Angular Distributions of $B^{10}(d,\alpha)Be^8$ Reactions from 0.6 to 1.5 Mev*

ROBERT L. BECKER†
University of Kentucky, Lexington, Kentucky
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Angular distributions of the two most energetic alpha-particle groups resulting from deuteron bombardment of B^{10} were measured at seven deuteron energies between 0.58 and 1.50 Mev. In addition to the usual pulse-height analysis of the detector output, pulse-decay analysis was also employed so that alpha particles could be distinguished from protons giving the same pulse size. The shapes of the angular distributions were somewhat energy dependent. Averaged over the range of energies studied, the angular distributions were not isotropic, the yield being slightly higher at back angles.

INTRODUCTION

MECHANISMS by which nuclear reactions proceed can often be inferred by observing the dependence of yield on bombarding energy or angle. In cases where the energy level density of the compound system is large, reactions which form a compound nucleus are expected to give an angular distribution symmetric about 90°.[1] Non-compound-nucleus processes are frequently but not always peaked in the forward direction.

Transitions to excited states of the residual nucleus are often observed with difficulty, because of experimental problems involved in separating different particle groups. Development at this laboratory of a technique by which either protons or α particles can be identified and separately detected in the presence of the other particle,[2] therefore, has proved helpful. This technique was employed in an investigation of the $B^{10}(d,\alpha)Be^8$ and $B^{10}(d,\alpha)Be^{8*}$ reactions from 0.6 to 1.5 Mev.

Previous studies of the ground-state α particles in this range of bombarding energies[3,4] have shown maxima in the yield at 1.0 Mev and at higher energies. Marion and Weber[4] also found, by measuring excitation curves at three widely different angles, that the yield when averaged over the energy range from 1.0 to 2.5 Mev does not depend strongly on angle. A shift from forward to backward peaking was interpreted as caused by interference of levels of opposite parity.

In the present work, the suppression of proton counts allowed observation of the α group leaving Be^8 in its first excited state at 2.90 Mev, in addition to the ground-state group. Angular distributions were measured at seven bombarding energies below 1.50 Mev.

APPARATUS

A deuteron beam from an electrostatic accelerator enters a scattering chamber through a series of collimating slits, passes through a thin solid target, and is collected in a Faraday cage. A scintillation detector inside the chamber, preceded by additional collimating slits, can be rotated about the target to any position more than 35° from the beam axis.

Targets of 95% enriched B^{10}, evaporated onto Al leaf, were mounted in a vertical plane making a 45° angle with the deutron beam.

The detector consists of a CsI(Tl) phosphor mounted on a Dumont 6467 phototube. This small tube was chosen because of the limited space in the chamber (inside dimensions 22 in. by 22 in. by $3\frac{1}{2}$ in. high). The detector output passes through a cathode follower and a short section of low-capacitance cable to a multi-pin connector in the base of the chamber, through which all electrical connections to the detector are made. Care was taken in designing the circuits so that the pulses, as they left the chamber, would have as nearly as possible the same time dependence as the intensity of fluorescence in the phosphor.

PULSE ANALYSIS

The arrangement of electronic circuits, shown in Fig. 1, was planned to take advantage of a reported dependence of fluorescence decay in CsI on the mass of the incident particle.[5] Pulse-height analysis was performed in the usual way, except that a gating signal in coincidence was required, to show that the fluorescence decay was within preset limits.

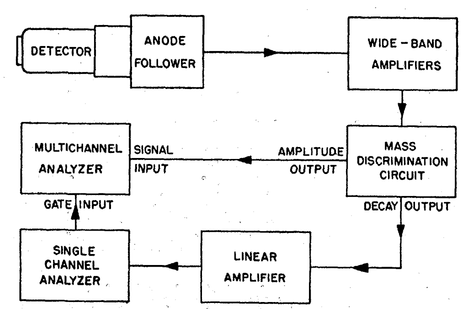

FIG. 1. Arrangement of the electronics circuits. The multichannel analyzer is gated only when the flourescence decay time is within limits present on the single-channel analyzer.

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† Now at Boston College, Chestnut Hill, Massachusetts.

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Generation of a signal proportional to decay time is accomplished by the device labled "mass discrimination circuit"[6] in Fig. 1. A block diagram is shown in Fig. 2. In this circuit, the input is attenuated by a factor of two and lengthened, then subtracted from the initial pulse in the difference anplifier. This provides a signal which is positive for a duration equal to the fluorescence half-life. Standard time-to-pulse-height conversion then gives the required output, which, if within the window of the single-channel analyzer, allows the multichannel analyzer to be gated.

With a narrow single-channel window, the amplitude spectrum of pulses from $B^{10}+d$ reaction products which were in coincidence with the single-channel output varied with single-channel base line as shown in Fig. 3. This diagram shows the dependence of the yield on pulse decay as well as pulse amplitude. To obtain these data, the detector was placed at 90° with respect to an 800-kev deuteron beam incident on a B^{10} target.

Alpha particles give rise to the ridge at the left. The groups in channels 28 and 23 along the pulse-height axis leave the residual nucleus Be^8 in its ground and first excited states, respectively. An unresolved continuum is seen at lower energies.

Four proton groups, having longer decay times, are also observed, corresponding to (d,p) reactions with B^{10} and, at lower energies, with contaminants on the target.

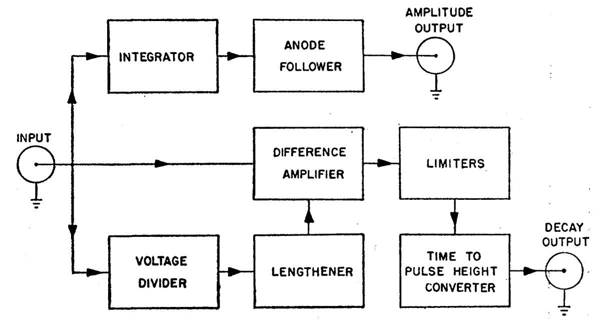

FIG. 2. Mass discrimination circuit. This circuit generates one signal (amplitude output) dependent upon the energy loss of the particle in the phosphor, and another (decay output) proportional to the fluorescence decay time.

Protons and α particles can be separated in decay time by 3 to 4 times the resolution of the decay-analyzing circuit. That the lighter particle has a longer decay is consistent with the information in reference 5.[7] The dependence of decay time on particle energy seen in Fig. 3 implies that the energy loss per interval of path length of the detected particle determines the decay time.

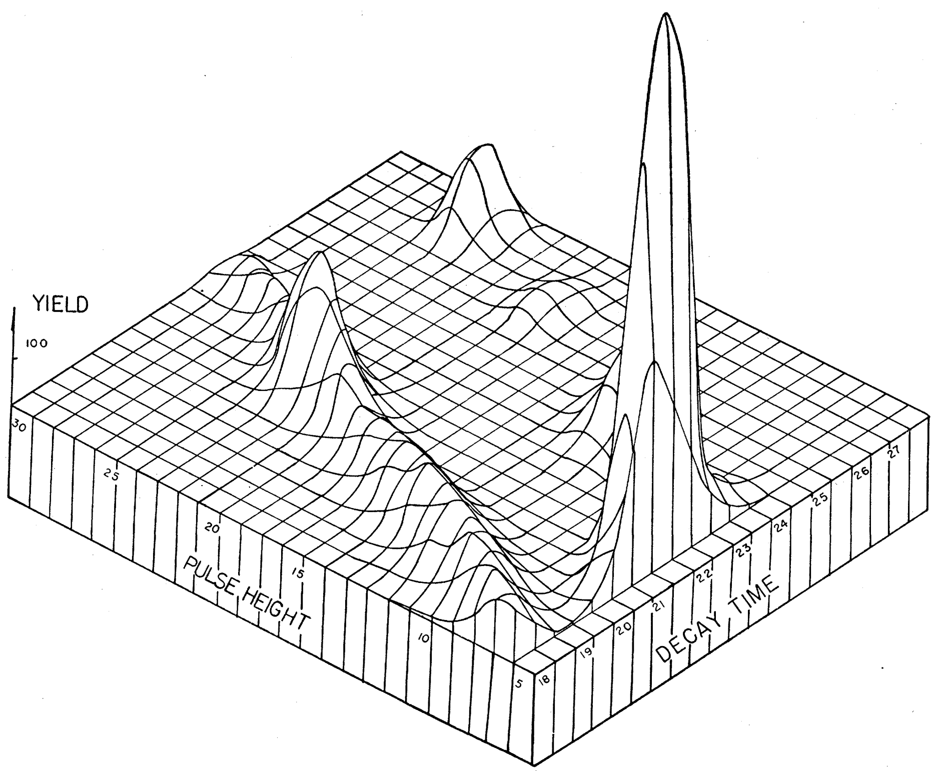

FIG. 3. Pulse-height spectrum of $B^{10}+d$ reaction products, as a function of fluorescence decay time. The four peaks at the right are proton groups, while the ridge at the left is caused by α particles.

[6] J. A. Biggerstaff and R. L. Becker, University of Kentucky Technical Report UK-59-1 (unpublished).

[7] R. B. Owen, in Atomic Energy Research Establishment, Harwell Report EL/R 2712 (unpublished), shows pulse shapes for CsI phosphors, in which only the rise time and the shape of the pulse at its maximum height appear to vary with specific ionization. It is not clear how the operation of our circuit, as characterized by Fig. 3, could be consistent with his measurements.

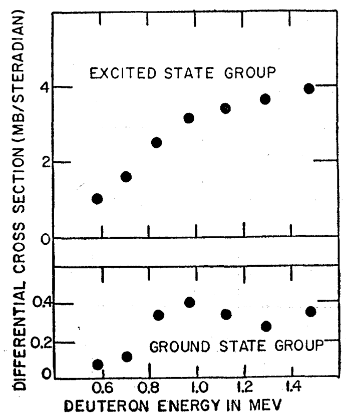

FIG. 4. Yield at 90°, as a function of energy, for $B^{10}(d,\alpha)Be^8$ and $B^{10}(d,\alpha)Be^{8*}$.

EXPERIMENTAL PROCEDURE

With the single-channel window set so that no proton counts could be recorded by channels in which the required α-particle groups were observed, runs were made until a predetermined amount of charge, usually 16.7 μcoul, was collected from the deuteron beam. Measurements were made at 10° intervals, from 90° to 140°, after which the position of the single-channel analyzer window was again checked. The angular distribution over this range of angles was repeated six times, to average out possible variations of current integrator sensitivity and of the position of the beam on the target, as well as to check on the reproducibility of the results.

Without moving the target, the detector was then rotated to the opposite side of the beam, where observations were made from 40° to 90°. The two sets of data were normalized, if necessary, at the 90° value common to both measurements.

Angular distributions were observed at deuteron energies of 0.58, 0.70, 0.84, 0.97, 1.13, 1.29, and 1.48 Mev, and are normalized to each other by means of an excitation curve, Fig. 4, made at 90°. The ground state

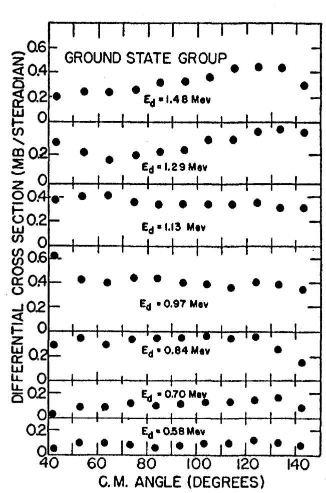

FIG. 5. Angular distributions of $B^{10}(d,\alpha)Be^8$ reaction at seven energies.

excitation curve, in turn, is normalized at 1.0 Mev to the data of Marion and Weber.[4]

The detector could be positioned to an accuracy of $\pm 0.5°$ or less. In this experiment, particles were accepted over a 1.0° spread in angle, with the detector subtending a solid angle of about 10^{-3} steradian.

From the known cross section, the target thickness could be found. The average thickness of the targets was about 21 kev for 1.0-Mev deuterons. This gave an energy spread of 14 kev at the highest bombarding energy and 35 kev at the lowest. The average energy was known to about ± 6 kev.

Because of the high Q value of the $B^{10}(d,\alpha)Be^8$ reaction, no background counts were observed in the part of the pulse-height spectrum being studied.

RESULTS

In Figs. 5 and 6 are shown the angular distributions for the ground and first excited states, respectively. Both cross sections and angles are in c.m. coordinates.

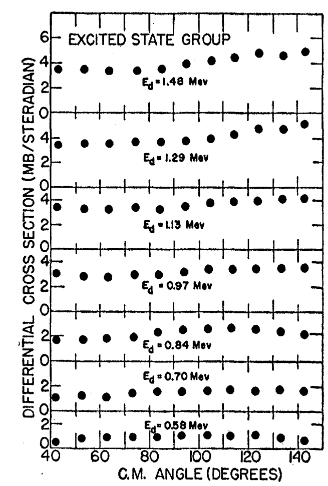

FIG. 6. Angular distribution of $B^{10}(d,\alpha)Be^{8*}$ reaction at seven energies.

Counting statistics contribute 1 to 3% uncertainty in the relative cross sections for the first excited state group, and 3 to 10% for the ground state, depending upon the cross section. Overlap of the low-energy α-particle continuum with the first excited state group gave an additional 4% error for this group. No other sources of error are believed to be significant, so that relative cross sections for both groups should be accurate within about 4% at the highest yield. A 15% uncertainty has been assigned the absolute cross sections to which these curves are normalized.

Both groups, when averaged over energy, are isotropic to within 10% in laboratory coordinates, indicating a slight preference for back angles in the c.m. system.

The yield of the ground-state group, integrated over angle, shows a maximum at 1.0 Mev, as previously reported,[3,4] but lacks sufficient detail to verify a maximum

at 1.4 Mev reported by Marion and Weber.[4] The angular distributions for this group, however, undergo noticeable fluctuations in shape both near 1.0 Mev and 1.4 Mev.

The first excited state group yield, integrated over angle, increases rapidly between 0.5 and 1.0 Mev, then remains nearly constant. In addition, each angular distribution measurement for this group is more nearly isotropic, and has a less energy-dependent shape, than the ground-state group. The yield is about 10 times the yield of the ground-state α particles.

Marion and Weber infer that the ground-state (d,α) reaction proceeds through states of the compound nucleus, and explain the variation of angular distribution with bombarding energy as arising from interference of levels of opposite parity. Such arguments could also be applied to the present results which show that, if such interference exists, its effects are less pronounced for the first excited state than for the ground-state particles.

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Excitation Curves and Angular Distributions for $N^{14}(d,n)O^{15}$†

THEO RETZ-SCHMIDT AND JESSE L. WEIL
The Rice Institute, Houston, Texas
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Excitation curves for the highest energy neutron group in the reaction $N^{14}(d,n)O^{15}$ have been measured at $\theta_{lab}=0°$, 30°, 90°, and 164° for deuteron bombarding energies between 0.66 and 5.62 Mev. A pulse shape discrimination detector was used to eliminate the pulses due to γ rays from the neutron spectra. There is considerable resonance structure in the excitation curves, with the anomalies appearing at different energies for the different angles. The angular distribution of this neutron group has also been measured at bombarding energies of 0.91, 1.17, 1.51, 1.88, 2.58, 3.13, 3.56, 4.36, 4.80, and 5.27 Mev. The shape of the angular distribution changes rapidly with energy at low bombarding energy, but above 3.5 Mev the shape becomes more stable. The maximum cross section at any angle was 5.5 millibarns per steradian.

INTRODUCTION

THE present investigation of the $N^{14}(d,n)O^{15}$ reaction was undertaken for the following purposes: (1) to see if the exchange stripping theory of Owen and Madansky[1] can be applied to this reaction, (2) to see if information could be obtained about states in O^{16} above an excitation of 20 Mev, and (3) to investigate this reaction more thoroughly as a possible source of monoenergetic neutrons using a Van de Graaff accelerator. The recent development[2] of a neutron detection system which is insensitive to γ rays and has a high efficiency for neutron detection made possible the more complete investigation of this low cross-section reaction in a reasonable amount of time. The performance of this experiment is a demonstration of the capabilities of this detection system, because of the high γ-ray flux produced in this reaction.

There have been several earlier measurements on this reaction. Nonaka et al.[3] measured the angular distribution and absolute cross section at 1.96 Mev. Morita[4] has measured relative cross sections at $\theta=0°$, 90°, and 165° from 1.0- to 2.15-Mev bombarding energy. Weil and Jones[5] have measured the 0° differential cross section from 1.0- to 5.4-Mev bombarding energy. Their results showed three strong peaks in this energy region, but poor energy resolution and bad statistics prevented the observation of any fine structure. All these measurements are in good agreement where they can be compared.

A fairly good fit to Nonaka's angular distribution was made by Weil and Jones[5] using the exchange stripping theory of Owen and Madansky.[1] Weil and Jones also made a good fit to eight angular distributions of the $N^{15}(d,n)O^{16}$ reaction using this same theory. It was hoped, before the present measurements were started, that the angular distributions for $N^{14}(d,n)O^{15}$ would be amenable to the same type of analysis.

Photodisintegration experiments on O^{16} by several experimenters[6] have indicated that there are a number

† Supported by the U. S. Atomic Energy Commission.
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