# Back-angle differential cross section measurements for $(d,p)$ reactions on light nuclei at low bombarding energies

F. E. Cecil and R. F. Fahlsing
*Department of Physics, Colorado School of Mines, Golden, Colorado 80401*
(Received 20 April 1981)

Thick target yields of the $(d,p)$ reaction on $^6$Li, $^9$Be, and $^{10}$B have been measured at a scattering angle of 150° for deuteron bombarding energies between 29 and 170 keV. The differential cross sections were deduced from the thick target yields using recently published values of the stopping power of low energy deuterons in matter.

[NUCLEAR REACTIONS $^6$Li, $^9$Be, $^{10}$B$(d,p)$, $E_d = 29-170$ keV. Measured thick target yield. Deduced $\sigma(\theta_p = 150°)$.]

Charged particle induced nuclear reactions on light nuclei have been widely studied at energies generally in excess of 100 keV or so. There is justification for extending the measurements of deuteron induced nuclear reactions on light nuclei ($6 \leq A \leq 10$) to still lower energies. These reactions, for example, constitute some of the primary reaction mechanisms for "advanced" fusion fuels in the CTR technology[1] and may play a secondary role, such as in a diagnostic capacity,[2] in the first and second generation fusion reactors.

In the application of low energy nuclear reactions to nucleosynthesis in stars, the proton and alpha induced reactions have played a dominant role by virtue of their elemental abundances. Recent models[3] of element production in the early universe suggest a higher abundance of deuterium than in contemporary stellar systems. As such, the knowledge of deuteron induced reactions at relatively low energies may provide needed input to the future consideration of such models.

In the present work we have measured back angle ($\theta_p = 150°$) absolute differential cross sections for the $(d,p)$ reaction on $^6$Li, $^9$Be, and $^{10}$B to particular low lying levels in the final nuclei. The highest energy (160 keV) at which the measurements were made overlapped with the lowest energies of previously reported measurements.[4–6] The lowest energies at which the cross sections were measured on $^6$Li, $^9$Be, and $^{10}$B in the present work are, respectively, 36, 68, and 92 keV.

The experiment consisted of measuring the thick target (in which the beam stopped in the targets) yields for the $(d,p)$ reactions on targets of isotopically enriched $^6$LiO$_2$, $^9$BeO, and isotopically enriched metallic $^{10}$B. The bombardments were carried out in a small (30 cm diameter) scattering chamber with the magnetically analyzed beam from the Colorado School of Mines Physics Department 180 keV Cockcroft-Walton accelerator. Charged particles from the reactions (alphas as well as protons) were detected in reflection geometry ($\theta \simeq 150°$) with a 0.5 mm surface barrier silicon detector. The accumulated beam charge was measured by integrating the current from the target itself (since the beam stopped in the target). A bias voltage on the target effectively eliminated any uncertainty in the measurement of this charge due to electron knockout from the target. In addition, the fact that the beam was magnetically analyzed immediately upstream from the target prevented any neutral deuterium from striking the target. The energies of the detected particles were calibrated with a $^{241}$Am alpha source.

Typical spectra on the three targets are shown in Fig. 1. (It should be noted that the relatively good resolution of the states is possible given the thick target nature of the measurements, since the range of the incident deuterons is very much less than the range of the products in the three exothermic reactions.) We note (apologetically) that the charge particle detector was of insufficient thickness to stop the 9 MeV protons corresponding to the ground state of $^{11}$B in the $^{10}$B$(d,p)$ reaction. This state [labeled $p_0$ in Fig. 1(a)] is therefore shifted down about 1.8 MeV in the spectrum compared to where it would be had we a thicker detector.

The thick target yield $Y(E_0)$ at an incident deu-

 

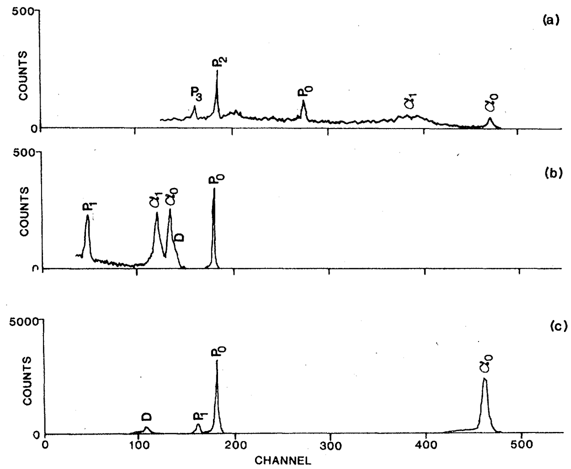


FIG. 1. Typical spectra for the reactions (a) $^{10}B(d,p)$, (b) $^{9}Be(d,p)$, and (c) $^{6}Li(d,p)$. The energies of the levels are given in Table I. The peaks labeled $D$ correspond to the 3.6 MeV protons from the reactions $^{2}H(d,p)^{3}H$ due to deuterium build up in the target.

teron energy $E_0$ is determined by the cross section and the stopping power $\epsilon(E)$ (Ref. 7) (in keV atom$^{-1}$ cm$^2$)

$$Y(\theta,E_0)=\int_{E_0}^{0}\frac{\sigma(\theta,E)}{\epsilon(E)}f\,dE\ , \tag{1}$$

where $f$ is the isotopic enrichment of the nucleus under consideration. For the $^{6}LiO_2$ and $^{9}BeO$ molecular targets, the stopping powers were taken as the sums of the constituent stopping powers. This approximation is valid to within about 10% for the reaction energies under consideration.[8] In the present work the yields were measured at equally spaced energy intervals ($\Delta E=24$ keV) (except for the lowest energy $^{6}Li$ measurements) and the cross sections were determined at intermediate effective energies $\bar{E}$ from Eq. (1) by the relation

$$Y(E_1)-Y(E_2)=\frac{\sigma(\theta,\bar{E})}{\epsilon(\bar{E})}(E_2-E_1)\ , \tag{2}$$

where the effective energy $\bar{E}$ is determined by the equation

$$(\bar{E}^{-1})\left[\exp\left[-\frac{44.5Z_T}{\bar{E}^{1/2}}\right]\right](E_1-E_2)$$
$$=\int_{E_2}^{E_1}(E^{-1})\left[\exp\left[-\frac{44.5Z_T}{E^{1/2}}\right]\right]dE\ . \tag{3}$$

In Eq. (3), $Z_T$ is the target nucleus charge and $E_1$ and $E_2$ are the laboratory energies (in keV) at which the yields in Eq. (2) are measured.

Equation (3) assumes that the differential cross sections are piecewise proportional to the Coulomb barrier penetration probability[9] and that the stopping powers are slowly varying functions of energy. A more detailed discussion of the extraction of cross sections from thick target yields can be found in Ref. 10.

The cross sections so determined are given in Table I (the reactions in Table I are specified by the excitation energy of the state in the final nucleus). For the sake of comparison with previous measurements,[4–6] the cross sections for the $(d,p_0)$ reactions (to the ground states of $^{7}Li$, $^{10}Be$, and $^{11}B$) are plotted in Fig. 2. Defining the astrophysical $s$ factor for the differential cross sections in the usual fashion [using the notation in Eq. (3)],

$$\sigma(\theta,E)=s(\theta,E)\exp\left[-\frac{44.5Z_T}{E^{1/2}}\right](\bar{E}^{-1})\ ,$$

we have calculated the values of $s(\theta,\bar{E})$ for the ground state differential cross sections given in

TABLE I. Differential cross section measurements at $\theta_p=150°$ for $(d,p)$ reactions on $^{6}Li$, $^{9}Be$, and $^{10}B$ (in mb/sr).

| Final state (MeV) | $^{7}$Li(g.s.) | $^{7}$Li(0.478) | $^{10}$Be(g.s.) | $^{10}$B(3.37) | $^{11}$B(g.s.) | $^{11}$B(4.44) | $^{11}$B(5.02) |
|---|---|---|---|---|---|---|---|
| Deuteron energy (keV) | | | | | | | |
| 161 | 3200 ±100 | 770 ±50 | 180 ±20 | 180 ±20 | 1.37 ±0.09 | 3.7 ±0.2 | 0.99±0.25 |
| 137 | 1500 ± 80 | 430 ±20 | 120 ±10 | 41 ± 5 | 0.48 ±0.03 | 0.78 ±0.04 | 0.25±0.10 |
| 114 | 720 ± 50 | 110 ±20 | 18 ± 2 | 11 ± 1 | 0.13 ±0.03 | 0.17 ±0.03 | 0.04±0.02 |
| 91 | 230 ± 40 | 34 ± 6 | 2.9 ± 0.4 | 3.1 ± 0.5 | 0.011±0.006 | 0.011±0.006 | |
| 67 | 34 ± 4 | 6.6± 0.9 | 0.44± 0.16 | 0.09± 0.02 | | | |
| 47 | 3.1± 0.6 | 0.1± 0.01 | | | | | |
| 36 | 0.6± 0.2 | | | | | | |

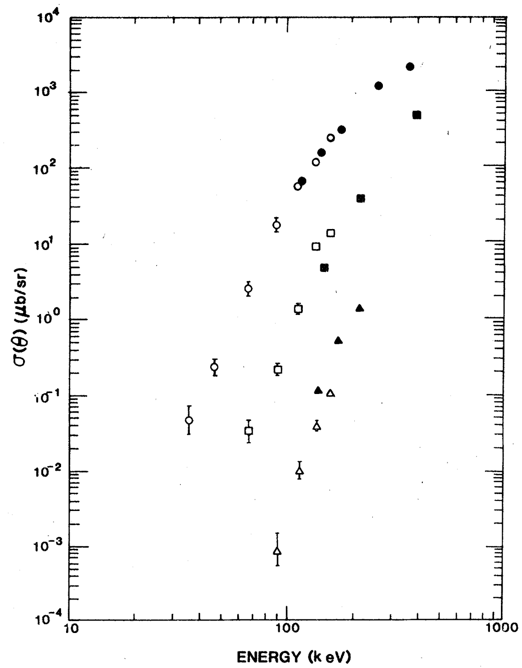


FIG. 2. Differential cross sections for the reactions $^6$Li($d,p_0$) (circles), $^9$Be($d,p_0$) (squares), and $^{10}$B($d,p_0$) (triangles). The open symbols are the present results and the solid symbols are earlier results (Refs. 4–6, respectively).

Table I. These are given in Table II. The values of $s(\theta,\bar{E})$ given in Table II support our assertion [used in Eq. (30)] that the cross sections are roughly proportional to the Coulomb barrier penetration probability.

The $^6$Li($d,p$) cross sections measured in the present work agree very well, as indicated in Fig. 2, with the earlier measurements[4] of this reaction. On the other hand, there is a significant disagreement between the present work and previous measurements of the ($d,p$) reaction $^9$Be (Ref. 5) and $^{10}$B (Ref. 6). While we are unable to ascertain the source of this discrepancy, we should emphasize that we sought to ensure identical experimental conditions and carried out analogous analyses during the course of the three sets of measurements.

The total cross sections for the ($d,p$) reactions on $^6$Li and $^{10}$B are given approximately by $4\pi$ times the differential cross sections given in Table I since earlier measurements at low energies of angular distributions[4,5,11] indicate near isotropy. Measurements of the angular distribution of the $^9$Be($d,p$) reaction[5,12–14] indicate a significant backward

TABLE II. $s(\theta,E)$ at $\theta=150°$ for ($d,p$) transition to ground states of final nuclei (in MeV b).

| Energy \ Target | $^6$Li | $^9$Be | $^{10}$B |
|---|---|---|---|
| 161 | 19.2± 2 | 36± 3 | 9.3±1 |
| 137 | 18.5± 2 | 66± 7 | 12 ±2 |
| 114 | 21.8± 2 | 36± 4 | 16 ±4 |
| 91 | 25 ± 3 | 34± 6 | 14 ±7 |
| 67 | 28 ± 4 | 81±25 | |
| 47 | 42 ±10 | | |
| 36 | 100 ±40 | | |

peaking in the angular distribution and consequently $4\pi$ times the $^9$Be differential cross sections in Table I would overestimate the total cross section.

Finally, we would like to present a justification for our present work in light of the fact that these reactions have already been measured down to relatively low energies. As noted in our introduction, a possible utilization the ($d,p$) reaction on light nuclei might be in the context of high temperature deuterium plasma diagnostics. Rolfs and Trautretter[15] discuss the nuclear reaction rate for two nuclear species at thermal equilibrium with $kT$ well below the nuclei's Coulomb barrier. They note, due to the cross section which decreases rapidly at low energies, and the population distribution, which decreases rapidly at high energies, that the reactions take place in a narrow energy range, known as the Gamow peak.

A knowledge of the reaction cross section at the energy of the Gamow peak is thus necessary and sufficient to predict the reaction rate when the two nuclear species are in thermal equilibrium. Using Eq. (6) in Ref. 15 for a temperature $T=100\times10^6\,°$K (a few keV above the ignition temperature of a $d$-$t$ fusion reaction[16]), we find that the Gamow peak centroid energies for the reactions $^6$Li($d,p$), $^9$Be ($d,p$), and $^{10}$B($d,p$) are 59, 74, and 98 keV, respectively. These energies are below the minimum energies at which the above reactions have, to date, been measured, but are within the range of the present measurements.

This work has been supported by the U. S. Department of Energy under Contract DE AC01-80ER10643.

[1]Goeffrey W. Shuy and Robert W. Conn, in *Nuclear Cross Sections for Technology,* edited by J. L. Fowler, C. H. Johnson, and C. D. Bowman, Natl. Bur. Stand. (U. S.) Special Publication No. 594 (1980), p. 254.

[2]F. C. Young *et al.*, Rev. Sci. Instrum. 48, 432 (1977); F. E. Cecil *et al.*, Nucl. Instrum. Methods 175, 293 (1980).

[3]David N. Schramm and Robert V. Waggoner, Annu. Rev. Nucl. Sci. 27, 37 (1977).

[4]A. J. Elwyn *et al.*, Phys. Rev. C 16, 1744 (1977).

[5]J. Cheng-lie *et al.*, Wuli Xuebo (Acta Phys. Sin.), 23, 362 (1974) [Chin. J. Phys. 23, 227 (1975)].

[6]G. R. Harrison *et al.*, Phys. Rev. 117, 532 (1960).

[7]H. H. Anderson and J. F. Zeigler, *The Stopping Powers and Ranges of Ions in Matter; Vol. 3, Hydrogen* (Pergamon, New York, 1977).

[8]J. F. Zeigler, private communication.

[9]C. A. Barnes, in *Advances in Nuclear Physics,* edited by M. Baranger and E. Vogt (Plenum, New York, 1971), Vol. IV, p. 142.

[10]H. Mak *et al.*, Nucl. Phys. A226, 493 (1974).

[11]C. H. Paris *et al.*, Physica 20, 573 (1954).

[12]Mira K. Juric, Phys. Rev. 98, 85 (1955).

[13]E. Freidland *et al.*, Z. Phys. 267, 97 (1974).

[14]D. de Jong *et al.*, Physica 18, 677 (1952).

[15]C. Rolfs and H. P. Trautretter, Annu. Rev. Nucl. Sci. 28, 115 (1978).

[16]F. L. Ribe, Rev. Mod. Phys. 47, 7 (1975).