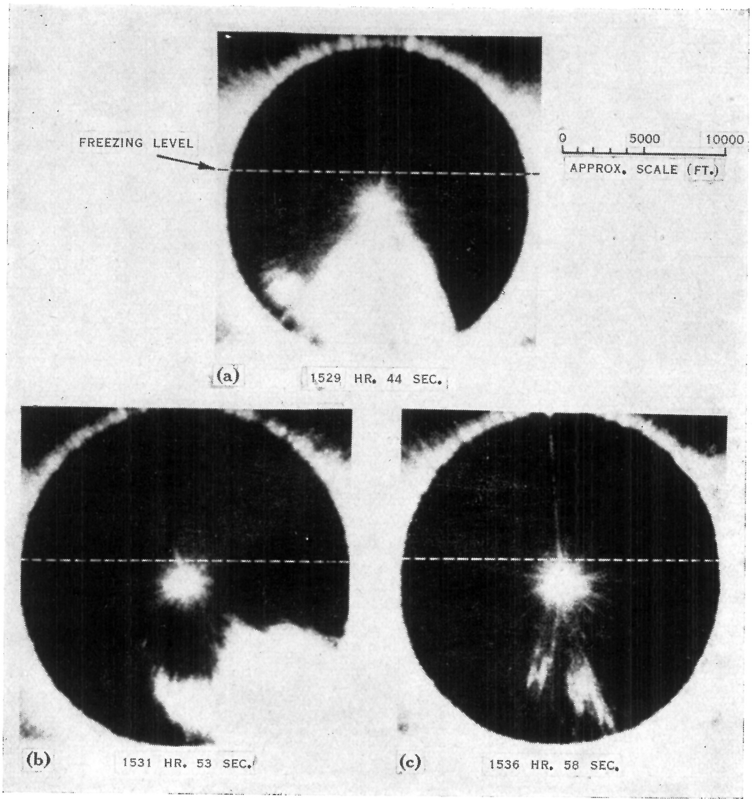
Airborne radar echoes from rain falling from non-freezing cloud on January 11, 1951 (Cloud No. 1).

RAIN FROM NON-FREEZING CLOUDS



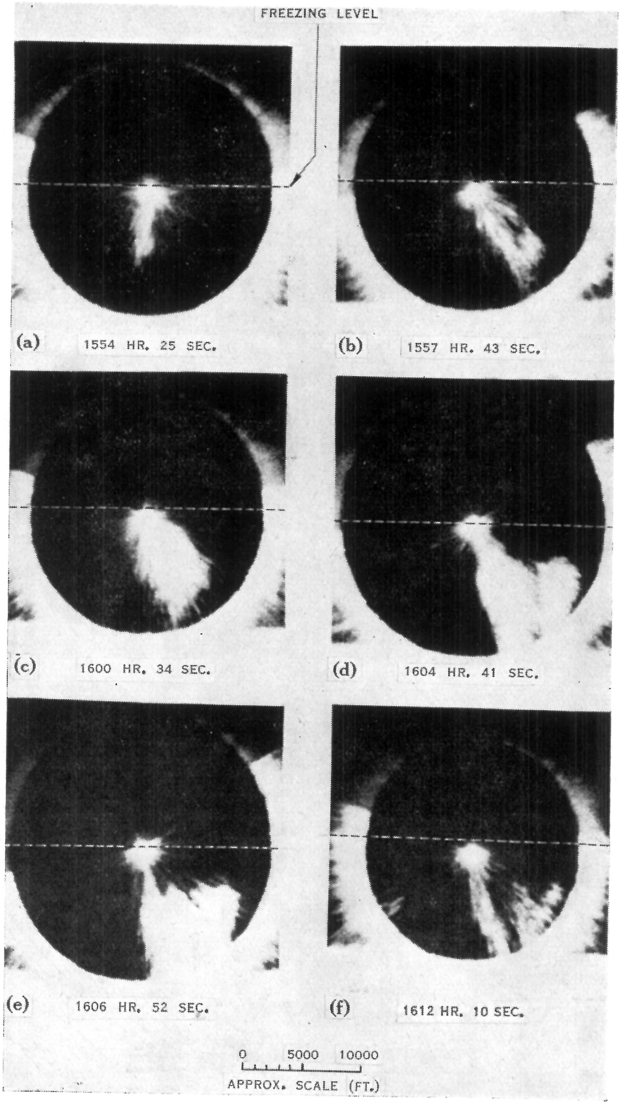
Airborne radar echoes from rain falling from non-freezing cloud on January 11, 1951 (Cloud No. 2).

RAIN FROM NON-FREEZING CLOUDS



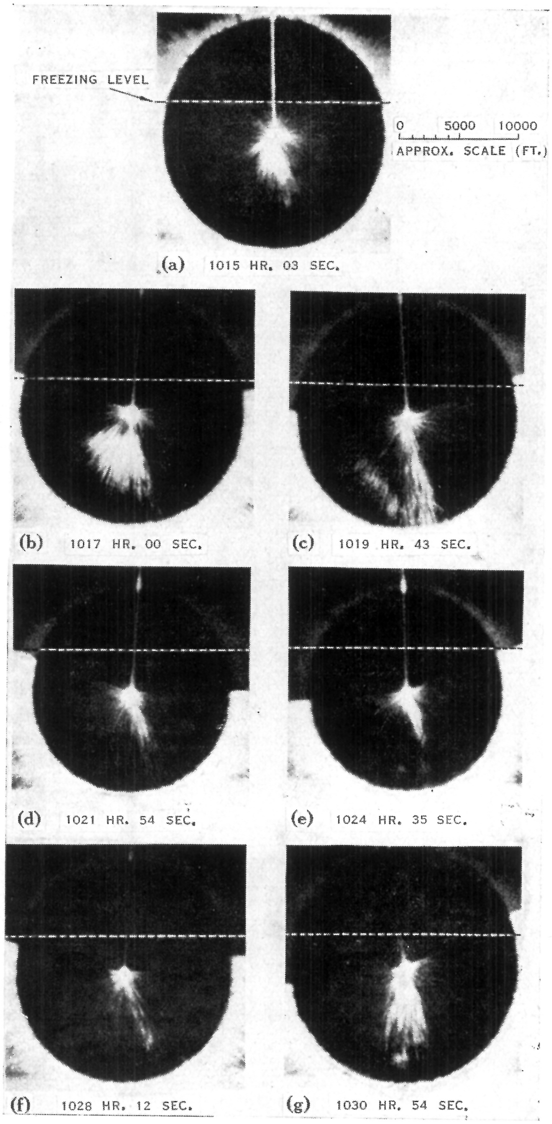
Airborne radar echoes from rain falling from non-freezing cloud on January 23, 1951.

RAIN FROM NON-FREEZING CLOUDS



Airborne radar echoes from rain falling from non-freezing cloud on January 24, 1951.

RAIN FROM NON-FREEZING CLOUDS



Airborne radar echoes from rain falling from non-freezing cloud on March 22, 1951.

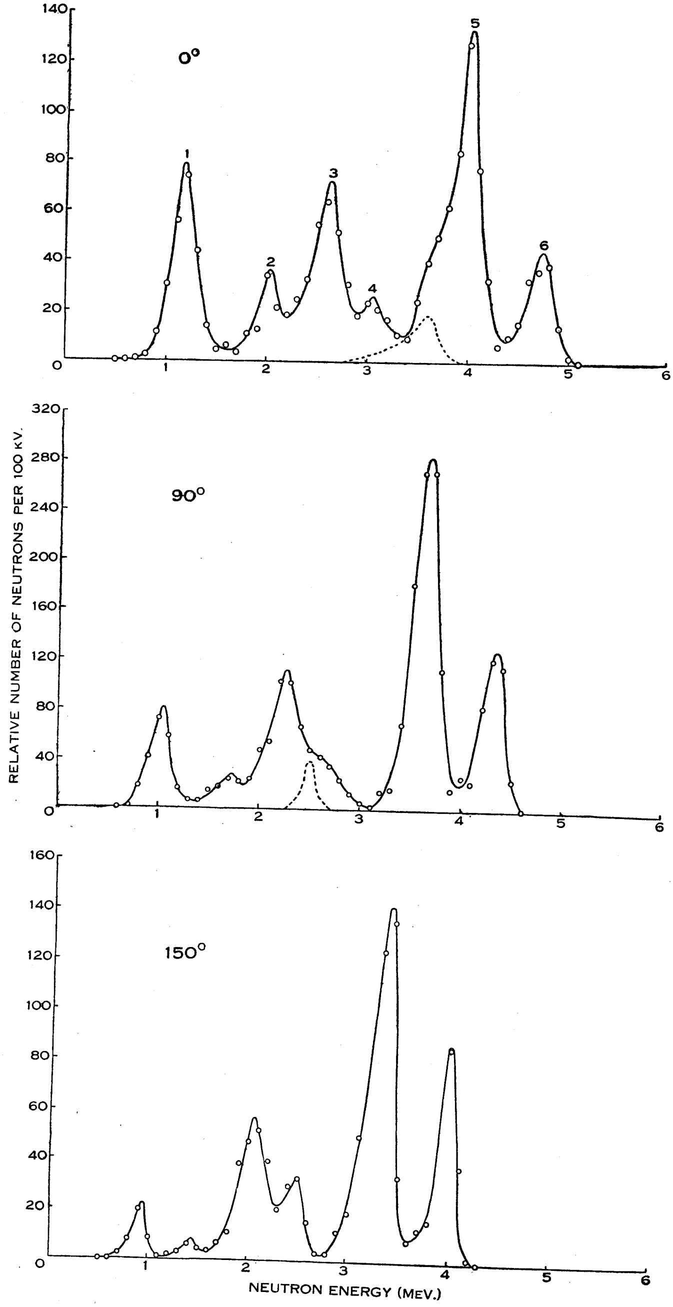


Fig. 1.—Neutron spectra.

were put into the integral form. This is a straightforward procedure for well-separated peaks (e.g. peak 6) but where overlapping peaks occur a suitable shape for each must be deduced.

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Livesey and Wilkinson (1948) showed that a differential thick target distribution can be expressed in the analytic form

$$f(y)=e^{-2\lambda y}\left\{1-\operatorname{erf}\left(\lambda\sigma-\frac{y}{\sigma}\right)\right\},$$

where the abscissa y is measured from the mean thin target energy. This expression is obtained by superposing a Gaussian straggling distribution of

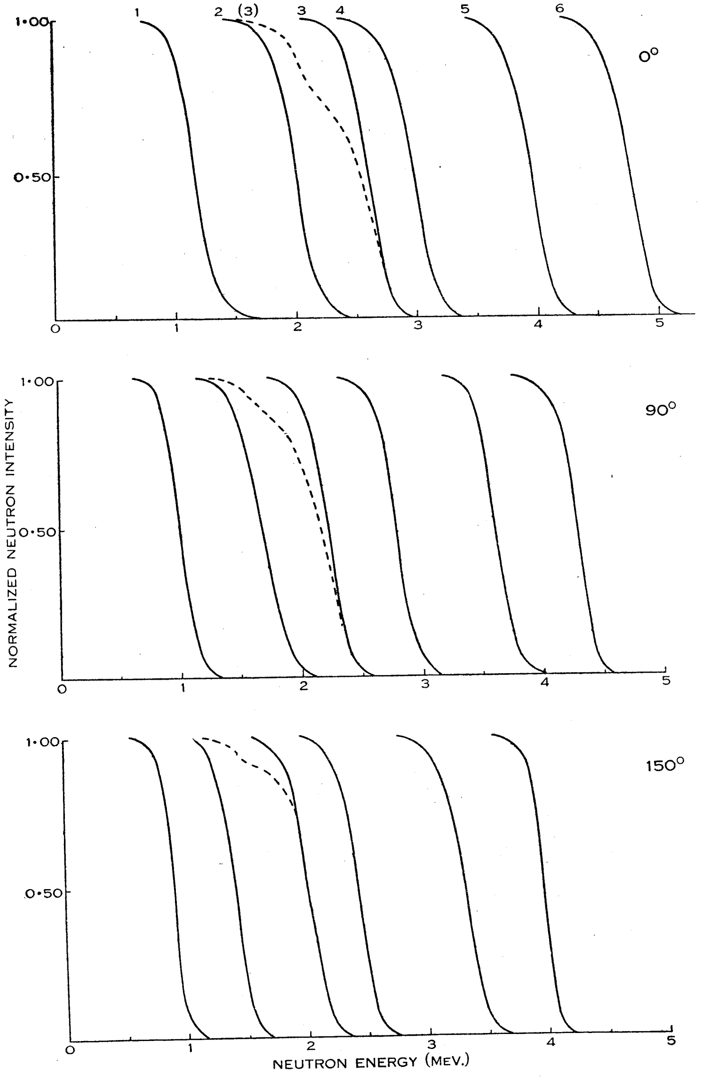

Fig. 2.—Normalized integral curves.

variance σ^2 on an exponential function $e^{-2\lambda y}$, which describes the theoretical neutron spectrum deduced from the excitation function. A value of σ of about 0·2 MeV. was found to fit the observed straggling and two sets of theoretical integral curves were drawn with σ equal to 0·16 and 0·24 MeV. for a range of λ of 1–9 MeV.^{-1}.

From the dynamics of the reaction it is expected that λ will be independent of energy for neutrons observed at 90° and will slowly decrease with energy at 0° and increase at 150°. Making use of this information together with the theoretical curves, the overlapping peaks were resolved and values of λ and σ found which fitted the observations in every case. In this way a set of curves for each spectrum was obtained and the total number of tracks in each curve was normalized to unity (Fig. 2).

The mean thin target energy can be obtained by the method of Livesey and Wilkinson in which the extrapolated energy from the theoretical curve is applied as a correction to the experimental extrapolated energy. This requires the drawing of the steepest gradient which is an inherently difficult procedure. An alternative method is to determine the fraction of the total number of particles having an energy greater than the mean thin target energy from the theoretical curve, and to find the energy for which this fraction occurs on the experimental curve. In most cases the results obtained by the two methods were nearly identical and a mean value was accepted. For those cases in which a discrepancy occurred it was felt that the second method gave a more reliable result. The Q-values obtained from these energy values were tabulated and a mean determined by weighting each according to the square root of the number, N, of tracks represented (Table 1).

Table 1

Q-VALUES FOR INDIVIDUAL NEUTRON GROUPS AT DIFFERENT ANGLES OF EMISSION

The errors expressed are probable errors

Angle \ Peak No.	1	$\sqrt{N}$	2	$\sqrt{N}$	3	$\sqrt{N}$	4	$\sqrt{N}$	5	$\sqrt{N}$	6	$\sqrt{N}$
0°	0·70	18	1·52	10	2·15	19	2·58	12	3·58	16	4·35	9
90°	0·72	13	1·51	8	2·10	14	(2·70)	5	3·61	19	4·35	11·5
150°	0·75	7	1·39	4	2·17	14	2·63	11	3·65	25	4·35	11
Mean	0·71±0·02		1·50±0·03		2·15±0·02		2·60±0·02		3·62±0·02		4·35±0·02	

The values tabulated correspond to the peaks numbered 1 to 6 in Figure 1. The dotted peaks are attributed to D–D neutrons and give a mean Q-value of 3·25±0·06 MeV. which is in excellent agreement with the result of Livesey and Wilkinson (1948). The Q-value obtained for neutrons observed at 90° for peak 4 was not used in calculating the mean value for this group since it depended very strongly on the intensity allotted to the D–D group immediately next to it. The Q-value of the ground-state transition 4·35±0·02 MeV. agrees with the value of 4·36±0·04 MeV. deduced from the most recent masses (Li *et al.* 1951).

V. Discussion

Peaks 1, 3, 5, and 6 are well-established beryllium neutron groups and peak 4 confirms the existence of the doublet reported by Ajzenburg (1951). Peak 2 has not been previously observed but since measurements were taken at three angles of emission, it is possible to check that it is a genuine beryllium group.

It can be seen from Table 1 that the Q-values for peak 2 obtained at 0 and 90° are in excellent agreement, while the value at 150° is still statistically significant. This can be investigated further by plotting the energy shifts $E_0 – E_{90}$ and $E_{90} – E_{150}$ against E_0 and E_{150} respectively, for each neutron group (Fig. 3).

It can be shown from the dynamics of a nuclear reaction that

$$E_0 – E_{90} = 2 \cdot 19 \sqrt{E_0} / (M+2)$$
$$E_{90} – E_{150} = 1 \cdot 90 \sqrt{E_{150}} / (M+2),$$

where M is the mass of the target nucleus. These expressions have been included in Figure 3 for a range of values of M. The experimental points lie about the

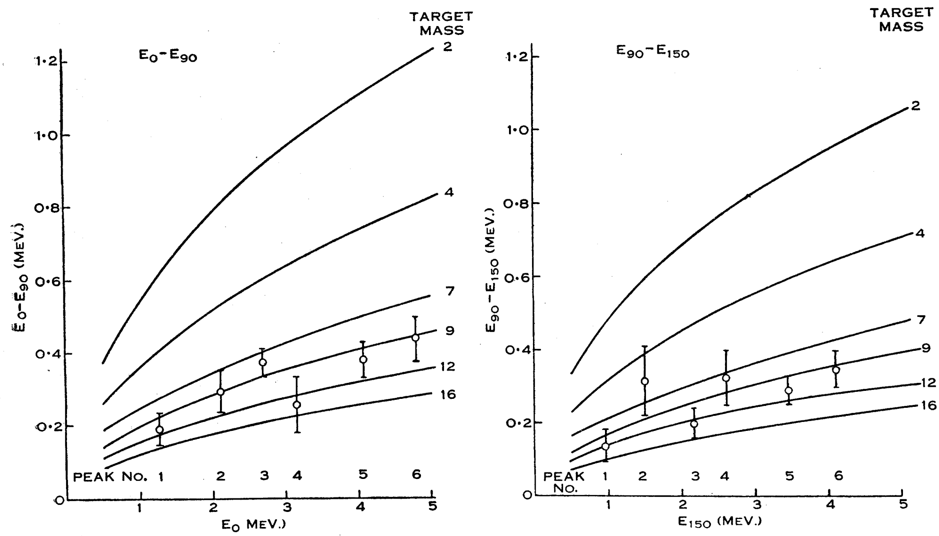

Fig. 3.—Energy shift curves.

curve $M=9$. Peak 2 could only arise from a reaction involving a target nucleus of mass <14, and no such neutron reactions giving these energies at the three angles are known.

If it is assumed that peak 2 does not exist, the integral curves for peak 3 are given by the dotted lines in Figure 2. The deviations of these curves from the required shape is far greater than can be explained by statistical fluctuations.

At a bombarding energy of 3·41 MeV. and using a thin target Ajzenburg (1951) reports that no neutrons were observed corresponding to this group. This author states that at a high bombarding energy one would expect that a large number of levels of the compound nucleus covering a wide range of angular momenta and of either parity would be involved in the reaction. Neutron groups should thus be observed corresponding to all existing levels of B^{10}. It must be pointed out, however, that the relative intensities of the various groups observed indicate that a considerable degree of competition between the various modes of neutron emission is still taking place. The possibility that a weak neutron group would escape detection under these circumstances, but would be observed for lower bombarding energies with a thick target is, therefore, not entirely ruled out.

It is interesting to note that, in the work of Staub and Stephens (1939) and Powell (1943) using a low bombarding energy and a thick target, there is in fact some evidence of a weak neutron group in this region which has been previously ignored. Since both these observations were made at an angle of 90° to the incident deuterons, the expected intensity would be small.

VI. Energy Levels in B^{10}

The Q-values in Table 1 lead to the energy levels of B^{10} presented in Figure 4, together with the corresponding values found by Ajzenburg (1951) and Pruitt,

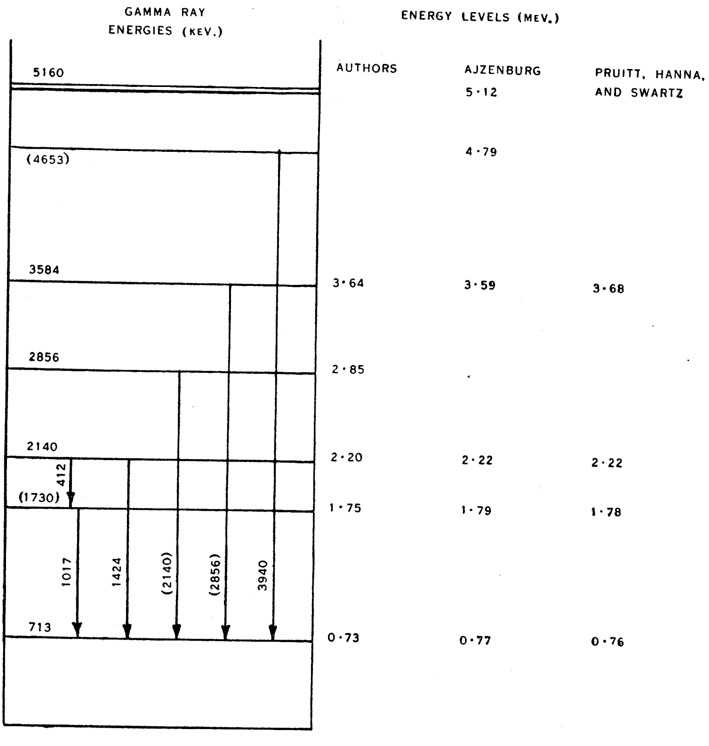

Fig. 4.—Energy levels in B^{10}, showing possible γ-ray transitions in addition to ground-state transitions.

Hanna, and Swartz (1952). It is reasonable to assume that the energies of the lower levels will be given more accurately by γ-ray determinations. The values obtained by Rasmussen, Hornyak, and Lauritsen (1949) are also shown in Figure 4.

The level scheme is essentially that proposed by Ajzenburg. All neutron measurements give consistently higher energy values than the γ-ray results but the agreement appears to be better in our case. The additional level at 2·86 MeV. gives a consistent explanation of the observed γ-rays as an alternative to the scheme of Ajzenburg. This level, together with the one at 1·3 MeV. reported by Haxel and Stuhlinger (1939) from the reaction $Li^7(\alpha,n)B^{10}$, again raises the possibility of equally spaced levels suggested by Rasmussen, Hornyak, and Lauritsen. No neutrons were observed, however, corresponding to a level at 1·4 MeV., and some explanation would be required for the raised levels at 1·73 and 4·65 MeV.

It is not possible to check the validity of the proposed level scheme by a comparison of neutron and γ-ray relative intensities, and no confirmatory evidence is available from other reactions giving rise to low-lying levels in B^{10}. Further work on neutron resonances and γ-rays is therefore desirable to check the existence and position of the energy levels.

VII. Acknowledgments

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