^{7}Li$(d,p)^{8}$Li reaction cross section near 0.78 MeV

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The total cross section for the ^{7}Li$(d,p)^{8}$Li reaction has been obtained at four energies near 0.78 MeV from measurements of the differential cross sections for the outgoing protons at laboratory angles between 20° and 155°. The average value, 146 ± 13 mb at an average deuteron energy of 0.781 MeV, is about 20% lower than the weighted mean of all previous absolute measurements. It is, however, in agreement with two other completely independent measurements, and the three experiments together provide a consistent (but lower) value for this important cross section.

NUCLEAR REACTIONS ^{7}Li$(d,p)^{8}$Li, $E_d=0.684-0.896$ MeV; enriched ^{7}LiF target; measured $\sigma(E_d,\theta)$, $\sigma(E_d)$, at $E_d\simeq0.781$ MeV, $\sigma(E_d,50°)$ at $E_d=0.684-0.896$ MeV.

I. INTRODUCTION

The absolute cross section for the ^{7}Li$(d,p)^{8}$Li reaction at deuteron energies near 0.78 MeV has been used to obtain the ^{7}Be target thickness in measurements[1–3] of the ^{7}Be$(p,\gamma)^{8}$B reaction cross section. An accurate determination of the cross section for this latter reaction, which is one of several steps in the hydrogen burning sequence of nucleosynthesis,[4,5] is of prime importance to the interpretation of the ^{37}Cl solar neutrino experiments.[6]

Over the years there have been a number of independent measurements[1,2,7–11] of the ^{7}Li(d,p) reaction cross section near 0.78 MeV. However, the results show considerable scatter. Of the three most recent studies, two[10,11] are in agreement, while the third[9] is lower by a factor of about 1.3. The experiments of Refs. 1 and 7–9 were performed by observing the beta decay of ^{8}Li, those of Refs. 2 and 10 by detection of the alpha particles from ^{8}Be following the beta decay, and that of Ref. 11 by detection of the beta decay but with the absolute cross sections obtained from normalization to previously measured[12] integrated proton angular distributions in the (d,p) reaction at energies greater than 2 MeV. Absolute values for the proton distributions in Ref. 11 were in turn determined by normalization to the ^{7}Li(d,d) back-angle scattering data of Ford[13] at energies between 1.6 and 1.8 MeV.

Because of the importance of the ^{7}Li(d,p) reaction to the astrophysical applications, and because of the uncertainties in the previous results, the present work was undertaken to provide a completely independent determination. The cross section has been obtained from measurements of the yields of the outgoing protons. This paper represents the first report, for energies near 0.78 MeV, of the detection of the protons in the reaction. Sellschop[14] had earlier measured proton angular distributions over a somewhat limited angular range at energies near and above 1 MeV.

II. EXPERIMENT

The experiment was performed at the Argonne Dynamitron accelerator. The experimental arrangement and procedures have been described previously[15] in a series of reports concerned with the accurate measurement of cross sections for light ions on ^{6}Li.

In order to avoid a molecular hydrogen contaminant, the mass 6 (D_3^+) molecular deuterium ion beam was used in the present measurements. After acceleration the beam entered a 76-cm diam scattering chamber through a number of defining apertures. The targets placed at the center of the chamber were thin films (36–45 μg/cm^2) of LiF (enriched to 99.99% in ^{7}Li) evaporated on 10 $\mu g/cm^2$ Al foils. The beam passing through the targets was collected in a Faraday cup, in which secondary electron loss was magnetically suppressed, and the total charge was measured with a current integrator whose operation was checked by the use of batteries and precision resistors and found to be accurate to better than 0.5%. The beam line and target chamber system were pumped by turbo-molecular pumps backed by liquid-nitrogen traps to typical chamber pressures of 10^{-6} Torr. The ion beam entered the chamber through an in-line liquid-nitrogen cold finger before impinging on the targets. Molecular-ion beam currents were kept very small (10−20 nA); even so, small amounts of carbon did build up on the targets during experimental runs. The amount of carbon buildup was monitored by observation of the ^{12}C(d,d) yields at 157.5°. At some back angles the proton group from the ^{12}C(d,p) reaction interfered with the determination of the ^{7}Li(d,p) yield. In such cases, corrections (usually $\lesssim 5\%$) were made, based on yields from supplemental experimental runs with thin C foils.[16]

The Dynamitron energy scale was calibrated at the neutron threshold (1.8806 MeV) in the ^{7}Li(p,n)^{7}Be reaction, and at the 872.1-keV resonance in the ^{19}F($p,\alpha\gamma$)^{16}O reaction. The deuteron energies quoted in this paper represent average values (i.e., the energy corrected to that at the center of the target). That is, they differ from the incident energies because of the energy loss ($\approx$16 keV at 0.78 MeV) in the LiF targets. Although the dissociation[17] in the target of the incident D_3^+ molecular ion introduced an additional spread in deuteron energy ($\sim$7 keV), the average energy was not changed.

Charged particles from deuteron-induced reactions on the targets were detected in a 300-μm thick collimated Si surface-barrier detector mounted on a movable arm within the scattering chamber. A second similar detector, fixed at an angle of 157.5° with respect to the incident beam, served as a monitor in the angular distribution measurements. Because of the small Q value for the ^{7}Li(d,p) reaction (i.e., $Q = -0.19$ MeV), it is difficult to distinguish, particularly at laboratory angles greater than 100°, outgoing protons from the far more intense yield of elastically scattered deuterons. To accomplish this separation, therefore, the incident beam was pulsed, and the mass of the outgoing particles identified by their time of flight. The beam pulse rate was 8 MHz, pulse width was $\sim$1 ns, and the flight path from target to detector was 17.5 cm. Time and pulse-height data from the movable Si detector were stored as a two-dimensional array in the PDP-11/45 computer and later transferred to magnetic tape. A typical two-dimensional spectrum is shown in Fig. 1. Subsequent off-line analysis allowed the separation of proton and deuteron spectra and the yields of the individual particle groups could be

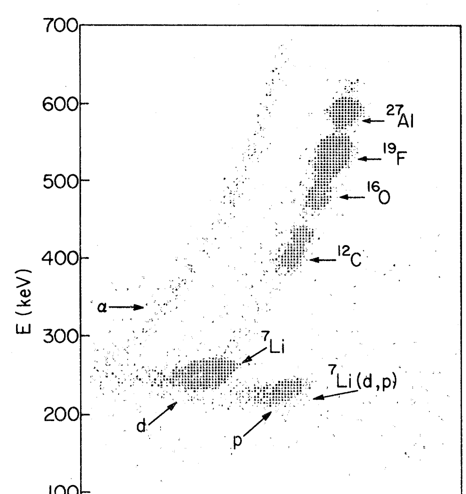

FIG. 1. Two-dimensional spectrum of pulse height (converted to energy units) vs time of flight at $\theta_{lab}=155°$ for $E_d=0.777$ MeV. Deuterons elastically scattered from the various target nuclei are indicated, as is the ground-state proton group in the ^{7}Li(d,p)^{8}Li reaction.

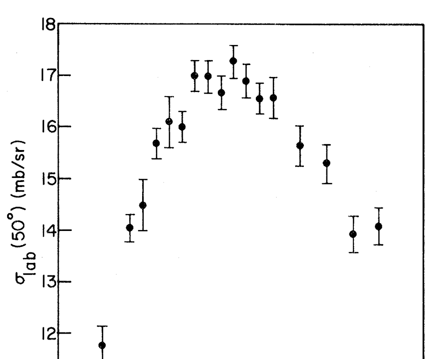

FIG. 2. Excitation function at a laboratory angle of 50° for the ^{7}Li(d,p)^{8}Li(g.s.) reaction. The error bars represent relative uncertainties only. The target thickness for these measurements was $\approx$16 keV for 0.78-MeV protons.

easily obtained.

Angular distributions of the protons were measured at 10 or 11 laboratory angles between 20° and 155° at four energies near 0.78 MeV. The yields were obtained relative to those in the fixed monitor detector, and both were corrected for electronic dead-time effects. These corrections were less than 6% except at very forward angles (20°) where they could be as large as 20%.

Absolute differential cross sections were obtained by normalization to a separately measured 50° excitation function, which is shown in Fig. 2. The observed peak is apparently associated with a broad ($\Gamma \approx 250$ keV) resonance structure[18] in ^{9}Be. These measurements were made at energies between 0.684 and 0.896 MeV, and the yields were corrected for any alteration of the charge state of the beam passing through the thin foils as well as for small-angle multiple scattering, as described previously.[15] The target thickness was determined by normalization of the measured yield of elastically scattered deuterons at 157.5° to that from a target in which the LiF was sandwiched between two thin layers of Au. The thickness of the "sandwich" target was obtained[15] from measurements of the energy loss of backscattered deuterons by use of atomic stopping powers tabulated by Andersen and Ziegler.[19] After making a small correction ($\approx 5\%$) to account for H and O target contamination (probably in the form of water), the final target thickness was (45 ± 4) μg/cm^2 of ^{7}LiF.[20] The major contribution to the indicated error arises from an uncertainty in the LiF stopping powers of $\sim 7.5\%$.

Differential cross sections at laboratory angles 75 – 135° obtained from normalization to the excitation function are shown in Fig. 3. These are compared with similar quantities determined by normalization of measured ^{7}Li(d,d) yields to the absolute values of Ford[13] (which have a quoted precision of 6%) between 0.75 and 0.8 MeV. The good agreement between the two independent determinations provides a convenient check of the consistency of

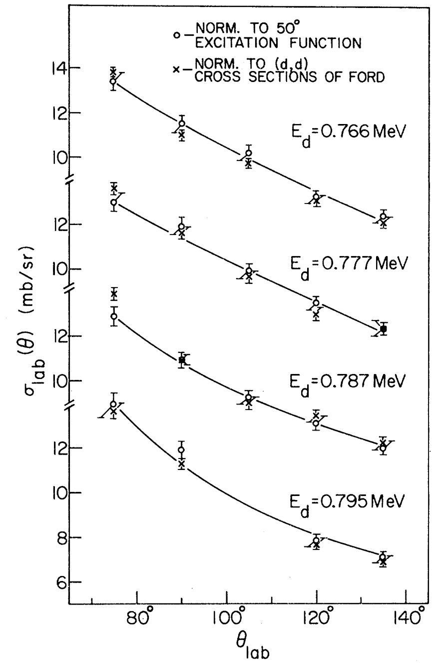

FIG. 3. Differential cross section in the laboratory system for ^{7}Li(d,p)^{8}Li at angles between 75 and 135° at the average deuteron energy indicated. The open circles represent cross sections normalized to the separately measured 50° excitation function. The crosses were obtained by normalization of elastic scattering yields to the ^{7}Li(d,d) cross sections of Ford, Ref. 13. The error bars represent relative uncertainties only.

TABLE I. Values of the coefficients B_L in the expansion of the differential cross section for the ^{7}Li(d,p)^{8}Li reaction into a series of Legendre polynomials, and the total cross section σ_r, where $\sigma_r = 4\pi B_0$. The errors on the coefficients are based on statistical uncertainties and the quality of the least-squares fit. The error on σ_r is the absolute uncertainty.

E_d (MeV)	B_0	B_1	B_2 (mb/sr)cm	B_3	B_4	σ_r (mb)
0.766	11.58	0.43	−2.25	−1.10	−1.34	146±13
	±0.09	±0.15	±0.21	±0.24	±0.27	
0.777	11.86	1.15	−1.17	−0.28	−0.80	149±13
	±0.09	±0.16	±0.23	±0.24	±0.26	
0.787	11.44	1.40	−1.32	−0.77	−1.08	144±13
	±0.06	±0.11	±0.11	±0.16	±0.18	
0.795	11.73	1.03	−2.10	−1.23	−0.25	147±13
	±0.11	±0.18	±0.26	±0.28	±0.31	

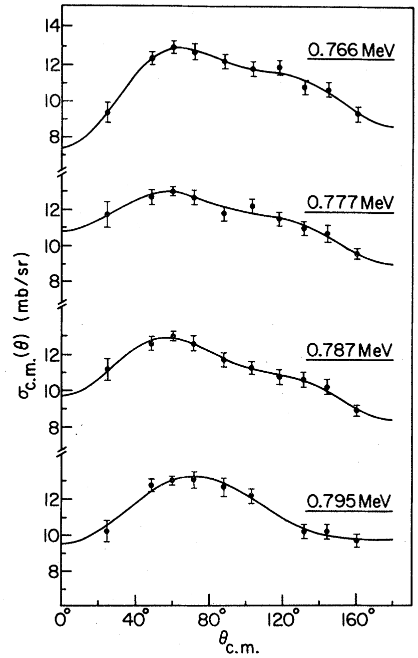

FIG. 4. Angular distributions in the center-of-mass system for the protons in the $^{7}Li(d,p)^{8}Li$ reaction, as a function of average incident deuteron energy. The error bars are relative uncertainties. The smooth curves at each energy represent the results of the Legendre polynomial fit.

the target thickness and integrated charge measurements in the experiment.

III. RESULTS AND DISCUSSION

The differential cross sections in the center-of-mass system are shown in Fig. 4 at each (average) incident deuteron energy. Relative uncertainties of about 6% on the measured 20° cross sections are between two and three times larger than for most other angles because of large backgrounds in the region of the proton peaks. The values shown here represent weighted averages of two independent experimental runs. The solid curves on Fig. 4 result from fitting the differential cross sections to a series of Legendre polynomials at each energy [i.e., $\sigma(\Theta)=\sum_{L=0}^{4} B_L P_L(\cos\theta)$]. The coefficients B_L in the expansion are listed in Table I.

Integrated (total) cross sections ($\sigma_r = 4\pi B_0$) are shown in the last column of Table I. The absolute error of about 9% includes an uncertainty of 3% estimated from values of σ_r obtained in the Legendre analysis by use of extreme values for the 20° cross sections in the two different experiments mentioned above, as well as a systematic uncertainty of about 8.5% (arising mainly from errors in solid angle and target thickness determinations).[21] An average of the four values listed in the table, $\sigma_r = 146 \pm 13$ mb, is plotted at an average deuteron energy of 0.781 MeV in Fig. 5. As observed, the present result agrees with the measurements of McClenahan and Segel,[9] the very early experiment of Bashkin,[8] and perhaps the reevaluated cross section of Kavanagh,[1,5] but disagrees with the fairly recent determinations of Schilling *et al.*[10] and Mingay[11] (although the quoted errors in the present results and those of Ref. 11 overlap slightly). It is furthermore 20% lower than the weighted mean, $\sigma_r = 183$ mb, quoted by Mingay,[11] and 17% lower than the weighted mean, $\sigma_r = 176$ mb, given by Parker.[5]

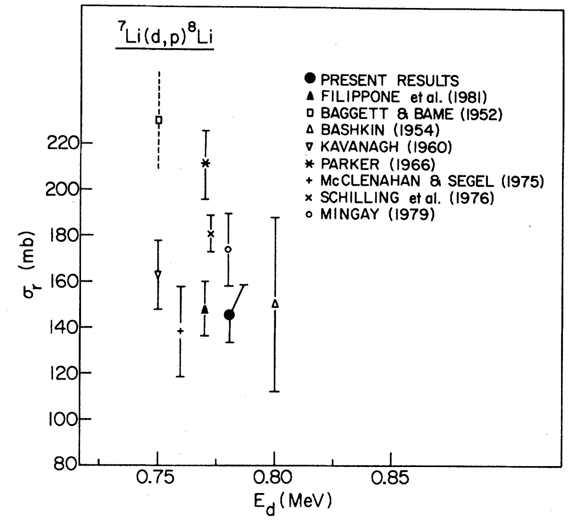

FIG. 5. The total cross section for the $^{7}Li(d,p)^{8}Li$ reaction at energies near 0.78 MeV. The present average value along with that of Ref. 22 is plotted with the previous measurements, which refer to Refs. 1, 2, and 7–11. The result of Ref. 1 is for the value quoted in Ref. 5.

Because of the disagreement of the present results with the previous delayed alpha particle experiments,[2,10] we have very recently completed an independent remeasurement of the yield of ^{8}Be alphas following the ^{8}Li beta decay. The experiment and the results are described in some detail in a paper by Filippone *et al.*[22] The value of the $^{7}Li(d,p)^{8}Li$ reaction cross section from that work, $\sigma_r = 148 \pm 12$ mb at $E_d = 0.770$ MeV, is in excellent agreement with the present result (see Fig. 5). It appears therefore that results from three independent measurements based on completely different experimental techniques—the observation[9] of the beta decay of

^{8}Li, the detection of the ^{8}Be breakup alpha particles,[22] and the counting of the protons in the reaction—provide a consistent value for the ^{7}Li(d,p) reaction cross section at energies near 0.78 MeV. The reason for the discrepancy with the previous results, particularly Refs. 10 and 11, is not understood. It is puzzling, in this connection, that both the present experiment and that of Mingay[11] appear to be consistent with the back-angle deuteron elastic scattering data of Ford[13] (although the comparison involves very different regions of energy), but give discrepant values for the cross section near 0.78 MeV. There can be subtle reasons for this which are difficult to uncover from published reports.

As mentioned in the Introduction, the ^{7}Li$(d,p)^{8}$Li reaction near 0.78 MeV has been used to provide the absolute calibration for the ^{7}Be$(p,\gamma)^{8}$B reaction. The ^{7}Be(p,γ) cross section is, in turn, one of the important nuclear parameters that enter into the calculation of the ^{37}Cl solar-neutrino capture rate; for example, in the latest estimate of Bahcall *et al.*[23] about three quarters of the total rate arises from the ^{7}Be(p,γ) reaction. The calculation by Bahcall *et al.* depends on the ^{7}Be(p,γ) cross section values given by Parker,[4] which are apparently based on ^{7}Li(d,p) values[4,5] $\sigma_r = 176-186$ mb. If instead of these, the ^{7}Li(d,p) cross sections from the present work ($\sigma_r = 146$ mb) are used to scale the (p,γ) cross section values, the rate which can be calculated by use of a simple formula[5,24] is $\sim 80\%$ of the Bahcall *et al.* estimate. The current predicted rate is 7.8 solar neutrino units[23] (SNU, where 1 SNU$\equiv 10^{-36}$ neutrino captures per ^{37}Cl atom per sec), or, in a more recent estimate[25] 7.0 SNU, and the revised value using our cross section is therefore lower by ≥ 1 SNU. Further discussion of the solar neutrino calculation in relation to the results of the current measurements is given in Ref. 22.

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[20]This value agrees within $\sim 1\%$ with determination of the thickness based on the broad width of the ^{19}F(d,d) peak observed on particle spectra at an angle of 157.5°.

[21]It is interesting to note that the lack of measured cross sections for laboratory angles smaller than $\theta = 20°$ (or, larger than $\theta = 155°$) makes little difference on the determination of σ_r unless these (unknown) forward-angle cross sections are unreasonably large. For example, the integrated cross sections, calculated on the assumption that all differential cross sections below 40° are set equal to the value (in the c.m. system) at 40°, are increased by only $\sim 2\%$ over the values shown in this report. This arises because the differential cross sections must be weighted by $\sin\theta$ in the determination of the reaction cross section.

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