# A SEARCH FOR LEVELS OF <sup>7</sup>Li BETWEEN 9.0 AND 9.55 MeV EXCITATION

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#### Summary

The cross section of the reaction  ${}^{6}\text{Li}(n,{}^{3}\text{H}){}^{4}\text{He}$  has been measured, with good energy resolution, over the neutron range  $2 \cdot 0 - 2 \cdot 65$  MeV. This corresponds to an excitation of <sup>7</sup>Li from  $9 \cdot 0$  to  $9 \cdot 55$  MeV, a region in which photodisintegration experiments indicate the presence of one or more levels. No resonance structure was observed in this experiment and possible reasons for this are discussed.

#### I. INTRODUCTION

Cross-section measurements for the neutron-induced reaction  ${}^{6}\text{Li}(n,{}^{3}\text{H}){}^{4}\text{He}$ have been made from thermal energies to a maximum neutron energy of  $18 \cdot 3$  MeV (Frye 1954; Weddell and Roberts 1954; Hughes and Harvey 1955; Ribe 1956; Bonner 1958; Kern and Kreger 1958). These results show that, with the exception of the broad *p*-wave resonance at 255 keV, no resonance structure is apparent over the whole of the measured energy range. This is surprising as several fairly well-established levels are known to be present in the compound system,  ${}^{7}\text{Li}^{*}$ .

In the experiments reported here, the cross section of  ${}^{6}\text{Li}(n,{}^{3}\text{H}){}^{4}\text{He}$  was measured, with good energy resolution, over a neutron energy range  $2 \cdot 0 - 2 \cdot 65$  MeV; this corresponds to an excitation of the compound <sup>7</sup>Li system from  $9 \cdot 0$  to  $9 \cdot 55$  MeV where a fairly well-established level of <sup>7</sup>Li is known to be present (Ajzenberg and Lauritsen 1955). From a knowledge of the neutron and triton partial widths which have been established for this level by  $\gamma$ -ray absorption experiments it would appear that, to an order of magnitude, the resonance cross section to this level by neutron absorption in <sup>6</sup>Li should be several hundred millibarns. The experimental techniques used here were sufficiently sensitive so that a 10 per cent. change in the cross-section curve having a 40 keV half-width should be readily detected.

II. EVIDENCE FOR LEVEL OF 7Li AT 9.3 MEV AND ITS POSSIBLE CHARACTER

The existence of a level of <sup>7</sup>Li in the neighbourhood of  $9\cdot 3$  MeV was first demonstrated by Titterton and Brinkley (1953), who used nuclear emulsion techniques to measure the differential cross section of the reaction <sup>7</sup>Li( $\gamma$ ,<sup>3</sup>H)<sup>4</sup>He. Their cross section went through a peak at  $9\cdot 3$  MeV with an experimental halfwidth of several hundred keV. By comparing these results with cross-section measurements which were carried out by Titterton (1953), who used 14.8 and  $17\cdot 6$  MeV  $\gamma$ -rays, from the <sup>7</sup>Li( $p,\gamma$ )<sup>8</sup>Be reaction, an approximate integrated

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cross section of  $0.2 \times 10^{-3}$  MeV barns can be associated with this level. Stoll and Wächter (1953), Erdos et al. (1954), Stoll (1954), and Miwa (1955) have also found resonance absorption of  $\gamma$ -rays between  $9 \cdot 0$  and  $9 \cdot 5$  MeV in similar experiments. Goldemberg and Katz (1954) have measured an integral spectrum for the reaction  $^{7}\text{Li}(\gamma,n)^{6}\text{Li}$ ; their results show a prominent break in the yield curve which they ascribe to a level in <sup>7</sup>Li at 9.6 MeV, and their approximate integrated cross section is also  $0.2 \times 10^{-3}$  MeV barns. Further evidence for the existence of the level has been provided by inelastic scattering data of Allen (1954), who scattered 14 MeV neutrons from 7Li. Silver (1957) has scattered 31.8 MeV protons from 7Li and reported a level of 7Li about 9.6 MeV. Recently. Titterton (personal communication) has remeasured the differential cross section using synchrotron bremsstrahlung of maximum energy 12 MeV. His preliminary results confirm the existence of resonant absorption of  $\gamma$ -rays around 9.3 MeV; the results also eliminate the possibility that the level which is present is populated by  $\gamma$ -ray cascade processes from levels at higher excitation of <sup>7</sup>Li. In this work we have assumed that the 9.3 MeV level, excited by the  $^{7}\text{Li}(\gamma, ^{3}\text{H})^{4}\text{He}$  experiments, is the same level as that found at 9.6 MeV by Goldemberg and Katz (1954).

## III. EXPERIMENTAL

Neutrons from the  $d(d,n)^{3}$ He reactions were used to bombard an enriched <sup>6</sup>LiI(Eu) crystal which served both as the target and scintillation detector for <sup>6</sup>Li neutron-induced reactions within the crystal volume. Energy variation of the neutrons arriving at the crystal was achieved by rotating the <sup>6</sup>LiI crystal about a vertical axis through the heavy ice target, maintaining the deuteron



Fig. 1.—Schematic diagram showing experimental arrangement.

beam energy constant at 350 keV. The neutron flux was monitored by a boronloaded 2 in. scintillation-detector\* placed in line with the <sup>6</sup>LiI crystal as shown in Figure 1.

The crystal detector consisted of a rectangular piece of <sup>6</sup>LiI(Eu) (96 per cent. <sup>6</sup>Li) of density 3.93 g/cm<sup>3</sup> and dimensions 0.525 by 0.534 by 0.090 in. The centre of the crystal was placed  $14.7 \pm 0.2$  cm from the heavy ice target.

\* Nuclear Enterprise Ltd., Ne400 scintillator.

Light pulses from the <sup>6</sup>LiI detector were viewed by a Dumont 6292 photomultiplier whose output was amplified and fed to a pulse height analyser and scaler of known bias level. Figure 2 shows a typical pulse height distribution from the <sup>6</sup>LiI detector recorded for a neutron energy of  $2 \cdot 6 \text{ MeV}$ . The low energy peak, centred around 18 V, is due to the reaction <sup>6</sup>Li( $n,^{3}\text{H}$ )<sup>4</sup>He induced by the background of thermal and epithermal neutrons which are present in the experimental area from scattering and from the carbon contamination in



Fig. 2.—Pulse height distribution from <sup>6</sup>LiI(Eu) detector.

the beam tube. The half-width of this thermal peak is about 8 per cent. for a freshly mounted crystal, and provides a useful calibration line of known width to check the electronics.

The high energy peak in Figure 2 arises from (n,t) reactions induced in the crystal by fast neutrons; it has a half-width considerably greater than the resolution of the equipment. Kern and Kreger (1958), Murray (1958), and Ophel (1958) have shown that this large width is due to the difference between the triton and  $\alpha$ -particle scintillation response, which is effective because centre of mass motion causes the emitted tritons and  $\alpha$ -particles to have a range of energies available to each of them in the laboratory system. The shape of the peak also depends on the angular distribution of the reaction. Spectra taken at various neutron energies showed that the shape of the high energy peak is the

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same over the whole energy range. To carry through a cross-section measurement a bias level was set at a known point in the high energy peak and all events producing a pulse greater than this were taken to be  ${}^{6}\text{Li}(n,{}^{3}\text{H}){}^{4}\text{He}$  events. The bias level was set sufficiently high so that no pulses from the thermal peak were counted by the scaler. Corrections were made to allow for the pulses, from the high energy peak, which were missed because of the high setting of the bias level.

The production of monoenergetic neutrons from the  $d(d,n)^3$ He reaction is made difficult because of the large background of neutrons which are produced in the accelerator beam tube owing to collisions of the beam with the defining stops and from the target backing. Because of this background flux it is necessary to use relatively thick targets, so that the yield is well above the background level. Unfortunately, thick targets reduce the range of the angle  $\theta$  (or neutron



Fig. 3.—Energy resolution of neutrons obtained from a 100 keVthick heavy ice target using an incident deuteron beam of energy 350 keV.

energy) which is available for a given energy resolution. In these experiments a continually replenished target of heavy ice was used. The thickness of the target was monitored by a measurement of the total neutron yield and was maintained throughout at 100 keV. Figure 3 shows the energy resolution of the neutrons obtained from a 100 keV thick target for a deuteron beam energy of 350 keV as a function of the emitted neutron energy and the angle  $\theta$  as calculated from the tables of Fowler and Brolley (1956).

The chief sources of background neutrons in the experimental area were at the analysing-magnet vacuum box, at the defining apertures, and at the backing of the heavy ice target. These background neutrons were reduced to less than 10 per cent. of the direct flux from the target by shielding and by locating the defining stops in the beam tube to be as far from the target as possible. Background counts in the detector and the monitor were measured by counting without a heavy ice target, for the same time-integrated beam current as was used in the experiments.

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The time-integrated neutron flux density in the experiments was determined with the aid of a boron-loaded scintillator by the  ${}^{10}B(n,{}^{4}He){}^{7}Li$  reaction. Cadmium and boron shielding was placed around the monitor to reduce the counts due to the epithermal background in the experimental area. This monitor was calibrated absolutely at 2.55 MeV by means of a triple-coincidence proton-recoil counter similar, in principle, to that described by Bame *et al.* (1957).

## IV. RESULTS AND DISCUSSION

Figure 4 shows the results of these cross-section measurements. The horizontal bars indicate the energy spread inherent in this type of neutron source; the vertical bars are the estimated errors in the measurements.

The main sources of error at each point when determining the shape of the cross-section curve are : the background subtractions, 3 per cent. ; uncertainties in the geometry, 5 per cent. ; counting errors, 4 per cent. The absolute deter-



Fig. 4.—Experimental cross-section data.

mination of the cross section is also dependent upon geometry of the recoilcounter telescope and its location with respect to the heavy ice target; this introduces a further uncertainty of 7 per cent.; the total error  $\pm 10$  per cent.

Over the energy range of  $2 \cdot 0 - 2 \cdot 7$  MeV the cross-section data show no significant indication of resonance structure but fall smoothly with increasing neutron energy. This suggests either that no levels are present in this energy range or that if they are present the triton partial width is so small (10 keV or less) that the energy resolution of the experiment prevented them being seen.

If the level under discussion has a spin and parity of  $5/2^+$  both the neutron and triton partial waves entering the reaction will be *d*-waves. The low transparency of the centrifugal barrier to these particles would give the narrow partial widths necessary to account for these experimental results and the apparent lack of compound nucleus formation.

An explanation which accounts for the bulk of the cross section of the  ${}^{6}\text{Li}(n,{}^{3}\text{H}){}^{4}\text{He}$  reaction and the measured angular distribution, above about 2 MeV, has been suggested by Dabrowski and Sawicki (1955) and Sawicki (1955). These authors have considered an " $\alpha$  plus d" model for "Li and have calculated

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the inverse-stripping cross section for  ${}^{6}\text{Li}(n,{}^{3}\text{H}){}^{4}\text{He}$  assuming a pick-up process which does not go through the intermediate system,  ${}^{7}\text{Li}{}^{*}$ . Sawicki's calculations, which include Coulomb corrections, are in reasonable agreement with the cross-section and angular distribution measurements of Darlington *et al.* (1953), Frye (1954), and Weddell and Roberts (1954). It seems likely that part of the reaction, at least, goes through direct processes for neutron energies greater than 2 MeV. However, while the direct process matrix elements appear to be very strong, it is still difficult to understand the apparent absence of resonance peaks corresponding to levels that are known to exist from  $\gamma$ -ray experiments on <sup>7</sup>Li.

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