Differential Cross Sections for the Reaction $B^{11}(d,p)B^{12}$ for $E_D=1$–2.6 MeV*

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The angular distributions of the protons from the nuclear reaction $B^{11}(d,p)B^{12}$ leading to the ground state of the residual nucleus were measured at bombarding energies of 1.0, 1.5, 2.0, and 2.6 MeV. Self-supporting boron films were used as targets, and the outgoing particles were detected with surface-barrier solid-state detectors. Protons from the reaction $O^{16}(d,p)O^{17}$ leading to the first excited state of O^{17} are practically indistinguishable from the protons under investigation, and were subtracted from the data during the analysis. The resulting absolute differential cross sections were fitted using the deuteron–heavy-particle stripping theory.

I. INTRODUCTION

IN this laboratory there is a continuing interest in the problem of the polarization of the residual nucleus in the reaction $B^{11}(d,p)B^{12}$. Theoretical predictions indicate that this is related to the polarization of the proton. Therefore it is essential that the polarization of the proton be measured. Efforts directed toward this measurement have begun with this current work on the measurement of the differential cross sections for the same reaction. A knowledge of these cross sections would be helpful in design work on the experiments to measure the polarization of the recoil nucleus as well as that of the proton. This angular distribution is vitally necessary in calculating the inherent left-right asymmetry in the double scattering experiment to measure proton polarization.

The earlier work on this reaction has all been done at higher energies. Holt and Marsham[1] used 8-MeV deuterons, while Gorodetzky *et al.*[2] used 5.5-MeV deuterons. Neither of these references considers quantitatively the problem of oxygen contamination in the boron, and neither gives the cross sections in absolute numbers. The gravity of the oxygen problem was emphasized by Buechner *et al.*,[3] who used a magnetic spectrometer. They did not, however, obtain a distribution. The protons from the reaction $O^{16}(d,p)O^{17}$ leading to the first excited state of O^{17} have approximately the same energy as the protons of interest. In the forward angles these two groups of particles are indistinguishable. It is virtually impossible to make a boron target that is oxygen free. In the work reported here efforts were made to minimize the amount present and compensate for the remainder in the analysis of the data.

The differential cross sections were measured at energies of 1.0, 1.5, 2.0, and 2.6 MeV and intervals of 15°. The data were fitted using deuteron and heavy-particle stripping.

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[1] J. R. Holt and T. N. Marsham, Proc. Phys. Soc. (London) **A66**, 1032 (1953).
[2] S. Gorodetzky *et al.*, J. Phys. Radium **22**, 573 (1961).
[3] W. W. Buechner, D. M. Van Patter, E. N. Strait, and A. Sperduto, Phys. Rev. **79**, 262 (1950).

II. EXPERIMENTAL PROCEDURE

Boron targets for this experiment were prepared by evaporating elemental boron onto a water-soluble substrate. The boron was then removed from the backing by placing in water until the film floated free. This film was then affixed to a wire frame. The procedure followed has been described by previous workers.[4]

The elemental boron was evaporated from pelletized powder by means of an electron-gun assembly. The material was deposited on a photographic ferrotype plate held on a water-cooled target holder. To minimize the oxygen contaminant, the evaporation was carried out at a pressure of less than 3 μTorr.

The counting equipment made use of a 3-ft-diam scattering chamber. The monitor counter was clamped rigidly to the roof of the chamber at a position of 90° with respect to the incoming beam and a few degrees above the scattering plane. The distribution counter was mounted on the turntable, and could be rotated through 360° in a horizontal plane about the target. The signals were fed through the vacuum wall by BNC pressurized bulkhead adapters.

The particle detectors used in this experiment were surface barrier silicon detectors made by ORTEC. Using a bare counter one would observe a high background due to alpha particles with energies well above the elastic peaks. This made necessary the use of stopping foils to decrease this source of difficulty.

Pulses from the distribution detector proceeded through the preamplifier to the main amplifier of an ORTEC 101-201 system. The post amplifier output entered the high-level input of a TMC 256-channel pulse-height analyzer. This information was stored in the first half of the memory.

The monitor detector pulses went through a TENNELEC preamplifier to a pulse shaping circuit. They then entered the amplifier input of the TMC analyzer. The second output of the pulse shaper was amplified by a Hamner amplifier. The discriminator output then triggered a monostable multivibrator that provided routing pulses for the analyzer memory location. These monitor pulses were stored in the second half of the memory.

[4] L. Yaffe, Ann. Rev. Nucl. Sci. **174**, 1962.

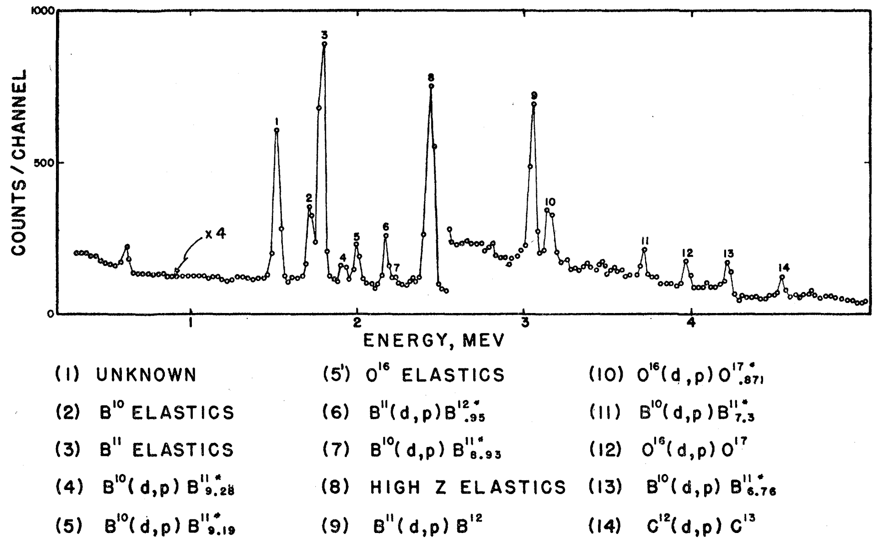

FIG. 1. Complete particle spectrum at 90°.

Using both the high level and amplifier input on the analyzer provided the proper pulse mixing without the use of additional circuitry. The analyzer memory content was recorded digitally on a Hewlett-Packard printer. An analog record was also made to facilitate the analysis of the data.

Before measuring an angular distribution it is necessary to have a positive identification of the complete spectrum delivered by the solid state detectors. Figure 1 shows such a spectrum for the detector positioned at 90°. This gives us the energy calibration for the detector. Another rough check on this calibration is made by using the alpha particles from Po^{210}.

The entire target chamber is electrically isolated, so it may be used as a Faraday cup to collect the beam current. This current was measured and integrated by an Eldorado Electronics current integrator. If the full beam hits the target and the target is uniform, the monitor counter will register a number that is proportional to the integrated charge. This was indeed the case to within a few percent.

The boron target was positioned in the beam so that the normal to its surface was horizontal and at 45° with respect to the beam. The angular distribution was measured at 15° intervals from 15 to 165°. Two passes were made to check reproducibility.

III. DATA ANALYSIS

The contamination of the target material with oxygen must be allowed for in the reduction of the data. Grosskreutz[5] has measured the absolute cross section for the ground state and first excited states of O^{17} in this reaction for bombarding energies between 1.0 and 2.5 MeV. Another measurement was made on the same reaction at E_d of 3.01 MeV by Stratton *et al.*[6] Using

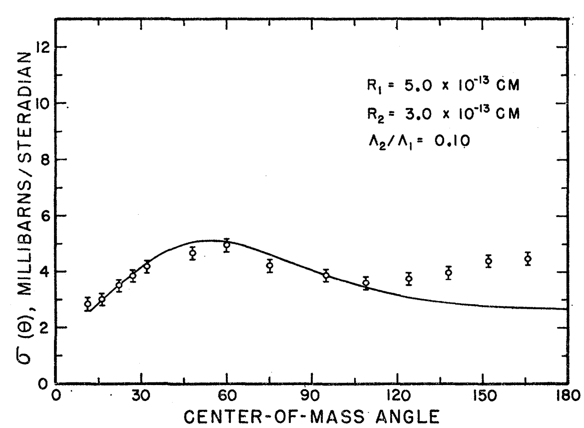

FIG. 2. Angular distribution, $E_D = 1.0$ MeV.

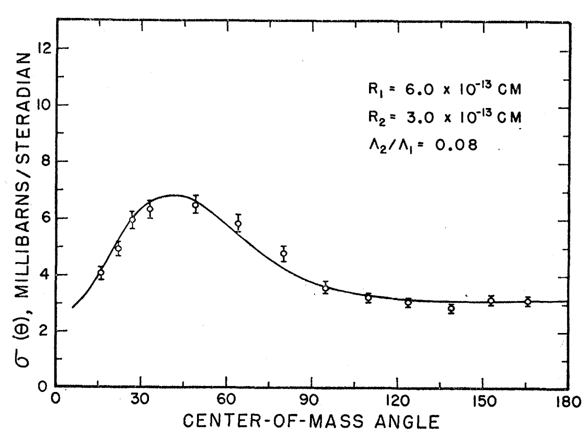

FIG. 3. Angular distribution, $E_D = 1.5$ MeV.

[5] J. C. Grosskreutz, Phys. Rev. **101**, 706 (1956).
[6] T. F. Stratton, J. M. Blair, K. F. Famularo, and R. V. Stuart, Phys. Rev. **98**, 629 (1955).

the intensities of the peak in the O^{17} ground-state reaction allows a fairly accurate oxygen analysis. Data is also obtained from the first excited state at $E_d=2.6$ MeV for angles greater than 90°. Under these conditions the resolution is satisfactory. Then having cross section data on the first excited state of O^{17}, one can calculate the intensities. These numbers are subtracted from the observed peaks to find the contribution due to boron. The magnitude of the oxygen peak was found to be as high as 30° of the boron peak.

The target thickness was measured by observing the energy shift in alphas from Po^{210} in passing though the material. The value of dE/dX was taken from Whaling[7] by interpolation. The resulting areal density was 187 (μg/cm^2).

The total cross sections were calculated using the above data and found to be 24, 25, 27, and 26 mb for deuteron energies of 1, 0, 1, 5, 2.0, and 2.6 MeV, respectively.

One may consider the relative standard deviation of the points in the angular distribution to be about 5%. This reflects primarily statistical uncertainties and reproducibility. The standard deviation on the absolute numbers should be taken to be approximately 15% for the higher two energies, and 20% for the lower two energies. A major contribution to this large uncertainty is due to the approximation made in the atomic stopping power for boron. In this analysis we have assumed the value to be 13.2 (10^{-5} eV-cm^2)$\pm 6\%$.

The above-reported total cross sections are in marked contrast to each of two previously reported results. Hudspeth and Swann[8] reported a value of 4 mb at $E_d=1.5$ MeV, based on a measurement of the β^-'s resulting from the decay of the recoil B^{12}. On the other hand, Kavanagh and Barnes[9] gave a value of 380 mb at the same energy from a similar measurement.

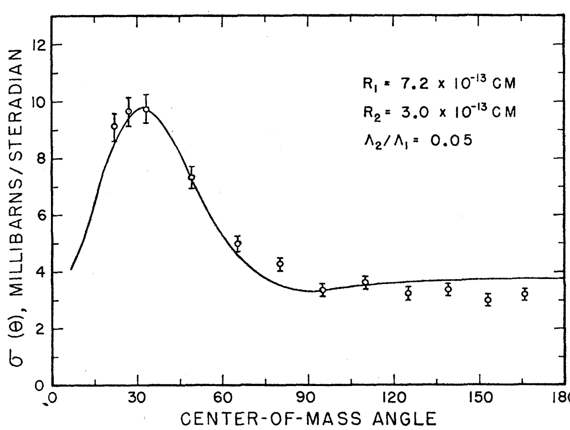

FIG. 4. Angular distribution, $E_D=2.0$ MeV.

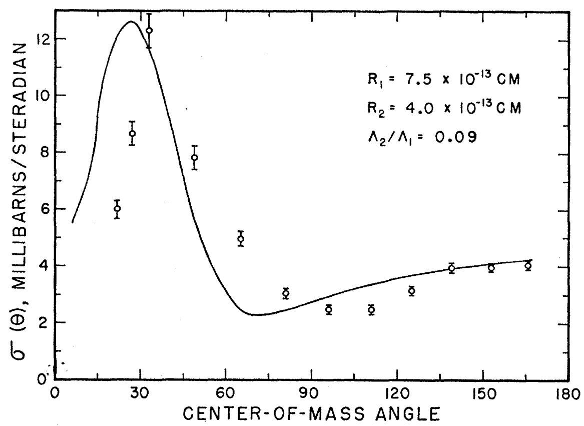

FIG. 5. Angular distribution, $E_D=2.6$ MeV.

The theoretical curves shown in Figs. 2 through 5 were calculated from the expression

$$\sigma(\theta)\propto |C_1G_dF_D|^2+72(\Lambda_2/\Lambda_1)^2|C_2F_HG_H|^2 - (24/9)(\Lambda_2/\Lambda_1)(C_1F_DG_D)^*\cdot(C_2F_HG_H)\cos\beta\,,$$

where the notation is that of Edwards.[10] It is assumed that the shell model is valid and that J–J coupling is applicable. The coefficients in the above expression were evaluated using the following values of the angular momenta:

$$\begin{array}{llll} j_N=\frac{1}{2} & j_C=0 & 1_C=0 & J_T=\frac{3}{2}^- \\ j_P=\frac{1}{2} & 1_N=1 & J_C=0 & J_F=1^+ \\ j_D=1 & 1_P=1 & J_N=\frac{1}{2}^- & J_P=\frac{3}{2}^-. \end{array}$$

Shown on the figures are the values of the parameters that were adjusted to fit the data. R_1 and R_2 are the cutoff radii in the integrals for the functions F_D and F_H. Λ_2/Λ_1 is a direct measure of the heavy-particle stripping and deuteron stripping admixture.

The fact that the forward lobe of the distribution grows with energy in a uniform manner tends to corroborate the assumption that a direct interaction is responsible. There are some indications that the waves may be subject to distortions, as indicated by the angular displacement of the peak for $E_d=2.6$ MeV. However, the curves have been fitted reasonably well with two-mode stripping theory with fairly uniform values for the parameters.

[7] W. Whaling, in *Handbuch Der Physik*, edited by S. Flügge (Springer Verlag, Berlin, 1958), Vol. 34, p. 193.
[8] E. L. Hudspeth and C. P. Swann, Phys. Rev. **76**, 1150 (1949).
[9] R. W. Kavanagh and C. A. Barnes, Phys. Rev. **112**, 503 (1958).
[10] S. Edwards, Jr., Phys. Rev. **113**, 1277 (1959).