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Nuclear Physics **A331** (1979) 50–60; © *North-Holland Publishing Co., Amsterdam*

CROSS SECTION OF THE REACTION ^{6}Li(p, γ)^{7}Be

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Received 12 June 1979

Abstract: The cross section of the reaction ^{6}Li(p, γ)^{7}Be has been measured using Ge(Li) γ-ray spectrometers for proton bombarding energies E_p from 200 keV to 1200 keV. At E_p = 800 keV, the total (p, γ) integrated cross section is found to be 3.1 ± 0.4 μb. The cross section adopted from consideration of this and previous measurements is in good agreement with that predicted from the known thermal neutron cross section for ^{6}Li(n, γ)^{7}Li on the assumption that properties of mirror direct capture reactions can be well described by optical potentials that use the same parmeter values for the two reactions.

E | NUCLEAR REACTIONS ^{6}Li(p, γ), E = 200–1200 keV; measured $\sigma(E)$. Enriched target.

1. Introduction

The assumption that nucleon direct capture cross sections may be calculated with optical-potential models having the same parameter values for mirror reactions has been used previously in order to predict the cross section for one such reaction by using parameter values obtained from fitting data on the mirror reaction [1]). It seemed desirable to test this assumption for a pair of mirror direct capture reactions where adequate data were available for each reaction. The most suitable pair appeared to be ^{6}Li(p, γ)^{7}Be and ^{6}Li(n, γ)^{7}Li. In preliminary calculations [2]), it was found that the observed features of these reactions for which different experimenters had obtained consistent results, e.g. branching ratios and energy dependences of the cross sections, were well reproduced by the calculations and were relatively stable against variations in potential parameters. However, there was difficulty in evaluating the calculations of absolute cross sections because of the scatter in the experimental values of the ^{6}Li(p, γ)^{7}Be cross section. For

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comparison purposes, we consider $\sigma_{p\gamma}(800)$, the integrated cross section at a bombarding energy of 800 keV. Values derived from various measurements are 3.0 ± 1.0 μb [ref. [3]], 0.35 ± 0.18 μb [ref. [4]], and 2.7 ± 0.4 μb [ref. [5]]. In deriving these values from published information, reasonable assumptions were made about branching ratios, angular distributions and energy dependence of the cross section; the errors given include allowances for the uncertainties involved in these assumptions.

It was decided to make an accurate remeasurement of the ^{6}Li(p, γ)^{7}Be absolute cross section; this became feasible with the availability of large volume Ge(Li) spectrometers, enabling some of the difficulties in the earlier measurements to be avoided. The high resolving power of the Ge(Li) detectors substantially reduced ambiguities in spectrum analysis (an imporant contaminant reaction is ^{19}F(p, $\alpha\gamma$)^{16}O which is a prolific source of 6 to 7 MeV γ-rays whose line shapes overlap the ^{6}Li(p, γ)^{7}Be γ-rays of interest); the relatively large size of the detectors used permitted counting rates which were not prohibitively low.

An energy level diagram, based upon that given by Ajzenberg-Selove [6]), is shown for reference in fig. 1.

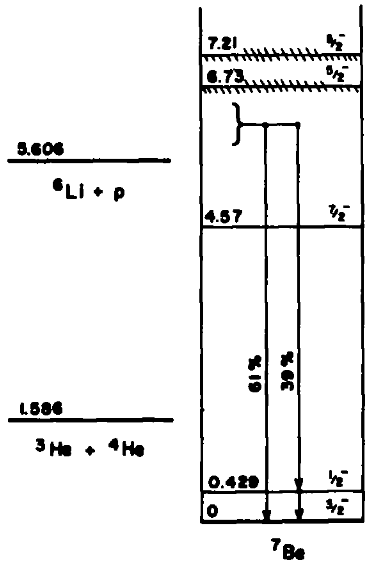

Fig. 1. Energy level diagram for ^{7}Be based upon that given by Ajzenberg-Selove [6]). Energies are given in MeV.

2. Experimental procedure

2.1. TARGETS

The major experimental problem in reliable determination of absolute cross sections for reactions involving Li target nuclei is almost invariably the preparation of targets which are durable under bombardment and for which the Li content is accurately known. The literature contains many examples of conflicting results, as well as elegant techniques for circumventing various problems [see Spinka *et al.* [7]) for an example of the latter]. In the present work two types of targets have been used.

The first was of the alloy type. A layer of spectroscopically pure gold metal of thickness 300 $\mu g/cm^2$ was evaporated onto a 0.025 cm thick blank of spectroscopically pure tantalum which had been previously outgassed *in vacuo* at red heat to reduce fluorine contamination. The pressure during the evaporation was 2×10^{-6} Torr. The evaporator bell jar was then vented with dry nitrogen and a tungsten boat loaded with Li metal, enriched to 99 % ^{6}Li, was installed. At a bell jar pressure of $\sim 10^{-6}$ Torr, a layer of Li approximately 100 $\mu g/cm^2$ thick was evaporated onto the gold surface. The resultant multi-layered film was annealed in vacuo by resistive heating of the tantalum substrate to a temperature of $\sim$ 300 °C for ten minutes. When withdrawn from the evaporator the target had a creamy-white appearance which remained unchanged after prolonged exposure to the atmosphere and was exceptionally stable under beam bombardment. It was subsequently determined, by measuring the width of the observed photopeaks of γ-rays from the non-resonant ^{6}Li(p, γ_0)^{7}Be reaction, that the alloy layer was 50 keV thick to 600 keV protons.

A second, thinner target was prepared by direct evaporation of lithium oxide, isotopically enriched to 99 % ^{6}Li, onto a 0.025 cm thick fine gold substrate. The composition of this target upon evaporation was not known, but measurement, using the same technique as described above for the alloy target, indicated that it was 22 keV thick to 600 keV protons. The presence of oxygen, carbon or possibly other heavier impurities did not affect the results of the present study.

The Li content of this target was determined using the narrow resonance in the ^{6}Li(α, γ)^{10}B reaction at an α-particle bombarding energy of 1175 keV [ref. [6])]. The state excited in ^{10}B is at an excitation energy of 5166 keV and decays via several γ-ray cascades which populate the 718 keV first excited state about 80 % of the time. A yield curve was traced out over the resonance by observing the 718 keV γ-rays with a Ge(Li) detector placed close to the target at 0°. Measurements extended over the bombarding energy range from 1170 keV to 1300 keV, and the resonance curve was found to have a full-width at half-maximum of about 80 keV. This yield curve was then compared with a thick target yield curve measured over the same resonance for a thick LiF targer in which the Li was greater than 95 % ^{6}Li. The experimental set-up was left undisturbed apart from the change of targets. If y is the integrated area (per incident particle) under the resonance curve for the lithium oxide target, and y_∞ is the step height (per incident particle) in the thick target yield curve for the LiF target, then according to the expression given by Gove [8]) the ^{6}Li content of the lithium oxide sample is given by

$$n = (y/y_\infty)(1/\varepsilon),$$

a result which is independent of the γ-ray angular distributions and branching ratios, detector geometry and efficiency, and coincident summing effects. The stopping power, ε, for the ^6LiF target for 1175 keV α-particles was determined from published compilations [9]) to be 63.0×10^{-15} eV · cm^2 per ^6Li atom on the assumption that the composition of the target was indeed LiF. This target is the same as that used in ref. [10]) where the validity of this assumption is well supported. The value obtained for n was $(1.06 \pm 0.12) \times 10^{18}$ atoms/cm^2. Cross section results obtained using the Li-Au alloy target were normalised to those obtained for the thinner lithium oxide target.

Given the established value of the resonance strength of the 1175 keV resonance to be 0.40 ± 0.04 eV [ref. [10])], analysis of the area of the lithium oxide yield curve over the 1175 keV resonance provided a value for n of $(1.03 \pm 0.12) \times 10^{18}$ atoms/cm^2, consistent with the value given in the preceding paragraph.

2.2. DETECTION GEOMETRY

The $^6Li(p, \gamma)^7Be$ cross section was measured with molecular HH^+ beams which were delivered by the University of Melbourne 5U Pelletron accelerator; proton beams of sufficient intensity were not available at the lowest energies of this experiment. After magnetic analysis, the beam travelled down an u.h.v. beam line and impinged normally on the target. About 30 cm before the target, the beam was defined by a grounded, 8 mm diameter tantalum aperture. This was followed by an electron suppressor ring held at -500 V. The target chamber consisted of a simple cylindrical stainless steel tube coupled to the beam line via an insulator. The downstream end of the chamber was a machined knife edge to which the target was bolted directly. In this configuration it was convenient to cool the target backing by directing a flow of compressed air against it. The chamber was maintained at a pressure of about 5×10^{-8} Torr by ion pumping. The target assembly constituted a 20 cm deep Faraday cup for beam current integration, which was considered accurate to better than 5 %.

Two different large volume Ge(Li) detectors were used at various times during this study. Initially a 60 cm^3 Ge(Li) detector was used in conjunction with the Li-Au alloy target. This detector was placed at 0° to the beam direction with its front face 2.8 cm from the target. When a much larger volume, 128 cm^3 Ge(Li) detector became available, this was used with the lithium oxide target. This detector was positioned at 0° with its front face 1.6 cm from the target. Neither detector was shielded. The γ-ray photopeak efficiency of the 128 cm^3 detector was measured in the experimental geometry: at low energies, calibrated γ-ray sources were used, and the calibration was extended to γ-ray energies of about 9 MeV by the method of Kennedy *et al.* [11]), which involves an analysis of the $E_p = 2046$ keV resonance in $^{27}Al(p, \gamma)^{28}Si$.

2.3. MEASUREMENT OF γ-RAY YIELD

Molecular beam energies $E(\mathrm{HH}^+)$ ranged from 400 keV to 2400 keV. The lower limit was set by accelerator instability and insufficient beam current. Bombarding energies were avoided where radiation from the $^{19}\mathrm{F}(\mathrm{p}, \alpha\gamma)^{16}\mathrm{O}$ reaction proved troublesome. At each bombarding energy, 4096-channel γ-ray spectra were obtained using an on-line PDP-11/40 computer and stored on magnetic tape or disk. Spectra were acquired for a collected charge of typically 5 mC to 10 mC. Molecular beam currents ranged from 2 μA to 8μA. The detection system dead time was determined by use of a reference pulser feeding the detector preamplifier and a parallel scaler. During these measurements the dead time did not exceed 6 %.

Frequently repeated γ-ray yield measurements verified that there was no perceptible deterioration of either target under bombardment. At the higher currents, forced air cooling was necessary. Inspection of the ^{6}Li depth profile from measurements of the (α, γ) yield curve before and after a long set of runs indicated a small redistribution of Li in the lithium oxide target which was consistent with the assumption of some Li diffusion into the gold backing. The energy dependence of the $^6\mathrm{Li}(\mathrm{p}, \gamma)^7\mathrm{Be}$ cross section is not sufficiently steep for this diffusion (which corresponds to an energy thickening of the target of about 5 keV for 600 keV protons) to be significant.

3. Results and analysis

3.1. ANALYSIS OF 429 keV γ-RADIATION

If the cross section is determined from measurements on the 429 keV γ-radiation corresponding to the decay of the first excited state of ^{7}Be (see fig. 1), it is necessary that there is no significant contribution from $^{10}\mathrm{B}(\mathrm{p}, \alpha_1\gamma)^7\mathrm{Be}$ arising from boron in the vacuum system components or as a target contaminant. The absence of any significant contribution from this source in the present experiment was deduced from the non-observation of 4.43 MeV γ-rays from $^{11}\mathrm{B}(\mathrm{p}, \gamma)^{12}\mathrm{C}$ and the known cross sections of this reaction and of $^{10}\mathrm{B}(\mathrm{p}, \alpha_1\gamma)^7\mathrm{Be}$ [ref. [6]]. Furthermore, as is shown later, the cross section for $^6\mathrm{Li}(\mathrm{p}, \gamma)^7\mathrm{Be}$ deduced from observation of the 429 keV γ-rays is in excellent agreement with that deduced from observation of the ground state radiation, γ_0, which is not subject to contributions from ^{10}B contamination.

An example of a γ-ray spectrum obtained at $E(\mathrm{HH}^+) = 1600$ keV is shown in fig. 2. In addition to the photopeaks attributed to γ-rays from $^6\mathrm{Li}(\mathrm{p}, \gamma)^7\mathrm{Be}$, there is evidence of deuteron induced reactions on ^{6}Li, ^{12}C and ^{16}O. The analysing magnet of the Pelletron does not separate HH^+ and D^+ beams; measurements performed from time to time suggest an abundance ratio in the analysed beam of $[\mathrm{D}^+]/[\mathrm{HH}^+] \sim 10^{-4}$. This ratio may vary by an order of magnitude or more, depending on conditions in the ion source. Because deuteron induced reactions are characterised by large cross sections (often hundreds of mb), even a small

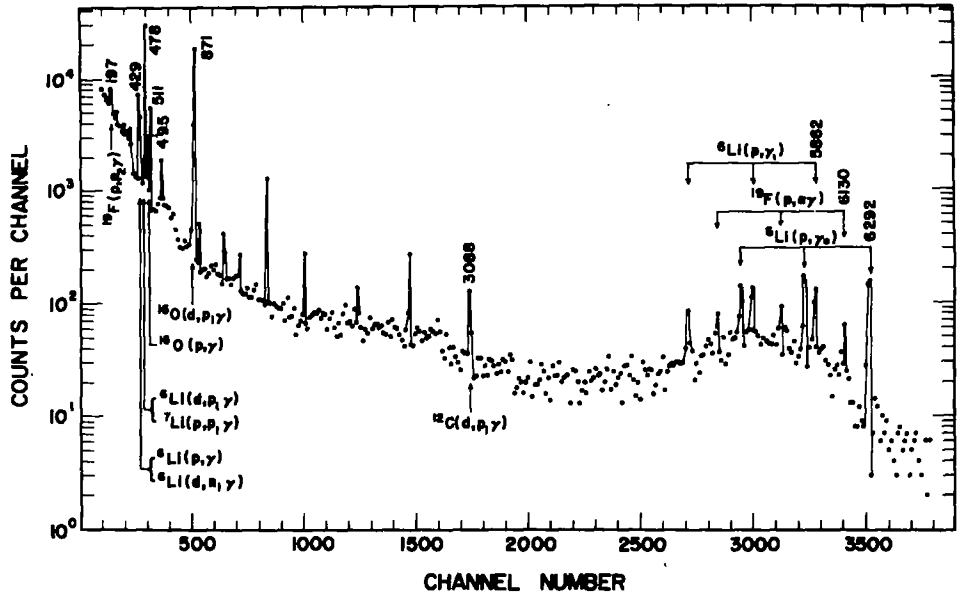

Fig. 2. Gamma-ray spectrum obtained with a molecular hydrogen beam (HH^+) of energy 1600 keV (corresponding to a proton energy of 800 keV) bombarding a lithium oxide target. The spectrum was acquired at 0° for an integrated HH^+ current of 16.7 mC. Every tenth channel is plotted except near the photopeaks, where the channel with maximum counts is also included. The photopeaks are labelled at the top by the γ-ray deexcitation energy in keV and at the bottom by the relevant nuclear reaction. All unlabelled photopeaks arise from room background. The high energy γ-rays from ^{6}Li(p, γ)^{7}Be and ^{19}F(p, αγ)^{16}O reactions are identified by their full-energy and first- and second-escape peaks.

deuteron component in the beam may produce relatively large contaminant signals when proton induced reactions with cross sections of microbarns are under investigation with HH^+ beams.

Since the ^{6}Li(d, nγ)^{7}Be reaction gives rise to the same 429 keV γ-ray as is produced in ^{6}Li(p, γ)^{7}Be, the deuteron contamination of the beam renders the interpretation of this γ-ray yield subject to qualification. We have attempted to separate out the (d, nγ) component from the (p, γ) component in the following manner. McClenahan and Segel [12]) have measured the ratio of yields of 429 keV γ-rays from ^{6}Li(d, nγ)^{7}Be and 478 keV γ-rays from ^{6}Li(d, pγ)^{7}Li, for deuteron energies up to about 3 MeV: this ratio is close to unity. Since both of these γ-rays are emitted isotropically from $J^\pi = \frac{1}{2}^-$ states, it is possible from the observed yield of 478 keV γ-rays to calculate the 429 keV yield which can be attributed to ^{6}Li(d, nγ)^{7}Be. It was found that, for data taken with $E(HH^+) \leq 1300$ keV, the (d, nγ) component varied from less than 1 % up to about 40 %. Such an analysis could not be extended to higher bombarding energies because at such energies ^{7}Li(p, p′γ)^{7}Li from the $\lesssim 1$ % ^{7}Li in the target produced large 478 keV γ-ray yields. The possibility that decay of the radioactive ^{7}Be nuclei ($T_{\frac{1}{2}} = 53$ d) created during this experiment could also contribute to the 478 keV yield was considered and rejected on the basis of the insignificant yield observed during several background runs.

During one set of runs the deuteron component in the beam was especially low and no correction was required to the 429 keV yield. Additional data were therefore taken at the higher energies, $E(HH^+) = 1600, 2000$ and 2400 keV with no change in ion source operating conditions, and the assumption was made that the (d, nγ) contribution was insignificant at these energies also. [The data of ref. [12]) show that the cross section for ^{6}Li(d, nγ)^{7}Be is roughly constant for $E_d > 1$ MeV.] The energy dependence and absolute values of the higher energy cross sections so obtained were completely consistent with the results obtained with a proton beam as described in the following paragraph.

In order to avoid the ambiguities arising from use of the molecular beam, a limited data set was taken with proton beams bombarding the lithium oxide target for incident energies of 800, 900 and 1000 keV and beam currents of about 2 μA. The 429 keV γ-ray yield thus obtained, and also the (p, γ_0) yields, were consistent with the molecular beam results and verified our data reduction procedure.

The cross sections obtained for the 429 keV γ-rays were used to estimate the

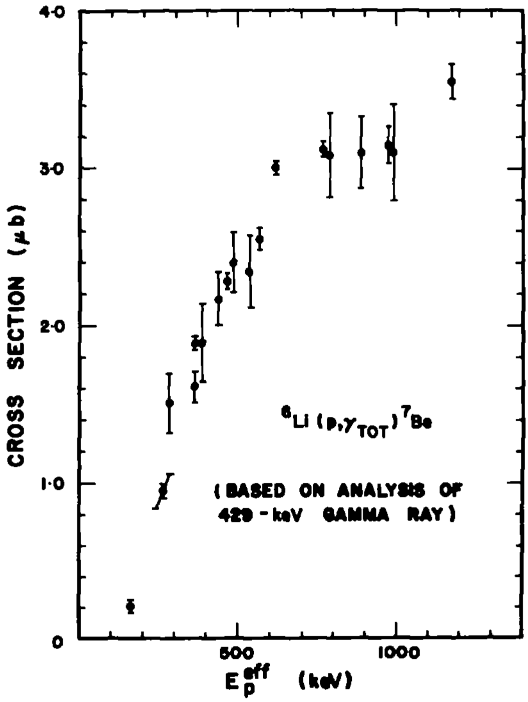

Fig. 3. Total cross section of the reaction ^{6}Li(p, γ)^{7}Be. Results are based upon analysis of the 429 keV γ-ray yield and assumption of 39 % branching to the 429 keV state. Cross sections are plotted for target-centred energies, E_p^{eff}. Error bars reflect statistical uncertainties only. Data points with large error bars for proton energies near 800, 900 and 1000 keV were obtained with a proton beam. All other data refer to results obtained with a molecular beam.

total (p, γ) cross section on the assumption of an energy independent branch of $(39 \pm 2)\%$ to the 429 keV state. The determination of this branching ratio is discussed in subsect. 3.2. No correction for anglar distribution effects is necessary because the 429 keV radiation is isotropic. The results are shown in fig. 3; they include data taken with both target-detector arrangements. The effective proton energy, E_p^{eff}, is the target-centred energy. The 429 keV γ-ray provides the most direct basis for determination of the (p, γ_1) cross section; analysis of the γ_1 yield is less straightforward due to poorer statistics and more serious background problems, and it also requires angular distribution corrections.

3.2. ANALYSIS OF γ_0 AND γ_1

For the lithium oxide target, photopeak areas for the γ_0 line could be unambiguously extracted (fig. 4). To convert these numbers to cross sections, it is necessary to know the γ_0 angular distribution at each energy. Warren *et al.* [4]) measured the angular distribution at $E_p = 800$ keV to be of the form $1+(1.05 \pm 0.15)\cos^2\theta$. Calculations of Barker [2,13]), based on the assumption that the reaction proceeds by the direct capture of s-, p- and d-wave protons with emission of E1 or E2 radiation, suggest that there should be an appreciable forward-backward asymmetry at this energy. The calculated angular distribution coefficients are reasonably stable against changes in the optical potential parameter values, restricted to fit other data from $^{6}Li+n$ and $^{6}Li+p$ scattering and reactions, the variations in the angular distribution coefficients being of the order of 20 % from the mean. To convert our 0° measurements to integrated (p, γ_0) cross sections, we use the calculated angular distribution coefficients as given by Barker [13]). An error of ± 40 % is assumed for the differences of this conversion factor from unity to allow for the spread of values found within the optical potential calculations, and for uncertainty due to the use of this particular model of the direct capture reaction [13]). This assumed error gives a range embracing the conversion factor obtained from the measurement of Warren *et al.* [4]) at 800 keV; it gives rise to an uncertainty in the deduced cross section which increases from 6 % to 12 % as the energy varies from 200 keV to 1200 keV. The total integrated (p, γ) cross section is then obtained by using the ground state branching ratio of $(61 \pm 2)\%$ (see following paragraph), and is shown in fig. 5.

The branching ratio for capture γ-rays populating the ground and first excited states of ^{7}Be was estimated from the areas of the γ_0 and γ_1 full-energy peaks. Calculations [2,13]), supported by experiment [4,14]) indicate that the γ_0 and γ_1 angular distributions are virtually identical. After taking due account of summing effects in our high efficiency geometry, we find the branches to the ground and first excited states to be $(59 \pm 3)\%$ and $(41 \pm 3)\%$, respectively, at $E_p = 800$ keV. These results are compared with previously reported values in table 1. In the estimation of a weighted mean, uncertainties of ± 5 % were assigned to the results of refs. [5,14]) and it was assumed that transitions to the 4.57 MeV state were negligible. The

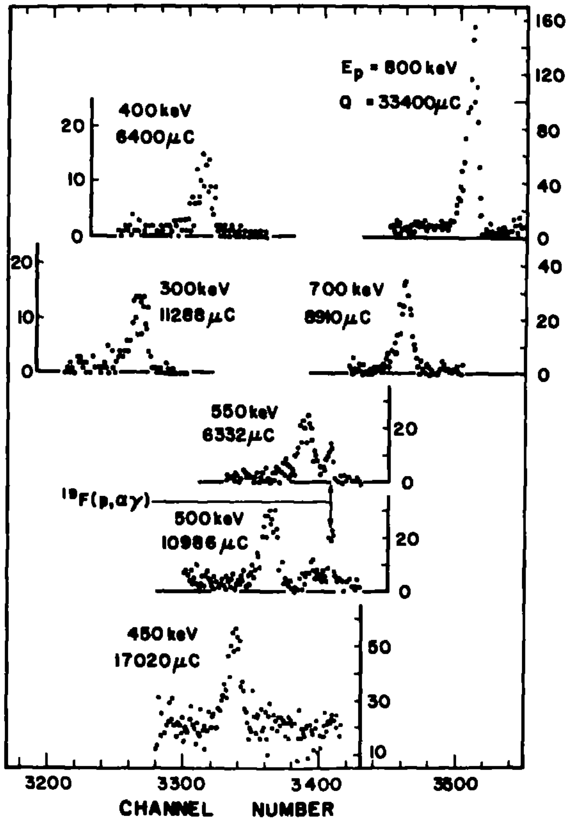

Fig. 4. Full-energy peaks of γ-rays from the ^{6}Li(p, γ_0)^{7}Be reaction. The portion of the spectrum in the vicinity of the γ_0 full-energy peak is shown for several representative bombarding energies. Each plot is labelled by the nominal proton energy (although the molecular HH^+ beam was used for the data shown) and the integrated current of protons in μC. The ordinate represents counts per channel. The analyser dispersion is 1.8 keV/channel. The 450 keV spectrum includes a high energy γ-ray contribution arising from the ^{7}Li(p, γ)^{8}Be reaction which is resonant at E_p = 441 keV.

adopted values were $(61 \pm 2)\%$ for γ_0 and $(39 \pm 2)\%$ for γ_1. Our data are consistent with previous experiments [4,5,14]) and with calculations [2,13]) in that they show no evidence of any significant energy dependence for this branching ratio.

4. Discussion

To compare our cross sections with those reported by previous workers, we evaluate $\sigma_{p\gamma}$ (800). We allow for possible systematic errors in detector efficiency (5 %), determination of ^{6}Li content of target (11 %), charge integration (< 5 %), branching ratio (5 % for the 429 keV data, and 3 % for the γ_0 data), and angular distribution corrections (10 % for the γ_0 data). The results obtained are 3.1 ± 0.4 μb

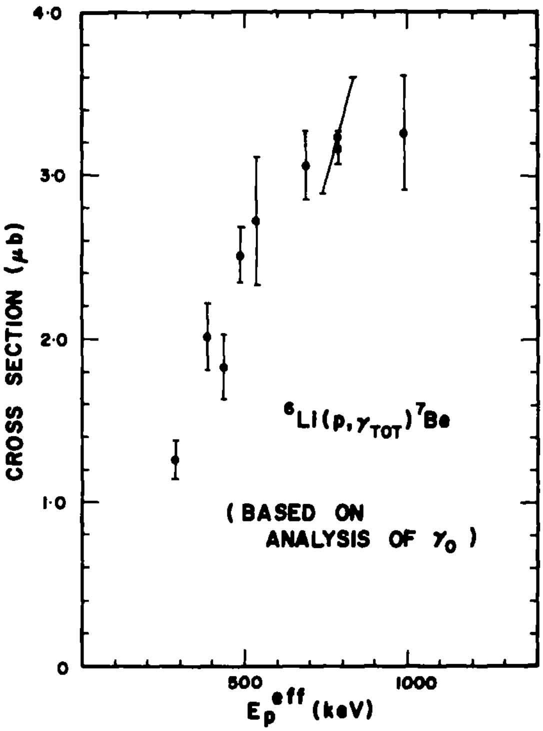

Fig. 5. Total cross section of the reaction $^6Li(p, \gamma)^7Be$. These results are based upon analysis of the ground state γ-ray, γ_0, assuming 61 % branching to the ground state and calculated angular distributions. Error bars reflect statistical uncertainties only. The two data points with large error bars for proton energies near 800 keV and 1000 keV were obtained with a proton beam.

for the 429 keV data, and 3.2 ± 0.6 μb for the γ_0 data. Since these are not completely independent determinations, we adopt $\sigma_{p\gamma}(800) = 3.1 \pm 0.4$ μb for the present experiment. This result is in good agreement with the two larger previous values of 3.0 ± 1.0 μb and 2.7 ± 0.4 μb derived from the work of Bashkin and Carlson [3])

TABLE 1

Branching ratios (%) for $^6Li(p, \gamma)^7Be$ for the proton energy range relevant to the present experiment

Ref.	Final state (MeV)		
	$0(\gamma_0)$	$0.429(\gamma_1)$	4.57
Bashkin and Carlson [3])	65 ± 5	35 ± 5	< 4
Warren *et al.* [4])	62 ± 5	38 ± 5	
Johnston [14])		38	
Sweeney [5])	61		
present work	59 ± 3	41 ± 3	
Weighted mean	61 ± 2	39 ± 2	

and Sweeney [5]), respectively, but disagrees with the smaller value of 0.35 ± 0.18 μb derived from the work of Warren *et al.* [4]). The weighted average of the present result and the two larger previous values is $\sigma_{p\gamma}(800) = 2.9 \pm 0.3$ μb.

Barker's [13]) direct capture calculations indicate that if optical potential parameters are chosen to fit the ^{6}Li(n, γ)^{7}Li thermal cross section, then application of these same parameters to the ^{6}Li(p, γ)^{7}Be reaction predicts $\sigma_{p\gamma}(800)$ to be in the range from 2.3 μb to 3.0 μb, depending on the fitting procedures used. This is in good agreement with the experimental value of 2.9 ± 0.3 μb given above, and provides substantial support for the assumption that properties of mirror direct capture reactions can be well described by optical potentials that use the same parameter values for the two reactions.

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