ANGULAR DISTRIBUTIONS IN THE REACTIONS $^{11}B(d, p)^{12}B$ AND $^{11}B(d, \alpha)^{9}Be$†

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In recent years considerable interest has centred on the reaction mechanism in nuclear reactions. At bombarding energies of above about 5 MeV, it has been apparent for many years that (d, p) and (d, n) reactions tend to be dominated by the direct stripping reaction. With the advent of distorted wave stripping theories such as those of Tobocman (1959) and Robson (1961), it now appears that those reactions may proceed by a direct mechanism even at very low bombarding energies. Robson and Weigold (1963) have satisfactorily analysed the angular distributions obtained in the reaction $^{11}B(d, p)^{12}B$ at bombarding energies of 1·02 MeV and 700 keV.

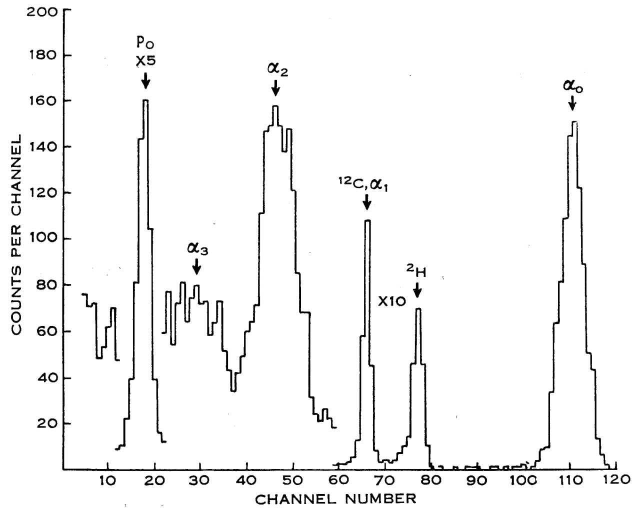

Fig. 1.—Typical pulse height spectrum (taken at 75° and deuteron energy 390 keV). The peaks marked ^{12}C and ^{2}H are attributed to protons from (d, p) reactions in those contaminant nuclei. There is also a small contribution to the ^{12}C peak, at this angle, from the α_1 group leading to the 1·75 MeV state of ^{9}Be. The energy scale for the proton groups is different from that for the alpha groups owing to the effect of the aluminium foil in front of the counter.

Similar attempts have been made to describe (α, d) reactions as two-particle stripping and (d, α) as two-particle pick-up reactions. These theories, due to El Nadi (1957), Newns (1960), Glendenning (1962), are all based on the plane wave approximation used by Butler (1957) for (d, p) and (d, n) stripping, and so, although they have had a certain degree of success at rather large bombarding energies, they are expected to break down at low bombarding energies. However, since it appears that

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direct interaction does dominate (d, p) and (d, n) reactions even at very low energies, it is of interest to determine whether this might be true also for the (d, α) reaction.

Distinction between compound nucleus and direct interaction mechanisms can often be made from an examination of angular distributions of the outgoing particle over a range of bombarding energies. If a compound nucleus is formed by deuteron bombardment, it frequently happens that the energy of such a compound state is greater than about 15 MeV, where the density of states is very large. It

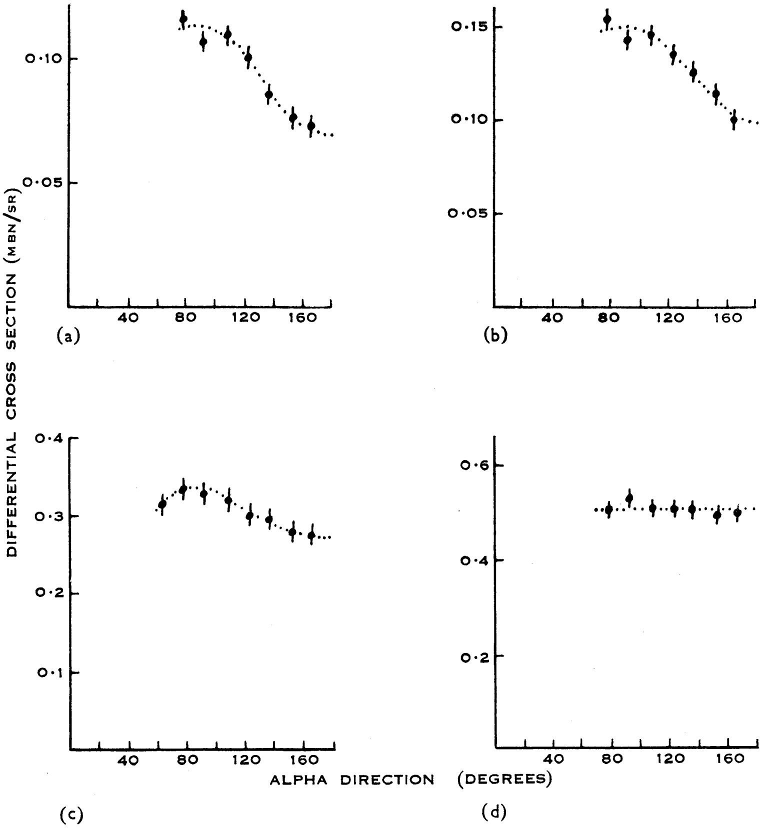

Fig. 2.—Angular distributions of the ground state alpha group, α_0. Deuteron bombarding energy (*a*) 390 keV, (*b*) 490 keV, (*c*) 600 keV, (*d*) 700 keV.

therefore follows that several interfering compound states are likely to participate in any compound nucleus process, and the resulting angular distributions may be expected to depend critically on the particular mixture of states involved. Hence, the shape of an angular distribution should vary rapidly with changing bombarding energy. In the case of direct interaction, on the other hand, since no compound nucleus state is involved, the angular distribution should vary only slowly with changing bombarding energy. In the present experiment, this technique was used to carry the investigation from a bombarding energy of 700 keV down to 390 keV in the reactions $^{11}B(d,\alpha)^{9}Be$ and $^{11}B(d,p)^{12}B$.

Deuteron Bombardment of ^{11}B

The target, which consisted of separated ^{11}B isotope deposited to a thickness of 16 $\mu g/cm^2$ on a thick nickel backing, and supplied by AERE, Harwell, was bombarded by a deuteron beam from the Melbourne 1 MeV electrostatic generator at energies of 700, 600, 490, and 390 keV. Charged particles resulting from this bombardment were detected with an ORTEC model SBC J050–60 silicon surface barrier

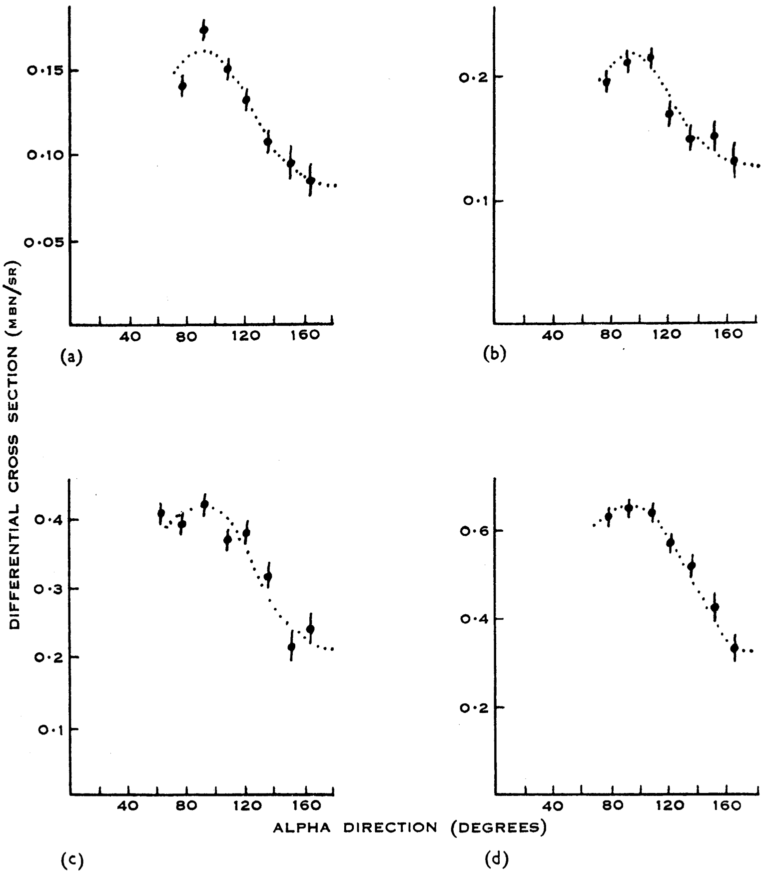

Fig. 3.—Angular distributions of the alpha group, a_2, leading to the 2·43 MeV state of ^9Be. Deuteron bombarding energy (*a*) 390 keV, (*b*) 490 keV, (*c*) 600 keV, (*d*) 700 keV.

detector, over the front of which aluminium foil of thickness 10 μm was mounted to stop the very high flux of elastically scattered deuterons. The detector was mounted at a distance of 13·2 cm from the target and was free to rotate between all angles up to 165°. The solid angle subtended by the counter at the target was $2 \cdot 8 \times 10^{-3}$ sr. The target was oriented such that the beam made a glancing angle of 37·5° with it, and particles were observed at intervals of 15° in directions from 75° to 165°. The particle groups, with their identifications, are shown in Figure 1.

Angular distributions were extracted for the α-particle groups leading to the ground state and 2·43 MeV state of ^{9}Be, and for the proton group leading to the ground state of ^{12}B. These angular distributions are shown in Figures 2, 3, and 4. Figure 5 shows the three excitation functions measured in the 90° direction normalized to the same value at 550 keV.

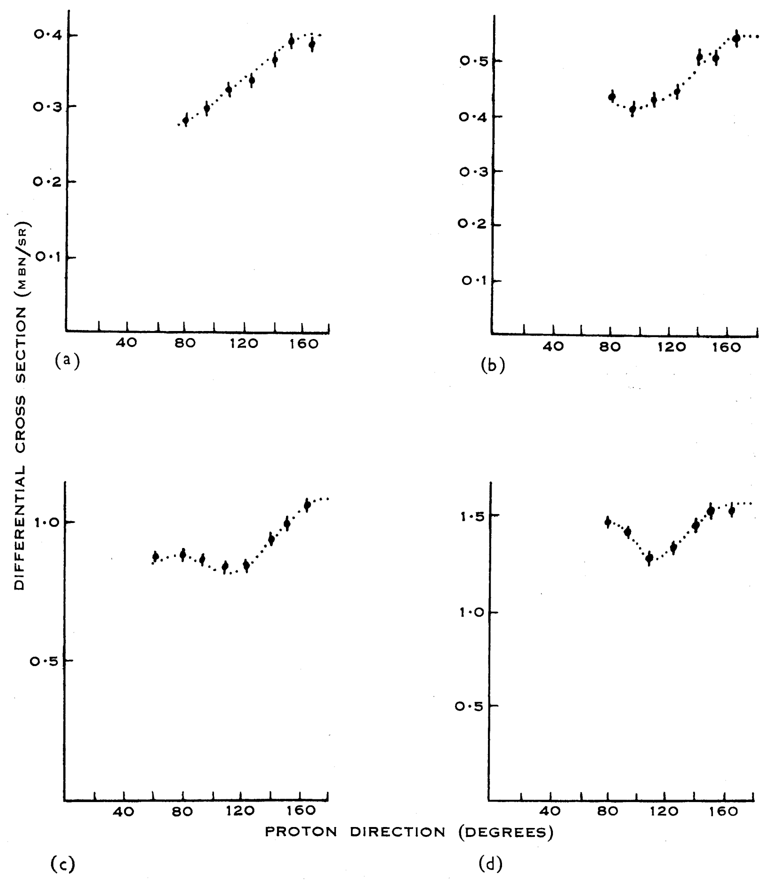

Fig. 4.—Angular distributions of the ground state proton group, p_0. Deuteron bombarding energy (*a*) 390 keV, (*b*) 490 keV, (*c*) 600 keV, (*d*) 700 keV.

Discussion

The angular distributions for the p_0 group have very much the same shape over the whole range of bombarding energies. The backward peaking persists in all the distributions measured, the main change over this energy range being a steady rise in the relative count rate around 90°. This insensitivity of the shape of an asymmetric angular distribution to energy is strongly suggestive of direct interaction. Further, the shape and its variation are consistent with the observations of Robson and Weigold (1963) at energies of 700 keV and 1·02 MeV, which they have successfully described with distorted wave direct interaction theory.

With the angular distributions for the α_0 group, on the other hand, the degree of anisotropy changes rapidly, suggesting a compound nucleus type interaction.

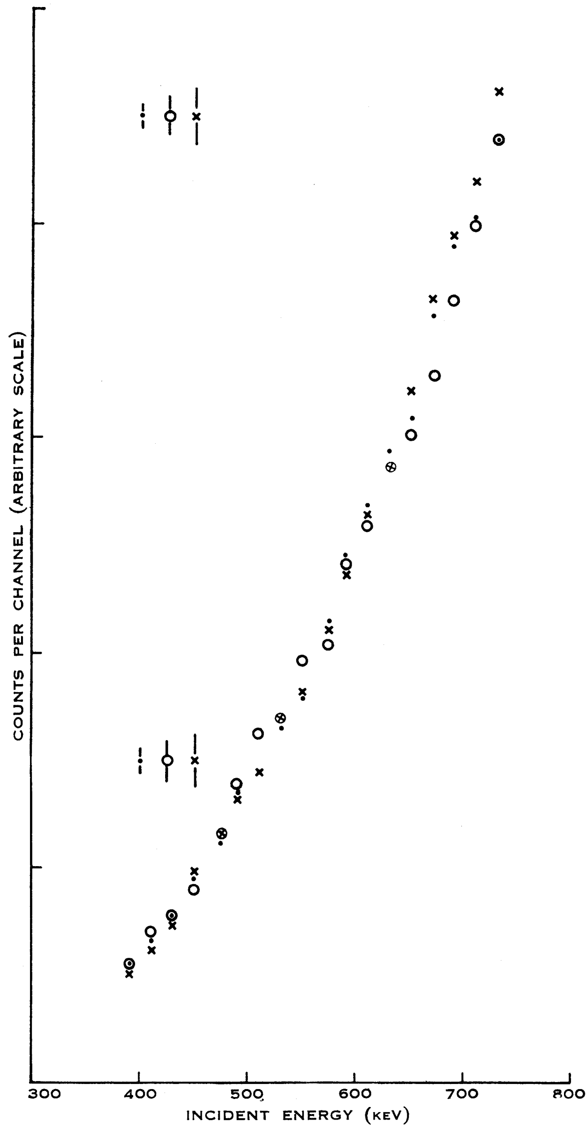

Fig. 5.—Excitation functions for the p_0 (•), α_0 (○), and α_2 (×) groups. The three curves of best fit have been normalized to the same value at a bombarding energy of 550 keV.

This group was also observed by Robson and Weigold at 700 keV and 1·02 MeV, and the trend in shape observed here is continued in their measurements, which were taken over an almost full range of angles and show symmetry about 90°.

The shape of the α_2 angular distributions is, to the accuracy of the measurements, virtually unchanged over the whole energy range from 390 to 700 keV. This is indicative of a direct interaction mechanism, particularly in view of the rapid change of shape observed for the α_0 group over the same energy range.

The fact that the one excitation function applied to all three particle groups observed is strange, since the various reactions proceed by way of different mechanisms. The explanation of this probably lies in the fact that the bombarding energy is so very low, and both types of reaction will be governed to a great extent by the Coulomb barrier, and the sharply rising excitation function simply reflects increasing barrier penetration with increasing energy.

From Figures 2 and 4 it is evident that the cross section for compound nucleus formation is certainly one-third of that for the (d, p_0) reaction, and yet the compound nucleus apparently plays no part in the (d, p_0) reaction. The three most obvious factors that might govern this behaviour are energy available for the compound nucleus to emit a particular particle, nuclear configuration, and angular momentum.

The fact that the compound nucleus, once formed, appears to decay overwhelmingly by alpha emission rather than proton emission can probably be accounted for on energy considerations. Thus the energy available for α_0 emission from the compound nucleus is 8·0 MeV whilst that for proton emission is only 1·1 MeV. When Coulomb barriers of 2·2 MeV for the α-particles and 1·6 MeV for the protons, together with possible angular momentum barriers, are taken into account, it is clear that energy considerations favour the alpha emission quite strongly.

We are unable to explain the apparent dominance of direct interaction in the (d, α_2) reaction and its absence in the (d, α_0) reaction. Both shell model and rotational model attempts to describe ^{9}Be ascribe similar configurations to the ground state and 2·43 MeV state, and it would therefore be expected that both reactions would proceed by way of the same mechanism. There also appear to be no angular momentum restrictions that would favour the observed difference of mechanism.

Finally, we mention that the α_1 group leading to the 1·75 MeV state in ^{9}Be was also observed and the spectrum was satisfactorily fitted on the assumption that the state can be described as an S-wave scattering event between a neutron and ^{8}Be. The best fit was obtained for a scattering length of 20×10^{-13} cm, in agreement with most other observations of this state.

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