Differential and Total Cross Sections of the $B^{10}(d,p)B^{11}$ Reaction at Low-Deuteron Energies*

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Differential cross sections have been obtained for production of the four highest energy proton groups in the $B^{10}(d,p)B^{11}$ reaction at $E_d=170$ to 250 kev and for the highest energy group at 140 kev. A laboratory angular range from 0° to 140° was covered by the scintillation spectrometer technique using a thin CsI(Tl) crystal. Gamow plots of the total cross sections yield slopes approximately equal to the value anticipated from the Coulomb barrier penetration factor.

I. INTRODUCTION

ANGULAR distribution measurements[1] of protons from the $B^{10}(d,p)B^{11}$ reaction exist for most of the lowest dozen levels of B^{11} at one or more bombarding energies up to 15 Mev. A few investigators[2] have studied the reaction with deuteron energies of six to eight Mev, at which the Butler stripping theory[3] without Coulomb or nuclear interaction corrections gives a rather good description of most of the observed angular distributions. The poorer fits among the low levels include the reactions going to the first and third excited states.

Other measurements[1] exist at deuteron energies between 0.8 and 4 Mev. The situation is in general much more complicated near or below the Coulomb barrier and the simplest forms of the theory are not so applicable. In addition to anticipated distortions because of Coulomb effects, there appear to be competition from and possible interference with compound nucleus reactions. Nevertheless, at these lower energies in special cases of some nuclei with low Q values, the usual stripping approximations may be applicable.[4]

At deuteron energies far below the Coulomb barrier, the proton angular distributions do not appear a useful tool for determination of nuclear level spins and parities. Direct interaction does appear to contribute to some reactions, as shown in the work of Paris *et al.*[5] on the $B^{10}(d,p)B^{11}$ reaction at deuteron energies between 200 and 650 kev. Calculations of stripping theory in this energy range, including Coulomb and nuclear effects and interference with compound nucleus formation, are very complex. They would be of interest, however, for a better understanding of the observed distributions.

By use of nuclear emulsion, Paris *et al.* measured the angular distributions of protons going to the four lowest levels in B^{11}. They supplemented these measurements with differential cross sections at 120° taken with a scintillation counter. For the results of this report, obtained at energies between 140 and 250 kev, the scintillation counter method was used for all angular distribution and cross-section measurements.

II. EXPERIMENTAL METHOD

A magnetically analyzed mass-two ion beam from a Cockcroft-Walton accelerator consisted of greater than 99% deuterons. This beam impinged on a boron-10 target located at the center of a reaction chamber as shown in Fig. 1. The chamber was equipped with a fixed detector arm for monitoring, at an angle of 58°,

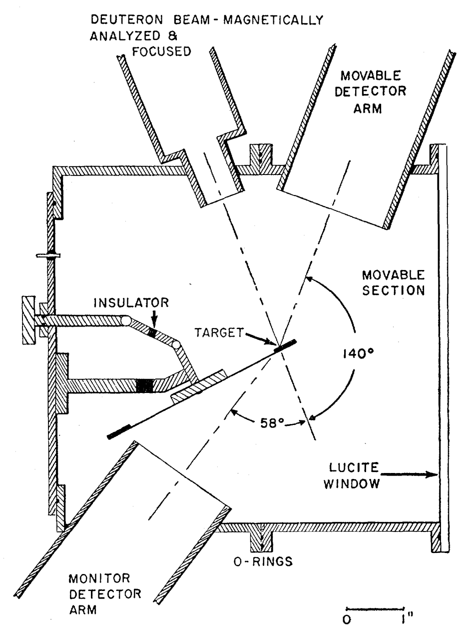

FIG. 1. Reaction chamber. The movable detector arm is continuously variable in position from 0° to 140°.

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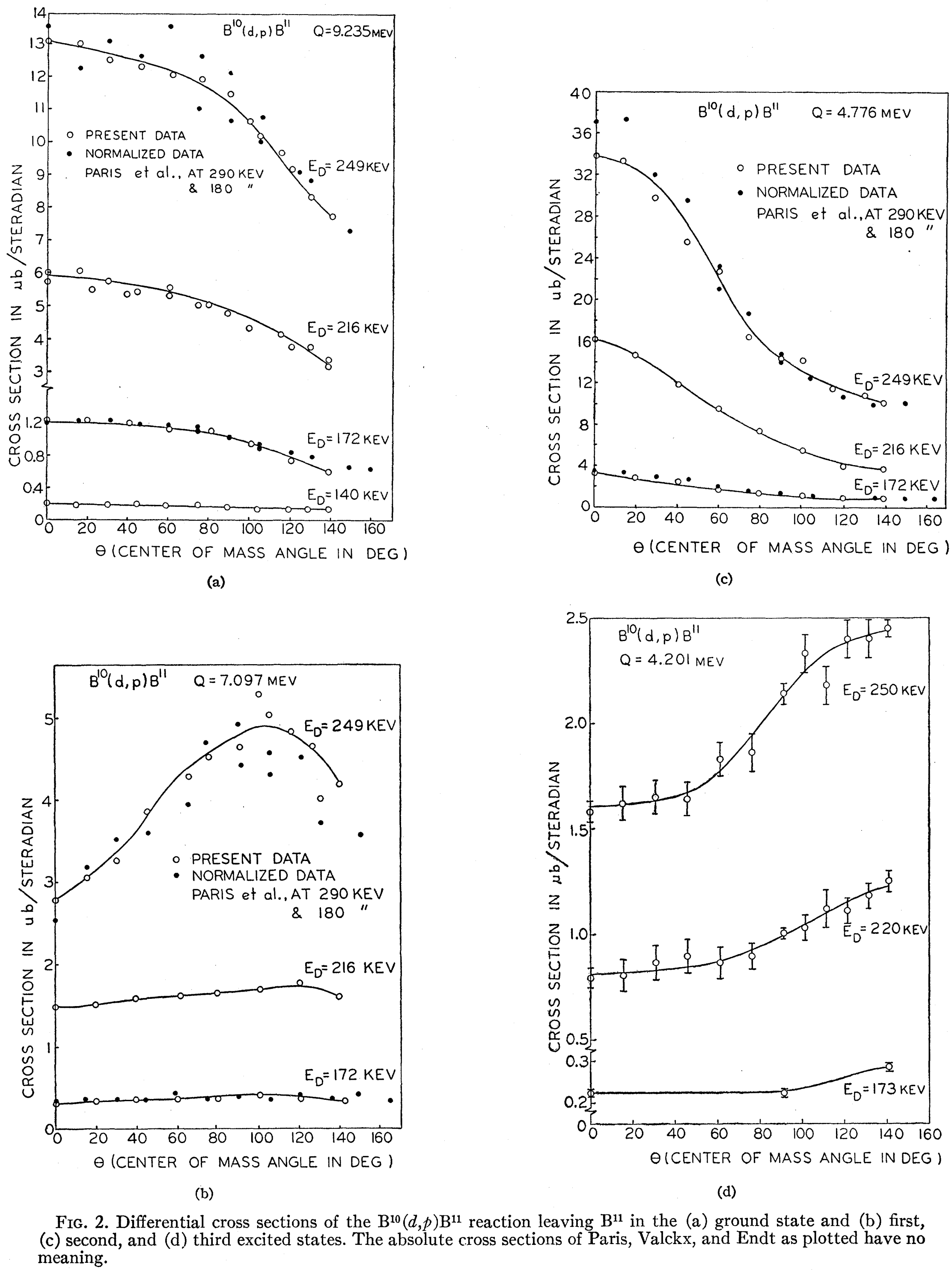

FIG. 2. Differential cross sections of the $B^{10}(d,p)B^{11}$ reaction leaving B^{11} in the (a) ground state and (b) first, (c) second, and (d) third excited states. The absolute cross sections of Paris, Valckx, and Endt as plotted have no meaning.

and a movable detector arm, which could be rotated from 0° to 140° with respect to the incident deuteron beam without breaking the vacuum. The target pedestal holding up to eight target foils could be externally rotated through 360°.

Various methods of measuring the ion beam current were used. These included measurement of collimated beam current to the target pedestal held at a voltage sufficient to suppress electron emission, use of the entire chamber as a Faraday cage, and, for purposes of

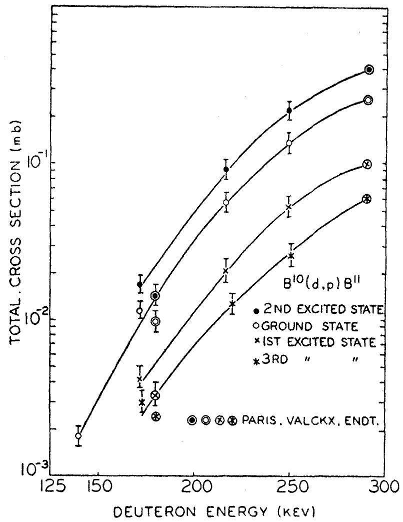

FIG. 3. Total cross sections of the $B^{10}(d,p)B^{11}$ reaction as a function of deuteron energy.

comparison, measurement of current to a Faraday cup attached to the movable detector arm in the forward position with the ion beam passing completely through the reaction chamber.

Several target deposits of near 60 and near 26 $\mu g/cm^2$ were prepared on aluminum backings. These target foils were oriented at 45° with respect to the deuteron beam.

As detectors, CsI(Tl) crystals of one mm and of 0.25-mm thicknesses were covered with 1.66-mg/cm² aluminum foil and mounted on light pipers attached to RCA 5819 photomultipliers. Each detector had a resolution of approximately 8% for 5.3-Mev alphas. The one-mm thick crystal showed a linear energy response to protons between 1.7 and 8.5 Mev.

With appropriate choice of absorber thickness placed in the path of the reaction products, the protons leading to the four lowest levels of B^{11} gave completely resolved peaks in the pulse-height spectrum with the absence of a background of continuum alpha particles or gamma rays. Angular distributions were obtained by integral counting of the protons in the peaks.

III. RESULTS AND DISCUSSION

The differential cross-section data for protons leading to the four lowest levels of B^{11} are shown in Fig. 2. The effective deuteron energies were determined by weighting according to the variation of cross section and stopping power through the boron deposits. Total loss of deuteron energy in the thicker and thinner targets, respectively, were approximately 50 and 25 kev. The data of Fig. 2(a) (b), and (c) are fitted with curves using Legendre polynomial series. There is rather pronounced peaking at the higher energies for all the proton groups. The data of Paris, Valckx, and Endt[5] at 290 kev and 180 kev are presented for comparison and agree well in angular distribution with the present data.

In our low-energy region, the usual forms of stripping theory with simplifying assumptions are unlikely to be valid. Therefore, the fact that one is able to fit approximately all the observed data in Fig. 2 by assuming an isotropic compound nucleus reaction combined with a noninterfering, conventional stripping contribution of suitable l_n values has little significance.

The believed values[1,2,6,7] for spins and parities of the ground through third excited states of B^{11} are, respectively, $\frac{3}{2}-$, $\frac{1}{2}-$, $\frac{5}{2}-$, $\frac{1}{2}-$(?). Higher energy data[2] at 8 Mev indicate that the neutron is captured for all these levels with $l_n=1$, in conformity with shell-model theory[8] giving excitation within the p shell. Since the spin of B^{10} is 3, the spin of $\frac{1}{2}$ cannot be reached with $l_n=1$ by normal stripping. The angular distribution for

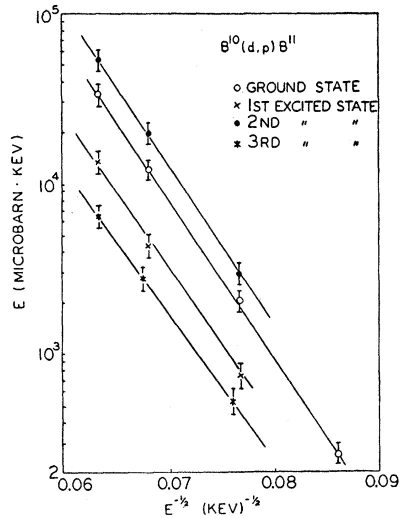

FIG. 4. Gamow plots of the $B^{10}(d,p)B^{11}$ reaction.

the first and third excited states is also somewhat anomalous at the higher energies. The correct spin of $\frac{1}{2}$ for the first excited state can be reached by nucleon exchange[9] or other spin-flip[7,10] stripping. Polarization measurement[11] of the emitted proton for this state gives evidence to support one of these mechanisms.

It will be noted that the data in Fig. 2 are rather strongly peaked forward for the ground and second excited states but peaked backward for the first and third excited states. It is not possible to say whether this difference may be caused in part by the relative

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difficulty for direct interaction to take place in the case of the latter states. The total cross sections, obtained by integration of the differential curves, are somewhat lower for these states, as seen in Fig. 3.

That Coulomb barrier penetration is an essential factor affecting the reaction at these low energies is indicated in Fig. 4. Gamow plots are made of the total cross sections of the four proton groups for *s*-wave deuterons. By neglecting the correction for the finite height of the barrier, one obtains a theoretical slope of 218 compared with an observed value for the combined proton groups of 215±7(kev)[3].

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Low-Lying Levels in P^{30}†*

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The reaction $Al^{27}(\alpha,n)P^{30}$ has been studied at 8.15-Mev bombarding energy using nuclear emulsions as detectors. Neutron groups corresponding to Q values of −2.70, −2.96, −3.59, −4.43, and −4.96 Mev were observed. Comparison of the resulting energy level structure in P^{30} with that obtained by other reactions suggests the possible inversion of the two isobaric spin ground states.

SELF-CONJUGATE odd-odd nuclei in the light mass region provide very favorable subjects for the study of isobaric spin, since they alone have more than one T value among their low-lying states. Of special interest is the study of their level structures to determine the position of the lowest $T=1$, $J=0^+$ state. P^{30}, for instance, has been investigated by several authors.[1–7] The results from $S^{32}(d,\alpha)P^{30}$ [1] and $Si^{29}(p,\gamma)P^{30}$ [3] in particular tend to identify the ground state as $T=0$, with the lowest $T=1$ level at 680-kev excitation. However, when these results are compared with those of several repeated $Al^{27}(\alpha,n)Si^{30}$ reactions,[5–7] it is seen that the level structures disagree beyond the limits of experimental error. The present investigation was an attempt to clarify this situation by a fourth analysis of this same reaction to check the previous data.

A thin aluminum target of 0.16 mg/cm² was bombarded with a collimated beam of magnetically analyzed alpha particles from the Yale cyclotron for a total integrated beam current of 7.5 millicoulombs. All charged particles were stopped in a 10-mil thick tantalum shield lined with 28 mg/cm² of high-purity gold foil. This latter served to reduce the probability of secondary (α,n) reactions being initiated by elastically scattered alphas in the absorbing ring.

The reaction neutrons were detected as proton recoils in 50 μ Ilford C-2 emulsions placed at scattering angles of 0° back to 162.5° at either side of the beam axis. The apparatus used has been previously described.[8] The detectors were placed normal to the scattering plane and inclined at 5° to the radius, which is the nominal particle direction. For most of the plates exposed, an auxiliary radiator of $\frac{1}{4}$-mil Mylar foil (0.86 mg/cm²) was placed immediately outside the absorber. The knock-on protons induced in this foil were then collimated by appropriate slits prior to detection in the emulsions.

The emulsions were scanned using a Leitz microprojector at 500× magnification. Only proton recoils ending in the emulsion and making an angle of no more than 10° with respect to the nominal neutron direction were accepted. An average of 1500 tracks were measured on each of the nineteen angles analyzed. A typical proton recoil spectrum is shown in Fig. 1. This particular spectrum was chosen since it illustrates all groups discussed below most clearly. To improve the counting statistics in the region of interest, additional areas of each plate were scanned, measuring only those tracks longer than a given minimum range, such as 60 μ in the case of Fig. 1.

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