$B^{10}(d,Li^6)Li^6$ Reaction at Deuteron Energies from 8 to 13.5 MeV*

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The breakup of C^{12} into two Li^6 particles has been observed in the reaction $B^{10}(d,Li^6)Li^6$. A self-supporting foil of B^{10} was bombarded with deuterons from the Argonne tandem generator. The pairs of Li^6 nuclei were detected by two silicon semiconductor counters placed at the appropriate pair of angles defined by the reaction kinetics. Angular distributions were measured for $20° < \theta_{c.m.} < 160°$ and were found to be peaked at about 40° (and, by symmetry, at 140°). The reaction may be understood in terms of a direct process. A distorted-wave Born-approximation calculation gives a good fit to the data when reasonable values for the well parameters are assumed.

I. INTRODUCTION

THE present investigation of the $B^{10}(d,Li^6)Li^6$ reaction follows earlier work at the University of Chicago[1] on the inverse reaction $Li^6(Li^6,d)B^{10}$ at a bombarding lithium energy of 2.1 MeV. It was pointed out by Morrison[2] that there is good evidence to believe that $Li^6(Li^6,d)$ and $Li^6(Li^7,t)$ reactions proceed by the transfer of an α particle to the target nucleus. The evidence for this mechanism lies principally in the failure of both of these reactions to leave B^{10} in its second exicted state, which is $T=1$. This effect has also been observed at higher energies by Bromley *et al.*[3] with 6-MeV bombarding lithium ions.

In our work on the $B^{10}(d,Li^6)$ reaction we measured angular distributions and cross sections at deuteron energies up to 13.5 MeV, which is equivalent to a bombarding energy of 16.5 MeV in the inverse reaction. At these energies one might expect the direct interaction mechanism to dominate.

Figure 1 illustrates the energetics of possible reactions following deuteron bombardment of B^{10}. The vertical scale is given in terms of excitation energy in C^{12}. This should not, however, be taken to imply that the reaction necessarily proceeds through states of C^{12}. The horizontal lines show the separation energies required for those channels which result in product nuclei stable against particle emission. It will be seen that the (d,Li^6) reaction has a negative Q value of 3 MeV. To facilitate comparison of the energy region covered by the present experiment with that covered in the inverse reaction, the bombarding energy scales in the laboratory system for the two reactions are shown. The shaded line labeled "B" represents the Coulomb barrier height for the two channels. The Chicago work was performed with a bombarding Li^6 energy of 2.1 MeV. This is equal to about half the Coulomb barrier height in that channel and is equivalent to a bombarding deuteron energy of 4.85 MeV in the (d,Li^6) reaction. In our study of the (d,Li^6) reaction, we have extended these measurements well above the Coulomb barriers in both exit and entrance channels.

II. EXPERIMENTAL TECHNIQUE

The measurements were made with an 18-in. scattering chamber designed by J. T. Heinrich and T. H. Braid of this laboratory. The deuteron beam from the tandem accelerator passed through a series of $\frac{1}{16}$-in. collimators, through the scattering chamber, and into a Faraday cup used to measure and integrate the beam current. The targets were self-supporting foils of boron enriched to 96% in B^{10}. These foils were about 25 $\mu g/cm^2$ thick and were prepared by an electron bombardment technique which was developed recently at Argonne.[4]

The reaction products were detected by two silicon surface-barrier counters of low resistivity. These were operated with low applied bias voltage so that the counters were fairly insensitive to protons, scattered

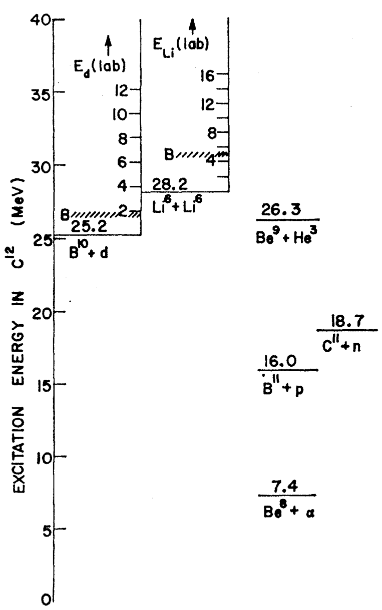

FIG. 1. Energy scale for possible reactions following deuteron bombardment of B^{10}.

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[2] G. C. Morrison, Phys. Rev. Letters **5**, 565 (1960).

[3] D. A. Bromley, K. Nagatani, L. C. Northcliffe, R. Ollerhead, and A. R. Quinton, *Proceedings of the Rutherford Jubilee International Conference, Manchester, 1961*, edited by J. B. Birks (Heywood and Company, Ltd., London, 1961), p. 597.

[4] J. R. Erskine and D. S. Gemmell, Nucl. Instr. Methods **24**, 397 (1963).

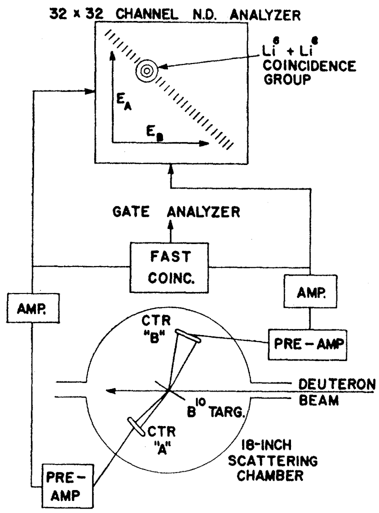

FIG. 2. Schematic diagram of experimental arrangement.

deuterons, and high-energy alpha particles. By placing the counters at two appropriate angles defined by the reaction kinetics, the pairs of Li^6 nuclei could be detected in coincidence. This technique resulted in a high degree of discrimination against other reactions such as (d,α) and (d,He^3). The output from the counters was fed into a fast coincidence unit which was used to gate a two-dimensional pulse-height analyzer operated in its 32×32-channel mode. Figure 2 illustrates the technique that was used and the type of two-dimensional plot obtained.

Once the coincidence group due to Li^6 nuclei had been detected at a given deuteron energy, it was a simple matter to follow it as the counter angles were varied. Since the sum of the energies deposited in the two counters is independent of angle, the locus of the coincidence group is a straight line on a two-dimensional plot such as this. The movement of this group with changing angle is illustrated in Fig. 2 by means of the shaded line.

In the center-of-mass (c.m.) system, the velocity of the out-going Li^6 nuclei is small enough to be comparable to the velocity (in the laboratory system) of the center of mass. This has the effect of making both the laboratory energy of the Li^6 nuclei and the c.m. solid angle of the detectors rapidly varying functions of the laboratory angle. The counter that was moved through the backward angles in the c.m. system was arranged to have a slightly smaller laboratory solid angle than the counter that moved through the forward angles in the c.m. system. In this way, one could be certain that the coincident counting rate was determined by the backward counter. That is, every Li^6 nucleus detected by the backward counter produced a coincidence pulse, whereas some counted by the forward counter did not. Consequently, when converting the measured angular distributions into c.m. distributions, the c.m. solid angle of the backward counter was used.

III. RESULTS

Differential cross sections for the reactions, measured at deuteron energies of 8, 10, 12, and 13.5 MeV, are shown in Figs. 3–6. In these figures the experimental points are shown for forward c.m. angles. However, as a consequence of the identity of the two emitted particles, the angular distributions must necessarily be symmetric about 90° in the c.m. system. Figure 3 also shows the differential cross section at $E_d=4.85$ MeV as calculated by detailed balance from the data of the Chicago group.[1] The strong influence of the Coulomb barrier on the cross section is evident. The total cross section decreases by a factor of about 30 in going from $E_d=8$ MeV down to 4.85 MeV and the angular distribution changes markedly.

The present data do not extend much below 20° (nor above 160°) in the c.m. system because of experimental

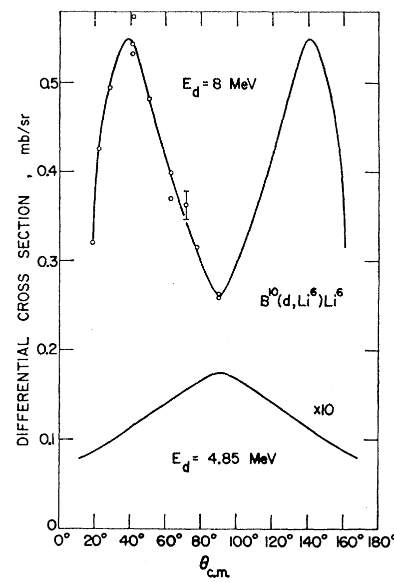

FIG. 3. Differential cross section for B^{10}-$(d,Li^6)Li^6$ at $E_d=8.0$ MeV and 4.85 MeV. The upper curve shows the present measurements while the lower one is inferred from work on the inverse reaction (Ref. 1).

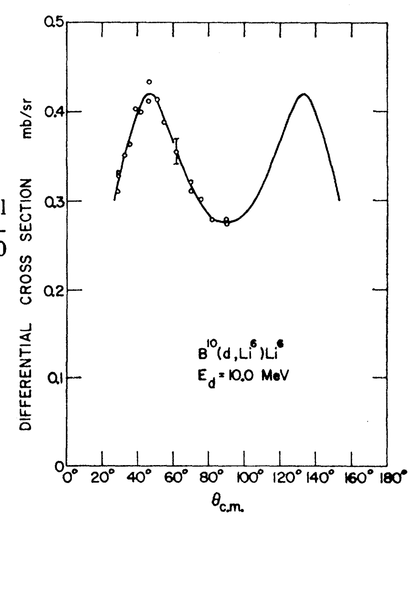

FIG. 4. Differential cross section for B^{10}-$(d,Li^6)Li^6$ at $E_d=10.0$ MeV.

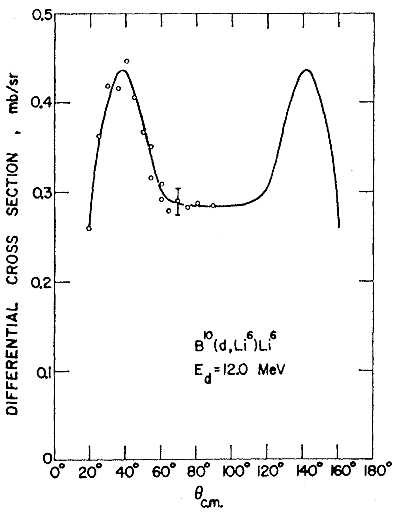

FIG. 5. Differential cross section for B^{10}-$(d,Li^6)Li^6$ at $E_d = 12.0$ MeV.

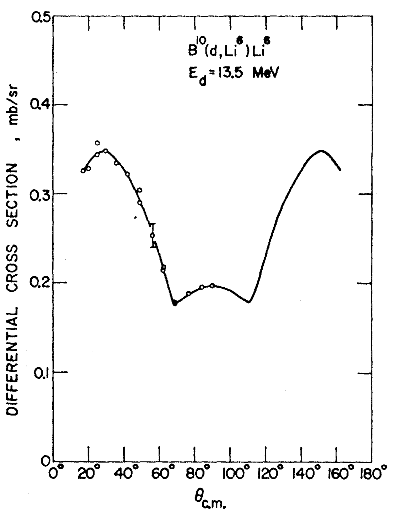

FIG. 6. Differential cross section for B^{10}-$(d,Li^6)Li^6$ at $E_d = 13.5$ MeV.

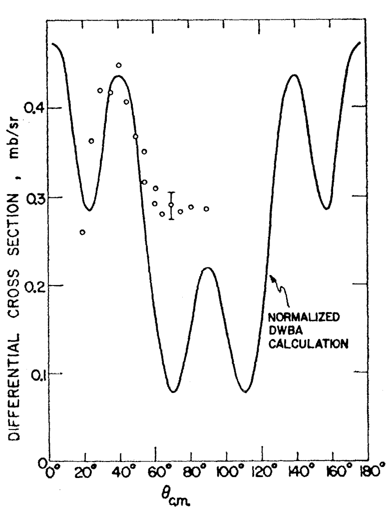

FIG. 7. Results of DWBA calculations together with experimentally determined points at $E_d = 12$ MeV. The parameters used in the calculation are given in Table I.

difficulties at these extreme angles (high counting rates in the forward counter and low-energy pulses in the backward counters).

IV. DISCUSSION

In view of the possibility that at the higher energies the reaction may be going via a direct process, we compared our data to a calculation by Satchler[5] of the angular distribution for the case of an $l = 2$ alpha-particle transfer. His results for a distorted-wave Born-approximation (DWBA) calculation at $E_d = 12$ MeV are shown in Fig. 7 together with our experimental points. The calculation was done in zero range and with a radial cutoff at 4.2 F. The alpha particle was assumed to move in a bound state in B^{10} in a Saxon-type well of radius 1.9 $Å^{1/3}$ F. The optical-model parameters used for the entrance and exit channels are given in Table I. This set of parameters was chosen because it gave fits to measurements on other (d,Li^6) reactions in light nuclei.[6] The fit obtained is quite encouraging, especially as far as the peaks at 40 and 140° are concerned. Experimentally, we see no sign of peaking at extreme angles although our data do not extend below 20 and above 160° in the c.m. system.

TABLE I. Well parameters used in optical-model calculations.

Channel	V (MeV)	W (MeV)	r_0 (F)	α (F)
$B^{10}+d$	55	18	1.5	0.6
Li^6+Li^6	40	25	2.0	0.6

The theoretical differential cross section (mb/sr) is written by Satchler as

$$d\sigma/d\Omega = xS_l\sigma(\theta),$$

where S_l is the spectroscopic factor for the $\alpha+Li^6$ in the B^{10} ground state, and x is the factor that includes the interaction strength as well as the overlap of a free-deuteron wave function with the deuteron in Li^6 and the overlap of the alpha cluster in the target with the one in Li^6.

If the calculation is normalized to the data at the peak of the differential cross section, this results in a value of $(xS_l) = 0.45$. This figure may be compared with the range $0.5 < xS_l < 5$ required to fit the Pittsburgh data for $l = 0$ and 1. That is, the over-all overlap factor for the particular case of $B^{10}(d,Li^6)$ is rather small when compared to those found for (d,Li^6) reactions in other light nuclei, indicating that one or both of these particular cluster descriptions are poor in this case. While the DWBA calculation gives a qualitative fit to the data, it is clear that more experimental and theoretical work must be done before (d,Li^6) reactions can be used to give precise information on nuclear structure.

[5] G. R. Satchler (private communication).
[6] L. J. Denes, Bull. Am. Phys. Soc. 8, 25 (1963).