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Nuclear Physics **A326** (1979) 47–54; © *North-Holland Publishing Co., Amsterdam*

ABSOLUTE CROSS SECTIONS FOR THE ^{6}Li(p, ^{3}He)^{4}He REACTION AT ENERGIES BELOW 1 MeV

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Received 9 April 1979

Abstract: Total cross sections and angular distributions in the ^{6}Li(p, ^{3}He)^{4}He reaction have been measured over the energy range E_p = 100–700 keV. The extrapolation of the cross section to the energy region which is of interest in controlled thermonuclear reactors is given. The values of the "astrophysical S-function" are deduced from the cross sections.

E | NUCLEAR REACTIONS ^{6}Li(p, ^{3}He), E = 0.1–0.7 MeV, measured $\sigma(E_p, \theta)$, astrophysical S-function.

1. Introduction

It has been suggested [1,2]) that the nuclear reactions involving light nuclei in the low energy region might be important in the development of a "clean" controlled thermonuclear reactor (CTR). In particular, the ^{6}Li(p, ^{3}He)^{4}He reaction is of considerable interest in the CTR program, suggesting the feasibility of a fusion reactor without a neutron blanket. However, detailed evaluations for the performance of an advanced fuel system such as p–^{6}Li still require knowledge of the absolute reaction cross sections at energies from 100 keV to a few MeV.

The total cross sections have been measured by several authors in the energy range from 20 keV up to a few MeV. Gemeinhardt *et al.* [3]) have measured the total cross sections at E_p < 200 keV by detecting the ^{3}He from the reaction using a ^{6}Li metal target. Bertrand [4]) and Beaumevieille [5]) have also measured the total cross sections at E_p = 300 keV. Audouze and Reeves [6]) have made a survey of all results below 1 MeV proton energy concerning the ^{6}Li(p, ^{3}He)^{4}He reaction cross section. Some disagreements in the cross section still remain. It seems that these discrepancies are due to the uncertainties in the measured parameters (e.g. the determination of the number of target nuclei and the corrections to beam current integration arising from effects of incident beam charge exchange on passing through the target material) in total cross section studies with low energy charged particles.

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In order to avoid the difficulties with solid targets, Spinka et al. [7]) have measured the total cross section of the ^{6}Li(p, ^{3}He)^{4}He reaction for two the proton energies 151.0 and 317.0 keV using a lithium beam and a CH_4 gas target. Their cross sections are in agreement with those of Gemeinhardt et al. [3]).

In the present paper we report on cross section measurements for the ^{6}Li(p, ^{3}He)^{4}He reaction for proton energies ranging from 100–700 keV. The aim of this work is to determine the "astrophysical S-function" which is a quantity of interest for a controlled thermonuclear reactor.

2. Experimental procedure

Hydrogen ion beams below 400 keV were obtained from a Cockcroft-Walton accelerator and a 90° bending magnet which were calibrated using the 163 keV resonance in ^{11}B(p, γ) and the 340 keV resonance in ^{19}F(p, $\alpha\gamma$). For ion beams above 400 keV, the Dynamitron accelerator was used, and the 1.88 MeV threshold reaction in ^{7}Li(p, n) was measured for the calibration of the 60° analyzed beam. The energy resolution (FWHM) of the accelerated beam was about 5 keV for the Cockcroft-Walton and less than 2 keV for the Dynamitron. The ion beam was defined by a pair of slits (0.8 mm and 1 mm in diameter) located 50 cm apart from each other. A larger slit was also used in order to remove the ions scattered from the front-slit edges.

The target was mounted at the end of a rod rotatable around the vertical axis of a 40 cm diameter scattering chamber (shown in fig. 1). The layer of ^{6}Li (thickness 10 μg/cm^2) was evaporated onto the thin backing of nickel and copper (total thickness 30 μg/cm^2) or aluminium (total thickness 20 μg/cm^2). The beam current was measured with a cylindrical Faraday cup, 4 cm in diameter and 40 cm long, which had a secondary electron suppressor electrode. The whole system was evacuated by an oil diffusion pump with a liquid nitrogen cold trap located near the first slit. The

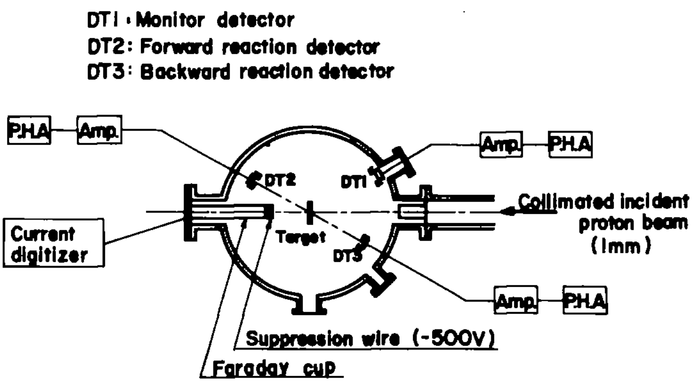

Fig. 1. Experimental arrangement.

pressure in the scattering chamber was maintained at less than 1.5×10^{-5} Torr during experimental runs.

Two silicon surface-barrier detectors for detecting the reaction products, ^{3}He and ^{4}He, were mounted on a turntable at distances of 8.8 cm and 9.5 cm from the center of the scattering chamber. The solid angle of each detector was about 0.5 msr, defined by a 1 mm hole in a copper disk in front of each detector. The signals from the detectors were stored in two 200-channel quadrants of a 800-channel pulse-height analyser. The third silicon surface-barrier detector was placed at a distance of 14 cm from the axis of the chamber at an angle of 150° with respect to the proton beam. The target thickness was monitored by observing the Rutherford-scattered protons from the target. The energy resolution of the monitoring detector was about 10 keV for 400 keV protons. A typical spectrum of ^{3}He and ^{4}He particles at $E_p = 350$ keV is shown in fig. 2.

3. Results and discussion

Angular distributions of ^{3}He particles from the ^{6}Li(p, ^{3}He)^{4}He reaction were measured at 20° intervals from 37° to 160° in the laboratory system for proton energies from 100 keV to 700 keV. These results were fitted to the equation

$$W(x) = \sum_{n=0}^{2} b_n P_n(x)$$

by the method of least squares. Here $P_n(x)$ is the Legendre polynomial of order n, where $x = \cos\theta$. Typical curves of the angular distribution in the c.m. system, normalized to the value at $\theta_{c.m.} = 90°$, for various incident proton energies in the

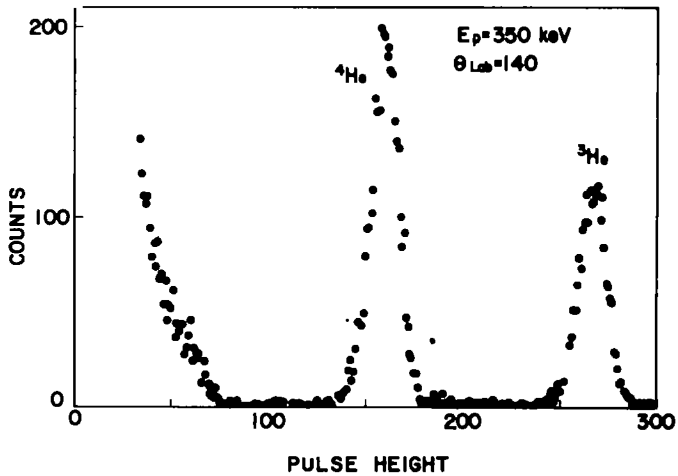

Fig. 2. Representative energy spectrum of ^{3}He and ^{4}He from the ^{6}Li(p, ^{3}He)^{4}He reaction.

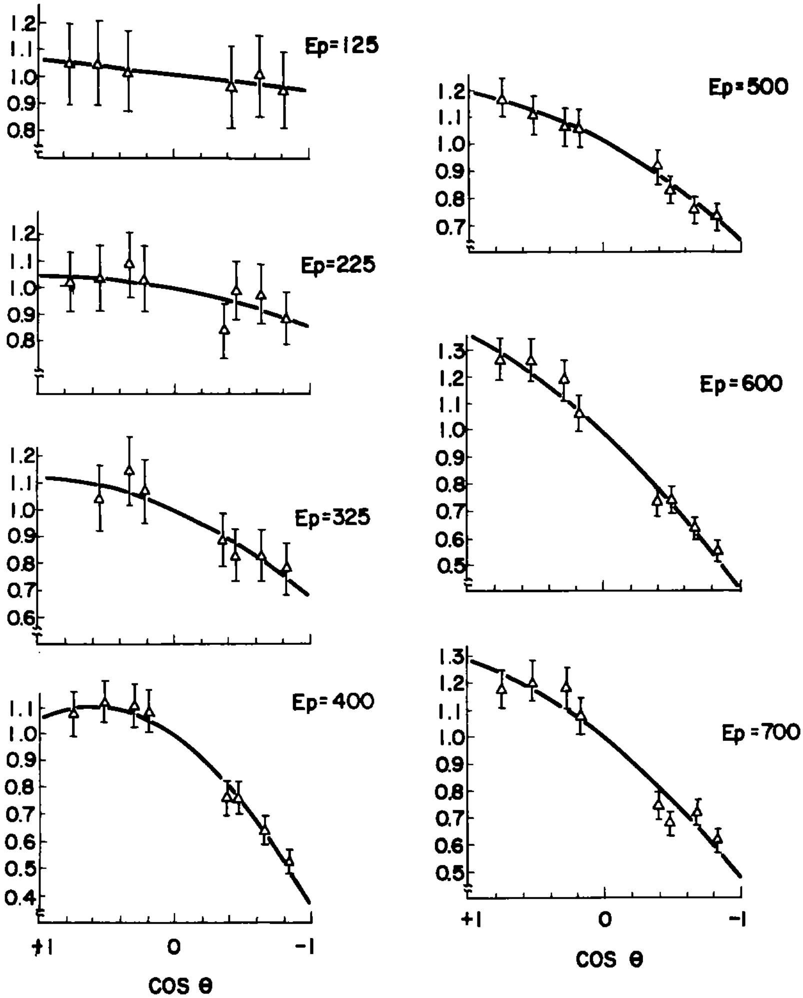

Fig. 3. Angular distributions of ^{3}He from the ^{6}Li(p, ^{3}He)^{4}He reaction, normalized to the value at $\theta_{c.m.} = 90°$, for various proton energies.

laboratory system are shown in fig. 3. The solid lines in these figures are Legendre-polynomial least-square fits to the data. The coefficients (b_0, b_1/b_0) of the polynomial approximation for the angular distribution of the ^{3}He particles as a function of proton energy are presented in fig. 4 together with Beaumevieille's data [5]). It is found that the angular distributions are approximately isotropic below $E_p = 250$ keV and are forward peaked above $E_p = 250$ keV. These features are consistent with the results of Gemeinhardt *et al.* [3]), Beaumevieille [5]), and Johnston and Sargood [9]).

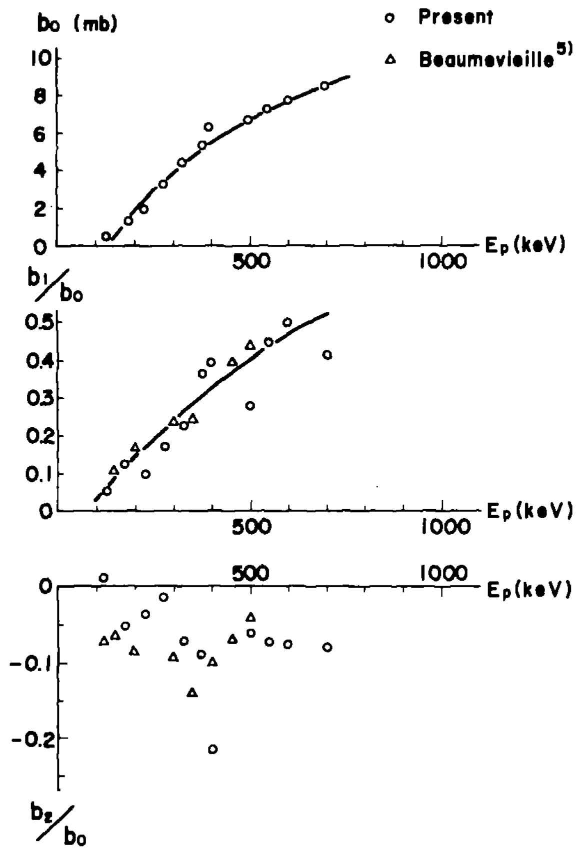

Fig. 4. Coefficients in a Legendre polynomial series approximation to the ^{3}He angular distribution as a function of proton lab energy.

Total cross sections were obtained by integrating the fitted curves of the angular distributions. These results are shown in fig. 5 together with previous data; the numerical values are summarized in table 1. It is found that the present values are about 50 % greater than those by Beaumevieille [5]) and by Bertrand *et al.* [4]) above E_p = 350 keV, and are consistent with the cross sections reported by Gemeinhardt *et al.* [3]) and Spinka *et al.* [7]).

The main error sources in the present measurements are due to the determination of the number of target nuclei and the correction for effects of beam charge exchange and of multiple scattering of the proton beam by the target nuclei. In order to determine the number of nuclei with high accuracy, the energy spectrum of Rutherford scattered protons from the target were analyzed by using the peak analysis code TIZZY [ref. [8])]. The corrections to the energy loss caused by impurity build-up and the determination of the ^{6}Li target nuclei were also performed during the ex-

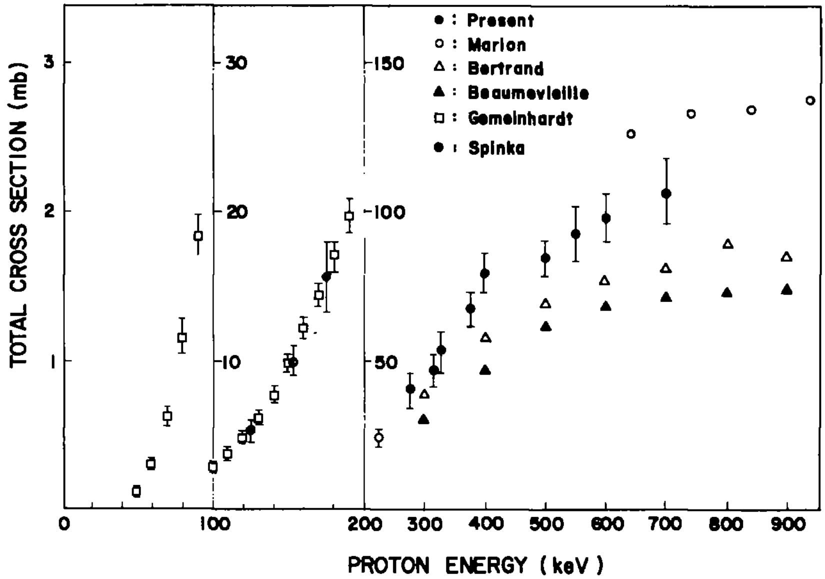

Fig. 5. Excitation curves for the $^6Li(p, ^3He)^4He$ reaction.

perimental run. The amount of charge variation was measured by integrating the proton current with and without the target in position. Fig. 6 shows this correction factor. The neutral charge fractions of protons passing through the target have been measured to estimate the correction for beam charge exchange. The relative errors of these effects were approximately evaluated to be 8 % and 10 %, respectively. The total errors in the absolute cross sections were, therefore, estimated to be less than 14 %.

TABLE 1

The total cross section and its uncertainty for the $^6Li(p, ^3He)^4He$ reaction

E_p (keV)	σ (mb)	$\Delta\sigma$ (mb)
125	5.31	0.82
175	15.61	2.21
225	24.61	3.25
275	40.52	5.53
325	53.35	6.81
375	67.74	6.07
400	79.64	6.57
500	84.52	5.81
550	92.73	8.78
600	97.67	8.06
700	106.85	11.13

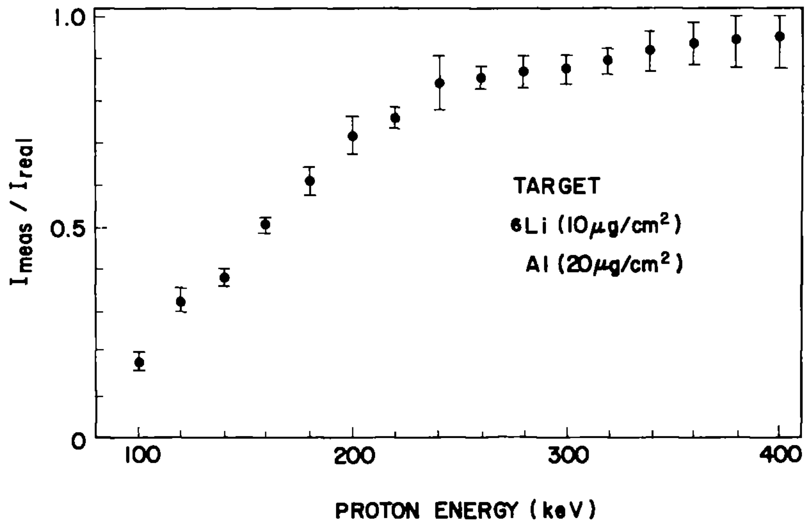

Fig. 6. The ratio of the beam current measured at the Faraday cup to the current striking the target, as a function of proton energy.

It is important to obtain the reaction cross section in the thermal energy region because of its usefulness in the evaluation of controlled thermonuclear reactors and in astrophysics. The "astrophysical S-function" has been calculated with the present values. For this energy region below the Coulomb barrier, the cross section can be

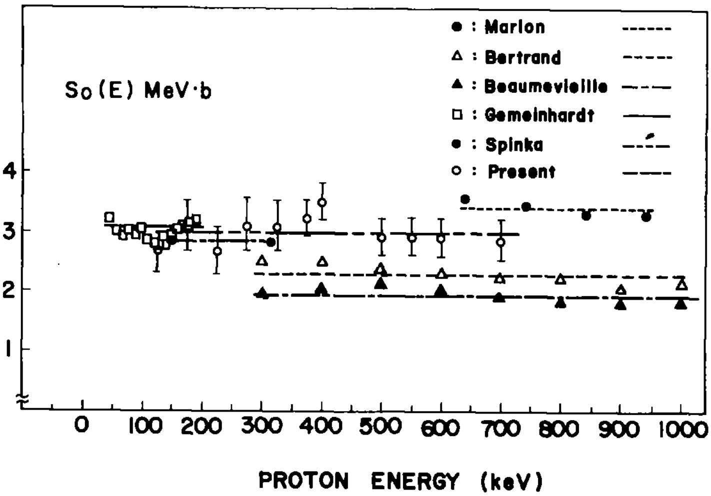

Fig. 7. The values of the "astrophysical S-function" $\bar{S}_0$(av), for proton lab energies ranging from 50–1000 keV.

written as

$$\sigma(E) = \frac{S_0(E)}{E}\exp\left\{-\frac{2\pi Z_z e^2}{\hbar v} - \frac{\sqrt{2}e}{\hbar}\left(\frac{m_r R_0^3}{Z_z}\right)^{\frac{1}{2}} E\right\},$$

for s-wave protons participating in the reaction. This is the first-order expression for the barrier-penetration probability, with $m_r = m_1 m_2/(m_1+m_2)$ and $R_0 = r_0(A_1^{\frac{1}{3}}+A_2^{\frac{1}{3}})$, where indices 1 and 2 indicate the proton and ^{6}Li, respectively. The values of the proton energies are taken in the c.m. system. The factor $S_0(E)$ can be considered to be constant or to depend linearly on energy, and can be calculated from the experimental points by fitting. The results are shown in fig. 7 together with previous data, where the errors of $S_0(E)$ are taken from σ_{tot}, and the value of r_0 is taken as 1.3 fm. The average values of $S_0(E)$ over the proton energy are shown in table 2. It is concluded that the average values $\bar{S}_0$(av) are about 3.0 MeV · b from

TABLE 2

Comparison of the values $\bar{S}_0$(av) for the ^{6}Li(p, ^{3}He)^{4}He reaction (in MeV · b)

present	3.0
Marion *et al.* [10]	3.4
Gemeinhardt *et al.* [3]	3.2
Spinka *et al.* [7]	2.85
Bertrand *et al.* [4]	2.3
Beaumevieille [5]	1.9

Gemeinhardt *et al.* [3]), Spinka *et al.* [7]) and the present data. This value is 1.5 times too high in comparison with the values by Beaumevieille [5]) and Bertrand *et al.* [4]), and 25 % higher than the estimated value by Audouze and Reeves [6]).

The authors wish to thank Dr. K. Kotajima for valuable discussions. We also thanks S. Tanuma, H. Aoki, S. Yoshida and the accelerator crew for their help in the experiments.

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