Activation measurements of the ^{7}Li(p,n)^{7}Be reaction from 60—480 MeV

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Activation measurements of the ^{7}Li(p,n)^{7}Be(g.s. + 0.43 MeV) total reaction cross section have been made at proton energies of 60—480 MeV. The energy dependence of the total reaction cross section, $\sigma_T(E)$, is observed to vary inversely with the incident proton energy up to 480 MeV. These results are consistently lower than those reported earlier by Ward *et al.* in the energy range of 100—200 MeV, the difference being due to the composite nature (^{7}LiCl) of the targets used in the earlier study. The lithium activation, isospin Clebsch-Gordan ratio, and Monte Carlo code methods for determining neutron efficiencies are now in good agreement (±10%) up to 200 MeV.

I. INTRODUCTION

Activation measurements of the ^{7}Li(p,n)^{7}Be(g.s. + 0.43 MeV) total reaction cross section have been made at proton energies of 60—480 MeV. This reaction is of interest since it is often used to produce nearly monoenergetic secondary neutron beams and to calibrate large volume neutron time-of-flight detectors.[1] Watson *et al.*[2] have noted most recently that a comparison of methods for determining neutron detector efficiencies at medium energies using the isospin Clebsch-Gordan ratio (ICGR) and Monte Carlo calculational code disagree with the lithium activation (LA) results of Ward *et al.*[1] in the 100—160 MeV region by 10—20%. The blame for this discrepancy has been placed on the targets chosen for the Li activation in Ref. 1. They used ^{7}LiCl composite targets assuming that chlorine would not contribute appreciably in the 100—200 MeV energy range. This assumption was based on a cascade code calculation that predicted a negligible Cl(p,x)^{7}Be contribution at all energies below 200 MeV.

The ^{7}Li(p,n)^{7}Be reaction is also of some interest in the study of the nuclear effective interaction as noted by Anderson, Wong, and Madsen.[3] Locard *et al.*[4] have measured the total reaction cross sections for the ^{7}Li(p,p')^{7}Li(0.478 MeV) and ^{7}Li(p,n)^{7}Be(0.429 MeV) reactions between 23 and 52 MeV to obtain the energy dependence of the spin-isospin transfer part of the effective interaction. Austin *et al.*[5] have measured the ^{7}Li(p,n)^{7}Be reaction using 24—45 MeV protons to study the spin-isospin energy dependence of the effective interaction. In Ref. 1 the $1/E$ energy dependence of the ^{7}Li(p,n)^{7}Be reaction was well reproduced using the effective N-N interaction of Picklesimer and Walker[6] and compared with calculations of Love and Franey.[7] Petrovich[8] and Love[9] have obtained the energy dependence of the coupling potentials from a G matrix interaction and Brown, Speth, and Wambach[10] have investigated the physical origin of the isovector potential energy dependence using one-pion and one-rho exchange potentials. In the present study we have measured the energy dependence of the ^{7}Li(p,n)^{7}Be reaction in the energy range of 60—480 MeV; these results compare well with the calculations of Picklesimer and Walker[6] and Love and Franey.[7] Theoretically the extent to which the $1/E$ dependence continues to energies above 200 MeV depends upon the cancellation of energy dependent terms in the t-matrix element and the energy dependence of the optical potential in distorted wave impulse approximation (DWIA) analysis.[1]

II. EXPERIMENTAL TECHNIQUES

The total production cross section for the ^{7}Li(p,n)^{7}Be(g.s. + 0.43 MeV) reaction was measured by observing the 478 keV γ ray following the (10.39±0.06)% electron capture (EC) branch of the decay of ^{7}Be (53.29 d).[11] The targets used for the present study were isotopically pure (99.999%) ^{7}Li metal discs (diameter = 2 cm) with target thicknesses of 6—100 mg/cm^2. In addition, at IUCF ^{7}LiCl targets (~40 mg/cm^2) and KCl targets (~100 mg/cm^2) were also irradiated and the ^{7}Be yields measured at energies of 60, 135, 160, and 190 MeV. Irradiations at IUCF were performed in the neutron time-of-flight facility and in the isotope production area using an external Faraday cup to monitor the beam. Irradiations at the TRIUMF cyclotron were made at proton energies of 190—480 MeV using beam current integration by the simultaneous production of ^{24}Na in thin (≈5 mg/cm^2) aluminum catchers.[12] Behind each target was a stack of

three Al metal foils used both to monitor the incident flux and to estimate losses due to recoiling ^{7}Be nuclei. In addition, these foils were also used to obtain cross sections for the production of ^{7}Be in Al.

Irradiated targets at IUCF containing 10–500 nCi of ^{7}Be were counted periodically in a standard geometry for several months to ensure proper exponential decay. The samples were routinely counted using a 45 cm^3 PGT Ge(Li) detector whose efficiency was determined within ±3% using standard NBS precision γ-ray reference sources. Similarly at TRIUMF the irradiated targets and catchers containing the ^{7}Be activity were counted periodically in a standard geometry over a period of several months using an ORTEC Ge(Li) detector whose efficiency was determined within ±10% using standard precision IAEA γ-ray reference sources. The final errors on the cross sectional data were the following: counting statistics (3%), efficiency determinations (3–10%), target thickness determinations (5–10%), and beam current integration (5–6%), which combine in quadrature to yield total uncertainties of 6–18%.

III. RESULTS AND DISCUSSION

Results of the present study are given in Table I and shown in Fig. 1. The total uncertainties range from 6 to 18% for individual results with a relative uncertainty of ±9.7%. The largest contributing error comes from the uncertainty in the target thickness. Comparison of thick and thin target yields for a given energy were in agreement with a relative uncertainty of ±8.9% indicating little if any secondary particle production due to target thickness. The values listed in Table I for 60, 301, 400, and 480 MeV are weighted means of thick and thin target yields. No corrections for recoil loss were made since the ^{7}Be yields in the Al catcher foils indicated that the recoil losses were negligible. The ^{7}Li metal target results were fitted to

$$\ln\sigma(E) = -1.13\ln E_p + 7.05\ , \qquad (1)$$

where E_p is the laboratory energy in MeV and $\sigma(E)$ is in mb, with a correlation coefficient of 0.996.

The ^{7}LiCl results are also given in Table I, where the recent results at 60, 135, 160, and 190 MeV are in good agreement (±7%) with the previous results of Ward *et al.*[1] which were fitted to

$$\ln\sigma(E) = -1.05\ln E_p + 6.77\ . \qquad (2)$$

The differences between the metal and salt targets were shown to be due to the production of ^{7}Be in the Cl(p,x)^{7}Be reaction which has a strongly increasing excitation function between 60 and 200 MeV. At 60 MeV the Cl cross section was measured to be 0.29 mb or about 2.4% of the ^{7}Li(p,n)^{7}Be reaction cross section, whereas at 190 MeV the chlorine cross section was measured to be 0.78 mb which is 26% of the ^{7}Li metal result. The ^{27}Al(p,x)^{7}Be yields measured at 301, 400, and 480 MeV confirmed the energy dependence of the general (p,x)^{7}Be reaction and are in good agreement with the results of Lafleur *et al.*[13] In the study by Ward *et al.*[1] comparison of ^{7}Li metal and ^{7}LiCl results were made at 80 and 120 MeV. Those results were within ±8% agreement. No comparison was made at higher energies since it was not anticipated that the Cl(p,x)^{7}Be cross section would have such a strongly increasing excitation function. ^{7}LiCl targets were used in the earlier study because of the ease of

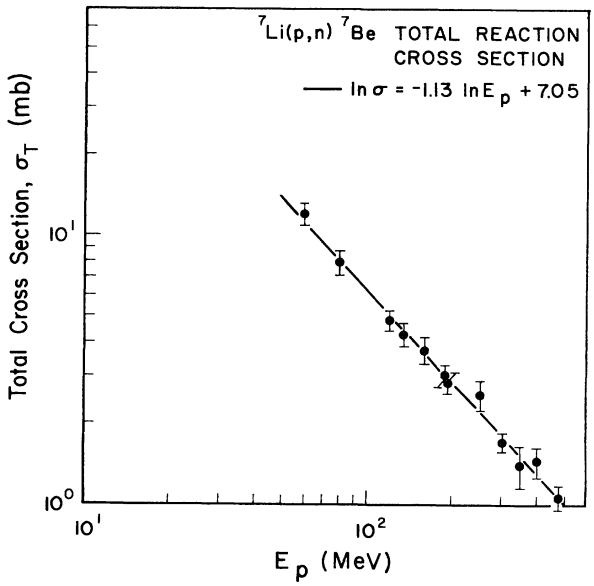

FIG. 1. The excitation function for the ^{7}Li(p,n)^{7}Be(g.s. + 0.429 MeV) total reaction cross sections showing the $1/E$ dependence.

TABLE I. Measured total cross sections for the ^{7}Li(p,n)^{7}Be(g.s. + 0.429 MeV) reaction.

Proton energy[a]	Measured cross sections (mb) ^{7}Li (metal)	^{7}LiCl (Ref. 1)
60.1	12.02±1.02	12.00±1.03[c]
62.0		11.28±1.58
69.4		10.78±1.02
79.1		8.09±0.71
80.0	7.96±0.80[b]	
88.9		7.46±1.00
100.1		7.29±0.77
119.4		5.29±0.45
120.1	4.88±0.41[b]	
135.0	4.30±0.41	5.31±0.53[c]
138.6		4.99±0.43
143.9		4.97±0.43
156.7		4.56±0.42
160.1	3.77±0.40	4.52±0.41[c]
174.5		3.50±0.36
190.0	3.01±0.24	3.50±0.35[c]
191.0	2.85±0.19	
199.1		3.46±0.35
252.0	2.58±0.30	
301.0	1.73±0.10	
349.0	1.41±0.26	
400.0	1.47±0.18	
480.0	1.08±0.07	

[a]Uncertainty in beam energy ±0.1 MeV.
[b]Reference 1.
[c]Measured in present study.

target storage over long periods of time without the need for vacuum storage. Recent counter experiments by Kwiatkowski *et al.*[14] have been investigating this unusual intermediate mass production process; however, the reaction mechanism is little understood since the reaction cross section cannot be calculated in a standard intranuclear cascade calculation at these energies (60—200 MeV).

In Fig. 2 is shown a comparison of the present results with LiA results of Valentin[15] and the total cross sections obtained by Watson *et al.*[2] from angle integration of differential cross sections. The earlier LiA results of Ward *et al.*[1] are given by the solid curve, which is 15—30% greater than the results of Watson *et al.*[2] or the LiA results of Valentin[15] at energies above about 100 MeV but agree with the present results within their experimental uncertainties below 100 MeV. Efficiencies for the neutron detectors used by Watson *et al.*[2] were calculated with the Monte Carlo code of Cecil, Anderson, and Madey;[16] their efficiencies agree with the isospin Clebsch-Gordan ratio (ICGR) method for determining efficiencies. The ICGR method compares the cross section ratio of (p,p′) and (p,n) reactions to analog excited states which are to a good approximation related by the ratio of the squares of the Clebsch-Gordan coefficients.[1,2] In the study by Watson *et al.*,[2] a comparison of (p,n) and (p,p′) reactions on ^{28}Si, ^{16}O, and ^{12}C were made at 135 MeV and on ^{12}C at 160 MeV. The agreement between efficiencies extracted from the ICGR results and the Monte Carlo technique was better than ±10% on the average. The present LiA results shown in Fig. 2 are in good agreement (±10%) with the results of Ref. 2 and the LiA results of Valentin *et al.*[15] Using the present LiA results for neutron detector efficiency calibrations with previous 0° (lab) cross section data for the ^{7}Li(p,n)^{7}Be reaction measured[17,18] at 120 and 160 MeV brings those data into good agreement with similar studies[2,19,20] which depend on the ICGR, Monte Carlo code, or associated particle efficiencies. All four neutron detector efficiency techniques are now in good agreement (±10%) up to 200 MeV.

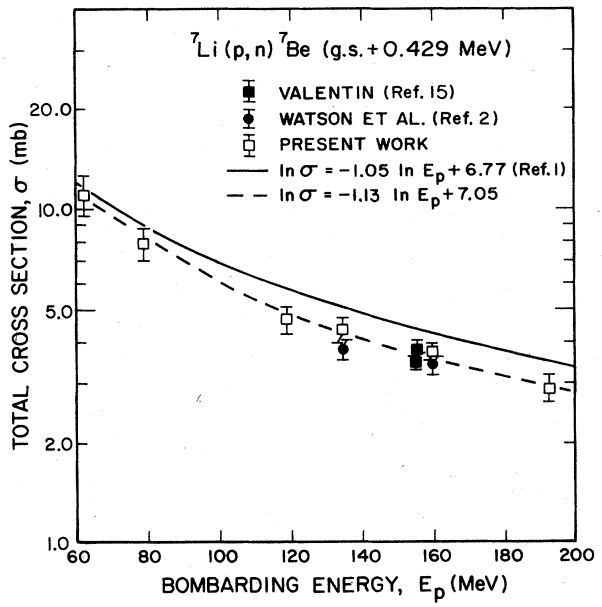

FIG. 2. Comparison of the total cross section for the ^{7}Li(p,n)^{7}Be(g.s. + 0.429 MeV) reaction obtained in the present study with the activation results of Valentin *et al.* (Ref. 15) and the integrated differential cross sections measured by Watson *et al.* (Ref. 2).

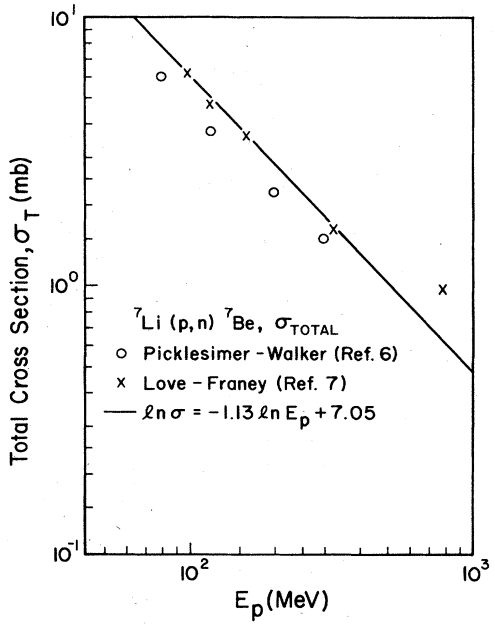

FIG. 3. The energy dependence of the ^{7}Li(p,n)^{7}Be(g.s. + 0.429 MeV) reaction cross section. The empirical results of the present study are represented by the solid line. Calculations using the Love-Franey (Ref. 7) t matrices are given by the crosses whereas those obtained using the Picklesimer-Walker (Ref. 6) t matrix are indicated by circles.

The energy dependence of the ^{7}Li(p,n)^{7}Be(g.s. + 0.429 MeV) reaction cross section measured in this work was compared with calculations using the Love-Franey (LF) interaction and the Pickelsimer-Walker (PW) interaction as shown in Fig. 3. The LF and PW calculational results were taken from Ref. 1 and details of the calculation can be found therein. We also include here a calculation at $E_p = 325$ and 800 MeV using the t matrices reported by Love and Franey.[7] The total cross section using LF reproduces the experimental data quite well both in magnitude and shape. The calculated point at $E_p = 800$ MeV is somewhat higher than the value extrapolated from the present data. The total cross section estimated using the PW interaction reproduces the $1/E$ shape, but is consistently smaller than the experimental values by a factor of 1.6. The theoretical interpretation of the data remains the same as in Ref. 1, namely the $1/E$ dependence of $\sigma_T(E)$ is likely due to cancellation of energy dependent terms in the t-matrix elements and in the energy dependence of the optical potential in a DWIA analysis.

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