INFORMATION ON ENERGY LEVELS IN ^{8}Be FROM NEUTRON ENERGY SPECTRA*

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Introduction

A number of measurements have been made of the neutron energy spectra emitted in the reaction ^{7}Li(d,n)^{8}Be, and, as is the case for other reactions leading to the same final nucleus, contradictory conclusions have been reached as to the number of levels observed.

Using nuclear emulsions as neutron detectors, early thick target experiments by Richards (1941) and Green and Gibson (1949) suggested the possibility of levels in ^{8}Be at 4·1, 5·3, and 7·5 MeV in addition to the well-known 3 MeV state. Trumpy, Grotdal, and Graue (1952), with somewhat better resolution,

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obtained similar results, and suggested the existence of a further level at 2·2 MeV, while Catala, Aguilar, and Busquets (1953) claimed to have resolved levels at 1·5, 2·2, 2·9, 3·4, 4·1, 5·3, and 7·5 MeV. However, Trail and Johnson (1954*a*, 1954*b*), using a neutron spectrometer to obtain good statistics, found no evidence for levels below 10 MeV excitation other than the broad 3 MeV state. Another neutron spectrometer experiment by Reid (1954) produced evidence for the 5·3 MeV level; but Ihsan (1955*a*, 1955*b*), again using nuclear emulsions, reached similar conclusions to Trail and Johnson.

In view of the possibility of theoretical interpretation of the ^{8}Be level scheme a further study has been made of this reaction and the results of an investigation of the resolution achieved in the measurement of neutron energies have been used to analyse the results of this and previous experiments.

Experimental Results

A 50 keV thick target of separated ^{7}Li obtained from a small isotope separator was bombarded by 920 keV deuterons for an integrated target exposure of 25,000 μC. Neutrons were detected with 400 μ Ilford C2 emulsions, using the camera and target arrangement described by Bird (1955), and the plates

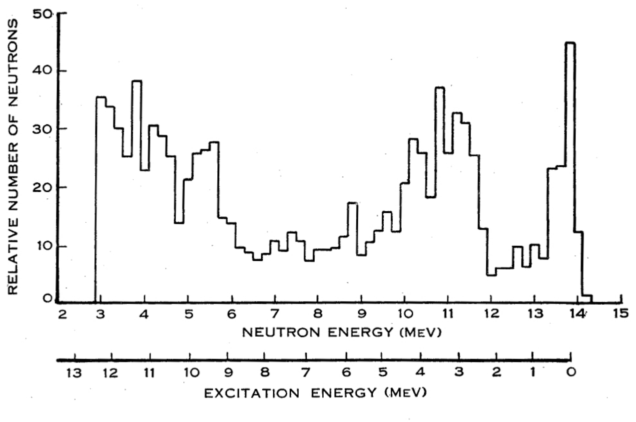

Fig. 1.—Energy spectrum of neutrons from ^{7}Li(d, n)^{8}Be.

were studied using the same measuring procedure. The neutron energies were obtained using the range-energy relation given by Gibson, Prowse, and Rotblat (1954). The results for 1200 tracks measured at 90° are shown plotted in 200 keV intervals in Figure 1; and a further 400 tracks at 45° gave similar results. Corrections have been made for the loss of tracks from the emulsion and the variation of the neutron proton scattering cross section. The correction factor has been normalized to unity at 9·7 MeV and increases to 1·4 at 14 MeV.

The spectrum is similar to that published by Trumpy, Grotdal, and Graue (1952) and shows no indication of the fine structure reported by Catala, Aguilar, and Busquets (1953). In a comparison of the various experiments it is important to consider the resolution achieved in each case and to compare this with the performance necessary to distinguish between the neutron groups corresponding to the various proposed levels.

The Straggling of Protons and Neutrons in Nuclear Emulsions

The peak widths observed in the study of neutron energy spectra using nuclear emulsions contain contributions from the straggling of proton ranges and the uncertainties in measurement of track lengths and recoil angles.

The straggling of monoenergetic protons in Ilford C2 emulsions has been studied by various authors but the results obtained show considerable variations. The first measurements, summarized by Dyer (1952), suggest that the straggling expressed as a percentage of the total proton range is considerably higher than the corresponding values for air at low proton energies and approaches the air straggling at energies of 4–5 MeV. However, the results of Han and Endt (1954) are higher than the air straggling at 8–9 MeV, while those of Barkas, Smith, and Birnbaum (1955) at 33 MeV are lower.

Measurements have been made of the straggling of the proton tracks used by Bird and Hines (1954) in a study of the multiple scattering of monoenergetic protons. These tracks were obtained using a similar experimental procedure to that used by Dyer (1952), but with better geometry, giving a smaller spread in energy and direction of the protons. The range of approximately 300 tracks was measured at each of a number of proton energies, accepting only those tracks which were free from marked multiple scattering. The standard deviations of the observed range distributions were used to give the width at half height of the corresponding energy distributions.

The " Cellophane " absorbers, used to prevent scattered deuterons from reaching the photographic plate, contribute to the observed range straggling, and the results obtained using one, two, and three thicknesses of " Cellophane " were plotted against thickness and a smooth curve drawn through the points corresponding to each value of incident proton energy. The widths obtained by extrapolating each curve to zero thickness have been corrected for the effect of target thickness and are shown in Figure 2 (*a*), together with the results from other experiments and the equivalent air straggling (curve I, as given by Livingston and Bethe (1937)). The present results fall between those of Dyer and of Han and Endt, and are considerably higher than the air straggling. Curve II has been drawn to give the characteristic proton resolution for C2 emulsion, although its position is not uniquely defined, particularly at low energies.

Explanations of the greater straggling in emulsions than in air, have been given by Wilkins (1952) and Barkas, Smith, and Birnbaum (1955). Statistical fluctuations in the relative amounts of gelatin and silver halide traversed by each proton and the possible random movement of developed grains during the shrinkage of the processed emulsion will increase the straggling in each experiment by the same amount. However, the effects of processing techniques on the size and spacing of the developed grains will not be the same and may alter the observed straggling appreciably. For example, the grain spacing observed at the beginning of 5–10 MeV proton tracks, using the temperature method of development, would give an estimated increase in the straggling variance of about 1 per cent. of the mean range. This will affect the results of Han and Endt but not those of Dyer or the present straggling measurements, which were obtained using a much stronger development. Also, the corrections for the effects of irregularities in absorber thickness, varying techniques in the selection and measurement of track lengths, and the straggling in energy of the incident particles have been made in different ways in each experiment, and may be responsible for part of the observed differences in results.

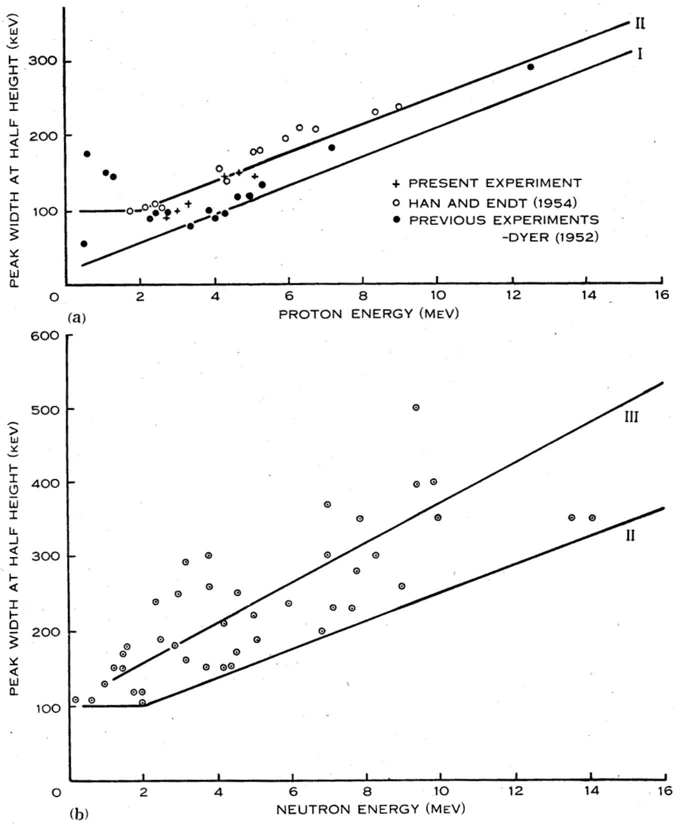

Fig. 2 (*a*).—Proton straggling. Curve I, equivalent air straggling; curve II, mean proton straggling.

Fig. 2 (*b*).—Neutron straggling. Experimental points from Gibson (1949), Nereson and Reines (1950), Ajzenberg (1952), Johnson (1952), Stelson and Preston (1952), Benenson (1953), Pruitt, Swartz, and Hanna (1953), Bird (1954), and Graue (1954). Curve II, as in Figure 2 (*a*) ; curve III represents average neutron straggling.

In the measurement of neutron energies by observation of recoil protons in nuclear emulsions an uncertainty of 2° in the measurement of each recoil angle will give an increase in straggling of the order of 10 per cent., but the actual increase will depend on individual measuring conditions. Figure 2 (*b*) shows values of the width at half height of neutron peaks from spectra published by a number of authors, plotted against neutron energy. These values have been corrected for the effects of target thickness. The results show large variations at all energies and the average values represented by curve III are approximately 50 per cent. higher than the corresponding proton straggling (curve II from Figure 2 (*a*)). Although a number of the observed widths are close to the proton curve, many are so high that additional neutron straggling is required to explain them. The large widths of neutron peaks has been noted by Ajzenberg (1951) and is in agreement with the high values of the straggling variance required to explain the shape of thick target neutron peaks (Dyer and Bird 1953).

Any small angle scattering of the neutrons before they produce proton recoils will give an additional spread in energy and direction. The presence of scattering is shown by the asymmetry which is typical of many thin target neutron peaks, and this asymmetry has been found to increase with the distance of the area of measurement from the leading edge of the photographic plate, accompanied by a decrease in the estimated number of neutrons per unit solid angle. These changes are more marked at low energies owing to an increase in the neutron scattering cross section. The scattering which occurs in the photographic plate may often be more significant than the scattering in the material of the camera used for exposing the plates, and should be considered in the design of experiments requiring good resolution or the accurate measurement of neutron energies and angular distributions.

Discussion

Since the ground state of ^{8}Be is known to have a small natural width, the observed ground state peak width in each of the studies of ^{7}Li(d,n)^{8}Be may be used, in conjunction with Figure 2 (*b*), to indicate the resolution achieved in each case.

The use of thick targets by Richards (1941) and Green and Gibson (1949) is responsible for ground state peak widths of 600–800 keV and would prevent them from observing the fine structure suggested by Catala, Aguilar, and Busquets (1953). The latter experiment shows a ground state peak with a half width of approximately 300 keV, which falls below the proton straggling curve in Figure 2 (*b*), and this has not been achieved by any of the experiments used in the preparation of that figure. Since the experimental techniques used by these authors are similar to those used in other experiments, their suggestion of a fine level structure requires confirmation.

The ground state peak width observed by Trumpy, Grotdal, and Graue (1952) was 470 keV, and in the present experiment a width of 430 keV was obtained. These values fall close to curve III in Figure 2 (*b*) so that this curve may be expected to show the trend of peak widths expected at other neutron energies. This would be adequate to resolve the neutron groups suggested by Catala, Aguilar, and Busquets, and the lack of evidence for all these groups indicates that any excited states that occur in addition to the 3 MeV state must either have considerable widths or be present with small intensity relative to a continuous background of neutrons produced by alternative modes of breakup of the compound nucleus. The recent experiment of Ihsan (1955*a*, 1955*b*) gives a ground state peak width of 600 keV which would be barely sufficient to distinguish between proposed states with a separation of 700 keV.

The performance of neutron spectrometers cannot be analysed in this way, but the experiment by Trail and Johnson (1954*a*, 1954*b*) shows a ground state peak width of 1200 keV which would prevent the observation of fine structure in the neutron groups. Since the experiment by Reid (1954) covered only a small portion of the neutron spectrum it is difficult to compare his resolution with that of other experiments.

All the photographic plate studies of the neutron spectrum since that of Richards (1941) have shown irregularities suggesting the presence of excited states at 4·1, 5·3, and 7·5 MeV. The evidence from any one experiment is not conclusive, but the systematic appearance of these irregularities is significant.*

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* As this paper goes to press Gibson and Prowse (1955) have published preliminary measurements in which a resolution of 300 keV has been achieved. Levels are indicated at 2·1, 2·9, 4·05, and 5·25 MeV.