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Absolute cross section for ^{7}Li(d,p)^{8}Li and solar neutrino capture rates

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The absolute total cross section for the ^{7}Li(d,p)^{8}Li reaction has been measured between 0.60 and 1.2 MeV by counting the beta-delayed alpha particles from ^{8}Be*. The cross section at the peak of the 0.77-MeV resonance was measured to be 148 ± 12 mb in good agreement with the new measurement of Elwyn *et al.* but disagreeing with several previous experiments. The effects of changes in this cross section on the calculation of solar neutrino captures rates is discussed.

[NUCLEAR REACTIONS ^{7}Li(d,p)^{8}Li, $E_d=0.6-1.2$ MeV; measured $\sigma(E)$, ^{8}Li delayed α particles; enriched targets; calculated ^{37}Cl solar neutrino capture rates.]

INTRODUCTION

The ^{7}Li(d,p)^{8}Li cross section at the peak of the 0.77-MeV resonance has been used as the calibrating reaction for nearly all measurements of the ^{7}Be(p,γ)^{8}B cross section.[1-4] In the solar interior it is this burning of ^{7}Be to ^{8}B with the subsequent emission of high energy neutrinos from ^{8}B decay that accounts for nearly 80% of the calculated neutrino capture rate[5,6] in the ^{37}Cl experiment of Davis.[7] The present discrepancy of about a factor of 3 between theory and experiment warrants a reexamination of the nuclear cross sections relevant to calculations of the neutrino flux from the sun.

Previous measurements[1,2,8-12] of the ^{7}Li(d,p)^{8}Li reaction have differed by up to 40% from each other, with each measurement claiming uncertainties of $\simeq$10%. While all of these experiments measured either the β or α activity following ^{8}Li decay, a new experiment by Elwyn *et al.*[13] has directly measured the protons from the ^{7}Li(d,p)^{8}Li reaction. The results from this new measurement are $\sim$20% below the mean value of the previous experiments but in good agreement with one[10] that measured the high-energy β's from the ^{8}Li decay. However, the previous measurements[2,11] of the delayed α's from the breakup of ^{8}Be* following the beta decay have yielded significantly higher cross sections. In light of this discrepancy and because of the importance of this cross section to the calculation of solar neutrino capture rates we have remeasured the ^{7}Li(d,p)^{8}Li cross section by counting the β-delayed alpha particles. Particular attention was paid to numerous consistency checks to look for possible sources of error. In addition, the effects of changes in this cross section on the solar neutrino capture rate are investigated using the solar model code of Filippone and Schramm.[6]

EXPERIMENTAL PROCEDURE

The experiment was performed at the Argonne 4.5-MV Dynamitron accelerator. Beams of the molecular ion D_3^+ (10–20 nA electrical) with energies ranging from 1.8–3.6 MeV (0.6–1.2 MeV deuterons) were analyzed by a bending magnet, collimated, and directed onto the target. The mass 6 (D_3^+) beam was used because a time- and source-dependent contamination of the mass 2 (D^+) beam with molecular hydrogen (H_2^+) was observed in backscattering experiments from a thin gold foil. The beam energy was calibrated by the ^{7}Li(p,n)^{7}Be reaction with a threshold of 1880.60 keV and the ^{19}F($p,\alpha\gamma$)^{16}O resonance at 872.11 keV.

Targets of LiF (enriched to 99.99% in ^{7}Li) ranging in thickness from 20–260 μg/cm^2 were sandwiched between thin layers of Au (5 μg/cm^2) by successive vacuum evaporation (Au-LiF-Au) onto carbon (10 μg/cm^2) and aluminum (0.8–1.2

mg/cm^2) foils. The thin C backings were used in studies of elastic scattering from Li and to search for any light contaminants that might be present in the target. The thick Al foils were used to stop the ^{8}Li recoils for the delayed α measurements. The Au sandwich configuration allowed continuous monitoring of the energy loss of the beam through the LiF by detection of backscattered deuterons.

The target thickness was determined primarily from the measured energy difference of deuterons elastically scattered from the front and back Au foils, along with the global fits to hydrogen stopping power of Andersen and Ziegler.[14] These fits to the individual elements agree with measurements typically to better than 5% for the energy range of this experiment. In addition, the stopping power calculated from these fits for the compound LiF (using Bragg's rule) agrees to better than 4% with the measured LiF stopping powers of Bader *et al.*[15] in the same energy range. A further check on the stopping power was made by comparing the target thickness derived from deuteron energy loss to that from ^{4}He energy loss with a $1-1.5$ MeV ^{4}He beam and the stopping power tables of Ziegler.[16] The agreement between these two methods was better than 5%. It should be noted though that the global fits for He are not entirely independent from those of H since interpolation to elements where there are no He stopping-power data relies to some extent on the systematics of the global H fits.

In order to verify that the ^{7}Li target thickness could be extracted from the energy loss and stopping power, the ^{7}Li(d,d)^{7}Li cross section was measured at 1.2 MeV where the elastically scattered deuterons were easily separated from protons from the ^{7}Li(d,p)^{8}Li and ^{12}C(d,p)^{13}C reactions. At $\theta_{\mathrm{c.m.}}=154°$ the measured cross section was 90 ± 7 mb/sr. This is in excellent agreement with the absolute cross section measurements of Ford[17] who obtained 91 ± 5 mb/sr at this angle and energy.

Oxygen contamination of the targets was found to be less than 1% from the yield of backscattered deuterons for a 60 μg/cm^2 LiF target on a thin carbon backing. Effects of the Coulomb explosion of the molecular deuterium as it passed through the target on the measured energy losses was small, since the energy loss of a mass 2 and mass 6 beam (for the same deuteron energy) agreed to within 2%. The stability of the targets with time was continuously checked since the target thickness was monitored by Rutherford backscattering during the measurement of an excitation function. Deviations during such a run were always $\lesssim 2\%$. Based on all of these considerations we have assigned an uncertainty of 7% to the target thickness determinations.

The target apparatus shown in Fig. 1 (essentially the same as in the experiment of McKeown *et al.*[18]) consisted of a bombardment chamber and a counting chamber. In the bombardment chamber too collimated silicon surface barrier detectors were placed at $+145°$ and $-170°$ with respect to the beam for backscattering analysis with angular acceptances of 0.9° and 0.5°, respectively. A third collimated silicon detector in the counting chamber was used to count the delayed α particles. A pulse to the stepping motor transferred the target, which was mounted on a rotating arm, from one chamber to the other within ~ 0.3 s. The system was kept at a pressure of $\sim 5\times10^{-6}$ Torr by a turbomolecular pump.

The two silicon detectors in the bombardment chamber were thick enough to stop the elastically scattered deuterons. A spectrum from the 145° detector at 780 keV deuteron energy is shown in Fig. 2. The energy scale for these detectors was determined from the beam energy and the kinematics for elastic scattering from the front Au layer. The alpha detector in the counting chamber was 300 mm^2 in area with a 50 μm depletion depth. The solid angles of all detectors were determined by use of a calibrated ^{241}Am source and from the geometry.

Total integrated charge was measured at an insulated Faraday cup that employed magnetic suppression of secondary electrons and a current integrator.

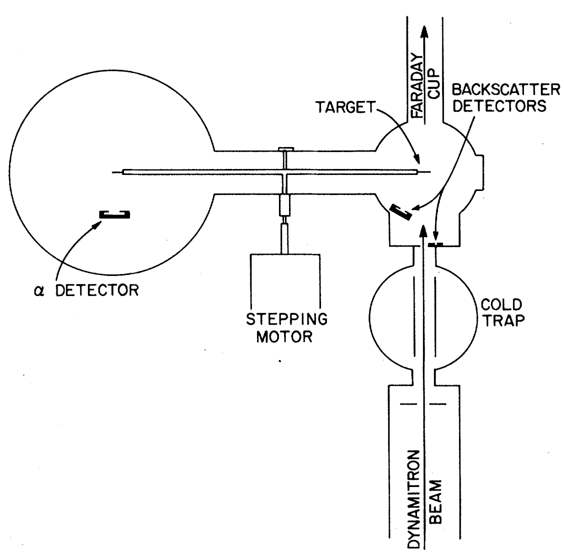


FIG. 1. Schematic diagram of the target apparatus.

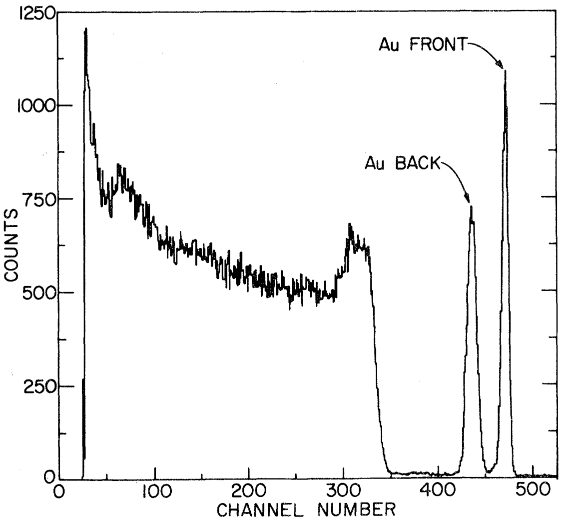
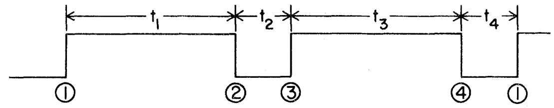


FIG. 2. Deuteron backscattering at 145° for a 69 $\mu g/cm^2$ LiF target sandwiched between two 5 $\mu g/cm^2$ Au layers on a 2.1 mg/cm^2 Al backing with $\bar{E}_d = 748$ keV. The two narrow peaks are elastically scattered deuterons from the front and back Au layers.



EVENT	FUNCTION	TIME INTERVALS
①	BEAM ON TARGET + ENABLE BACKSCATTER DETECTOR DATA ACQUISITION	$t_1 = 1.50$
②	TRANSFER TO COUNTING CHAMBER	$t_2 = 0.52$
③	INTEGRATE BEAM + ENABLE ALPHA DETECTOR DATA ACQUISITION	$t_3 = 1.50$
④	TRANSFER TO BOMBARDMENT CHAMBER	$t_4 = 0.52$

FIG. 3. Timing cycle. All times are in seconds.

The current integrator was checked with a precision battery and resistor chain. Problems due to secondary electrons from the target were eliminated by integrating the charge while the target was in the counting chamber and the beam was passed through a blank target frame.

The sequence of bombardment and counting was controlled by a crystal-driven sequence timer. The timing cycle is shown in Fig. 3. Prior to transfer of the target the beam was deflected vertically off target by a pair of deflection plates located in front of the analyzing magnet. A timing cycle with a 1-s delay between the transfer pulse and the start of both counting and bombardment (rather than the 0.52 s delay indicated in Fig. 3) was also used. The cross section derived from the two different cycles agreed to better than 2%.

All data handling used a PDP-11/45 computer. The bulk of the data acquired with the alpha detector were stored as two-parameter arrays in energy and time using a multiscaling analog-to-digital converter (ADC), while some of the data taken during target thickness checks, timing cycle variations, etc., were stored in one-parameter energy arrays alone. The dead time of the alpha detector was measured by scaling a fraction of the amplifier pulses, and comparing them with the same fraction gated by the busy signal from the computer. This dead time was typically $\lesssim 5\%$.

RESULTS

The $^7Li(d,p)^8Li$ cross section was calculated from the formula

$$\sigma(E) = \left[\frac{Y_\alpha(E)}{2N_i n_t \epsilon_\alpha} \right] \frac{\lambda t_1 \{ 1 - \exp[-\lambda(t_1+t_2+t_3+t_4)] \}}{(1-e^{-\lambda t_1})[e^{-\lambda t_2} - e^{-\lambda(t_2+t_3)}]} ,$$

where $Y_\alpha(E)$ is the dead-time corrected yield of α's at a given deuteron energy, t_i are the time intervals as described in Fig. 3, N_i is the total number of incident deuterons, n_t is the number of ^{7}Li nuclei/cm^2 in the target, ϵ_α is the geometric efficiency of the α detector, and λ is the ^{8}Li decay constant $= \ln 2 / t_{1/2}$.

Of the time-dependent exponential terms, those in the denominator account for decay of ^{8}Li during bombardment, transfer, and counting while those in the numerator correct for ^{8}Li buildup from previous cycles. This formula is valid for a steady beam and a large number of cycles, but because the cycle duration is nearly five half-lives long, small deviations from these assumptions have little effect. The factor of 2 in the denominator accounts for an effective increase in efficiency owing to the fact that 2 α's are emitted at nearly 180° in the decay. A half-life of 842 ± 6 ms (Ref. 19) was assumed in the above formula. The half-life of ^{8}Li was measured in the present experiment to be 847 ± 10 ms. This was done with a long timing cycle ($\sim$ nine half-lives) and a pulser-generated peak in the spectrum to monitor dead time.

The alpha spectrum at 772-keV average deuteron energy is shown in Fig. 4. To extract the total yield a smooth extrapolation to zero yield through the noise was necessary. This extrapolation contributed at most 2% to the total yield. The statistical error in the yield was always less than 0.5%.

A typical excitation function is shown in Fig. 5. In total, six separate measurements (five with different targets and one with a different timing cycle) were performed over the resonance at 770 keV. The average of these six measurements yields a total cross section of 148 ± 12 mb at an average deuteron energy of 770 ± 10 keV. The results from the individual measurements are shown in Table I.

The effects of target thickness on extracted peak cross sections has been discussed by Mingay.[12] Table I lists the ratio of peak cross sections for the 770- and 1020-keV resonances from the present experiment. Since the 1020-keV resonance is narrower ($\Gamma_{lab}=60$ keV) (Ref. 19) than the one at 770 keV ($\Gamma_{lab}=250$ keV),[19] one might understand the higher ratio obtained with the 260 $\mu g/cm^2$ target ($\Delta E = 100$ keV at 0.77 MeV). There appears to be little effect, however, at the 770-keV resonance as targets with thicknesses from 40–260 $\mu g/cm^2$ yield cross sections that agree to within 4% with the mean cross section.

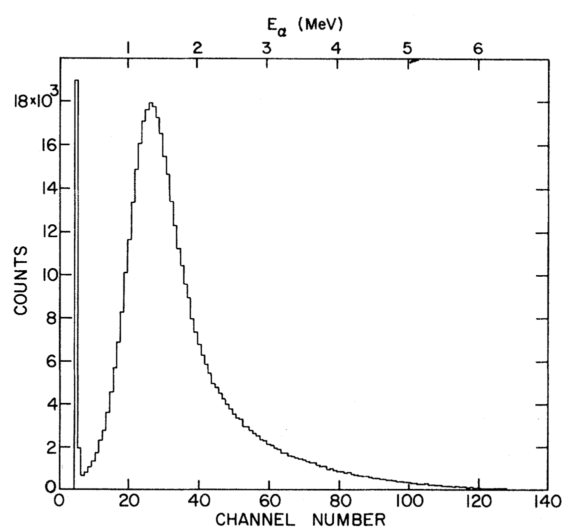


FIG. 4. Alpha spectrum from ^8Li decay at 772 keV average deuteron energy. The spike near channel 6 is the combined effect of the onset of noise and an instrumental cutoff.

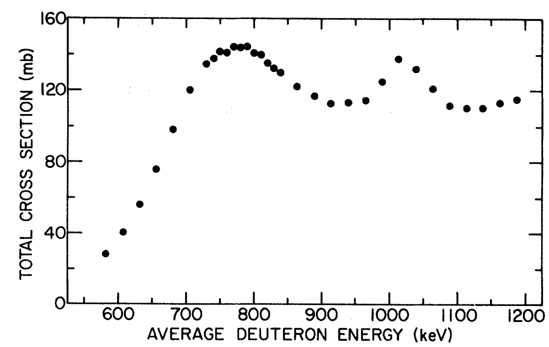


FIG. 5. $^7Li(d,p)^8Li$ excitation function for a 69 $\mu g/cm^2$ LiF target. The relative uncertainties are approximately the size of the points.

The uncertainty in the total cross section of ± 12 mb (8%) is ascribable chiefly to the 7% uncertainty assigned to the target thickness. The bulk of the remaining uncertainty is due to assigned errors of 2% and 3% to charge integration and solid angle, respectively.

DISCUSSION

As mentioned in the Introduction the relevance of the $^7Li(d,p)^8Li$ cross section to predicted solar neutrino capture rates lies in its use as a normalization for measurements of the $^7Be(p,\gamma)^8B$ cross section at low energy. The normalization procedure involves measuring the ^7Be target thickness by monitoring the buildup of ^7Li from the ^7Be electron capture decay ($t_{1/2}=53.3$ d). From the known cross section for $^7Li(d,p)^8Li$, the change with time of the amount of ^7Li in the target can be determined, and from this the ^7Be target thickness is obtained. Since the $^7Be(p,\gamma)^8B$ cross section (measured using the above procedure) is directly proportional to the assumed value of the $^7Li(d,p)^8Li$ cross section, the astrophysical S factor[20] for $^7Be(p,\gamma)^8B$ (it is usually designated S_{17} for this reaction) is *also* linear in this cross section. All but one of the previous $^7Be(p,\gamma)^8B$ cross section measurements used this normalization procedure. The one exception is a measurement of Wiezorek *et al.*,[21] where the ^7Be thickness was determined by mapping out the ^7Be distribution in the target by counting the 478-keV γ ray (10% branch in ^7Be decay) with a collimated Ge(Li) detector. However, this experiment was done at only one energy ($E_p=360$ keV) and had a relatively large uncertainty (25%).

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TABLE I. Results of measurements on individual targets.

Target No.	LiF thickness (μg/cm^2)	$\bar{E}_{\rm peak}$[b] (keV)	σ (770 keV) (mb)	σ (770)/σ (1020)
1	46	772	148±12	c
2	69	769	147±12	c
2	69[a]	765	153±12	c
3	70	767	146±12	1.05±0.04
4	94	772	142±12	1.06±0.04
5	260	778	151±12	1.13±0.05
Average		770	148±12	

[a]Longer timing cycle (see text).
[b]Average deuteron energy at the peak of the cross section ($\bar{E} = E_d - \Delta E/2$).
[c]Data taken only over 770-keV resonance.

^{7}Li(d,p)^{8}Li cross section at the 0.77-MeV resonance is summarized in Fig. 6. The early measurements of Baggett and Bame[8] and Bashkin[9] are not included because of the large uncertainties in the two measurements. The result of Kavanagh[3] (163±15 mb) is the value corrected to reflect a recent remeasurement[22] of the ^{7}Li(p,p)^{7}Li cross section (Kavanagh's normalization reaction), as discussed by Brown *et al.*[23] and Parker.[24] Except for the results of Parker[2] and the perhaps unreasonably high precision (a 2.5% error was assumed for the target thickness) attributed to the value of Schilling *et al.*[11] the various experiments are in fairly good agreement within their stated accuracy. It is important to note, however, that the present results and those of the independent measurements of McClenahan and Segel,[10] and Elwyn *et al.*[13] appear to lie systematically lower than the others. The investigation of possible sources of error, particularly in the present experiment and that of Ref. 13, provides additional confidence in a lower accepted value for this cross section.

The effects of changes in the ^{7}Be(p,γ)^{8}B S factor on the calculated neutrino capture rate for a ^{37}Cl detector are shown in Fig. 7, using the solar model code described in detail by Filippone and Schramm.[6] Based on a value of 0.032 keV b for S_{17} the above code gave an estimate[6] of 7.0 SNU (SNU = solar neutrino unit $\equiv 10^{-36}$ captures per target atom per second) for the ^{37}Cl capture rate. With

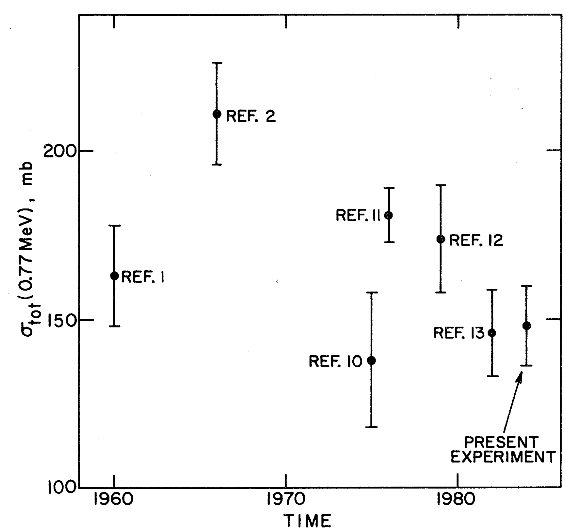

FIG. 6. Summary of experimental measurements of the ^{7}Li(d,p)^{8}Li reaction at the 0.77 MeV resonance.

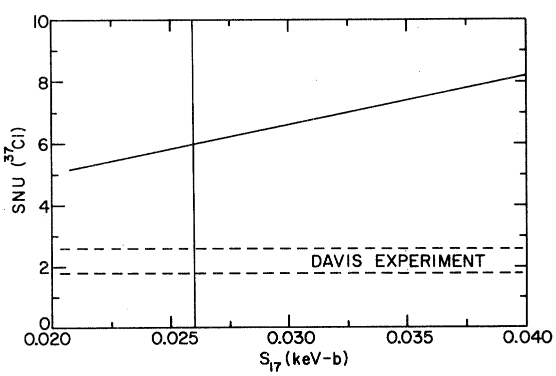

FIG. 7. Predicted ^{37}Cl neutrino capture rate (in SNU) vs S_{17}, the ^{7}Be(p,γ)^{8}Be S factor. The solid line is calculated with the standard input parameters of Ref. 6. Also shown is the allowed range in capture rate from the experiment of Davis.[7] The vertical line is the value of S_{17} inferred from the present experiment and the analysis of Parker (Refs. 24 and 25).

the present result of 148 ± 12 mb for the ^{7}Li$(d,p)^8$Li normalizing reaction and the discussions of Parker,[24,25] we obtain a value of 0.026 keV b for S_{17}; this lowers the predicted ^{37}Cl capture rate by 1.0 SNU.

It should be noted that a change in S_{17} has virtually no effect on the predicted capture rate for the proposed ^{71}Ga experiment[26] ($<1\%$ effect for a 35% change in S_{17}). This is because of the sensitivity of a ^{71}Ga detector to the high flux of neutrinos from the H$(p,e^+\nu_e)^2$H reaction which have energies below threshold for the ^{37}Cl detector.

The present results for the ^{7}Li$(d,p)^8$Li reaction are also of interest to a recent recalculation of the ^{7}Be$(p,\gamma)^8$B cross section by Barker[27] based on a direct-capture, optical potential model. This calculation uses parameters and spectroscopic factors required to fit data for the ^{7}Li$(n,\gamma)^8$Li and ^{7}Li$(n,n)^7$Li reactions along the lines of earlier work by Tombrello[28] and Aurdal.[29] The results of this new calculation for S_{17} are significantly lower than the experiments of Parker[2] and Kavanagh *et al.*,[3] where the normalizing ^{7}Li$(d,p)^8$Li cross section is assumed to be 193 mb. Barker notes that part of the discrepancy may lie with the normalizing cross section itself. The result of the present experiment (23% below the assumed 193 mb) is in the right direction to support this idea. In addition, in an earlier independent calculation by Robertson[30] the prediction for S_{17} was 27% below the experiment of Kavanagh[3] (again with the assumed 193 mb) although here parameter uncertainties were thought to be the cause of the discrepancy.

SUMMARY

The ^{7}Li$(d,p)^8$Li absolute total cross section has been measured to be 148 ± 12 mb at the peak of the 0.77-MeV resonance. When this value is used to normalize the previously measured ^{7}Be$(p,\gamma)^8$B cross section,[1–3] the predicted neutrino capture rate in a ^{37}Cl solar neutrino experiment is lowered by 1.0 SNU.

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