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^{7}Li($\vec{p}$, γ)^{8}Be reaction at $E_p = 80 - 0$ keV

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The ^{7}Li($\vec{p}$, γ)^{8}Be reaction has been studied in the laboratory energy range $E_p = 80$–0 keV. The vector analyzing powers $A_y(\theta)$ and the angular distributions of the cross section $d\sigma/d\Omega(\theta)$ for capture to the ground, first-, and third-excited states are reported. Additionally, the absolute cross section $\sigma_T(E)$ and (equivalently) the astrophysical S factor $S(E)$ have been measured for capture to the third-excited state. Calculations have been performed for all three transitions using the direct capture model to which the known nearby $M1$ resonances were added. While they predict the angular distribution observed for the cross section and analyzing power in the case of both the first and third-excited states of ^{8}Be, they do not reproduce those for the ground state. These calculations predict negligible $M1$ strength below 80 keV for capture to the third-excited state (2^+, $T = 0+1$, 16.6 MeV), and we therefore conclude that the extrapolation of the astrophysical S factor for the ^{7}Be(p, γ)^{8}B reaction, which has been performed previously by assuming pure $E1$ capture, is valid with regard to the neglect of any significant p-wave capture strength. [S0556-2813(97)04109-5]

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I. INTRODUCTION

The ^{7}Li(p, γ) ^{8}Be reaction has received considerable attention in the past few years. Cecil *et al.* [1] have examined capture to the ground and first-excited states at proton energies of 40–180 keV. In this work the authors suggest that the cross section is isotropic to within 10% and, using the direct capture (DC) model, extrapolate the astrophysical S factor to zero energy based on pure s-wave ($E1$) capture predicted by this model. However, a recent study by Chasteler *et al.* [2] has suggested otherwise. The authors of that work reported large analyzing powers ($\approx 40\%$ at 90°) and an anisotropic cross section ($\approx 30\%$). These data suggest the presence of p-wave capture (a strength of 18–95%) at low energies, contrary to the findings of Cecil *et al.* [1], who assumed a pure s-wave direct capture mechanism. Chasteler *et al.* argued that the presence of p waves in the ^{7}Li($\vec{p}$, γ_0) ^{8}Be reaction could imply the same in the ^{7}Be(p, γ) ^{8}B reaction, and thereby brought into question the extrapolation of the astrophysical S factor to zero energy based on the assumption of the validity of the direct capture model. This paper has spurred a series of reports, see Refs. [3–11]. Note that the data are not under suspicion since the anisotropic cross section has been confirmed by Hahn *et al.* [8], and the analyzing powers by Godwin *et al.* [7].

In the work of Chasteler *et al.* [2] an unconstrained fit to the data produced four distinct solutions. When all s-wave $E1$ and p-wave $M1$ transitions are allowed, the fit with the smallest amount of $M1$ strength which was able to fit the data amounted to about 50% of the cross section. If only the $p_{1/2}$ capture term is used, a solution is found which consists of 20% $M1$. Rolfs and Kavanagh [3] argue that the low-energy tail of the $M1$ resonance at 441 keV (proton energy) provides sufficient strength to account for the asymmetry of the cross-section data presented in Ref. [2]. However, Weller and Chasteler [4] point out that this conclusion does not consider the analyzing power data. When these data and the cross-section data are both accounted for, the 2% p-wave contribution reported by Rolfs and Kavanagh [3] is shown to be at least an order of magnitude too low.

Barker [5] has performed detailed R-matrix fits to the data presented in Ref. [2]. In this work he considers the tails of the two 1^+ resonances at 441 and 1030 keV to be the sole source of p-wave strength at low energies. The best fit to the data contained 9.2% $M1$ strength, although this result required that the two levels constructively interfere at 80 keV, which was achieved by reversing the sign of the 1030 keV resonance amplitude with respect to the 441 keV resonance. Both the shell model and fits to higher energy data imply otherwise. This paper also criticizes the conclusions of Chasteler *et al.* [2] in regards to the relationship between the ^{7}Li(p, γ_0) ^{8}Be reaction and the ^{7}Be(p, γ) ^{8}B reaction, since the former leads to a $J^\pi = 0^+$, $T = 0$ state and the latter a $J^\pi = 2^+$, $T = 1$ state and because of the vastly different γ-ray energies (17.3 MeV and 140 keV, respectively) of the two reactions.

At about the same time a set of data was published by Zahnow *et al.* [6]. Data for proton capture to the ground state and (unresolved) ground plus first-excited state of ^{8}B are presented for the energy range $E_p = 100$–1500 keV. Astrophysical S-factor values and forward-backward anisotropies are given. These authors used a direct capture model and added the two well-known 1^+ resonances. The data were fit quite well, and the data for the angular distribution of the cross section from [2] also roughly agree (two standard deviations) with their calculations. However, no attempt to ac-

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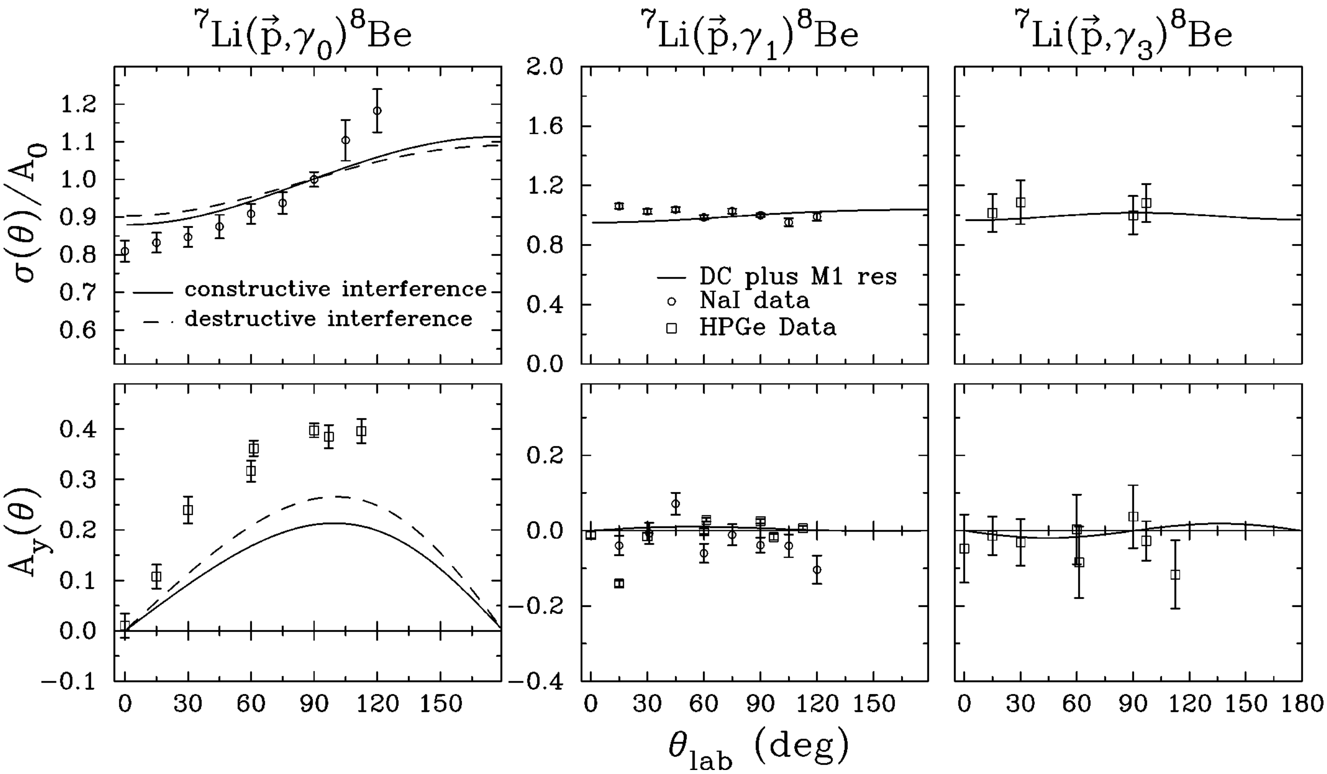

FIG. 1. Angular distribution of the cross section and analyzing powers at $E_p=70$ keV for the γ_0, γ_1, and γ_3 transitions. The data represent integrated yields from 80 to 0 keV. The curves are direct capture plus $M1$ resonances calculations.

count for the analyzing power measurements of Chasteler *et al.* [2] is made.

Continuing the study of the ^{7}Li$(p,\gamma)^8$Be reaction Godwin *et al.* [7] have reexamined capture to the ground state. Here the authors present a χ-squared plot as a function of $M1$%, which shows a broad minimum at 50% and two local minima above 80%. In addition, capture to the third-excited state of ^{8}Be is studied. This reaction is much more closely related to the ^{7}Be$(p,\gamma)^8$B reaction than is the ^{7}Li$(p,\gamma_0)^8$Be reaction (see Ref. [7] for a thorough explanation). An isotropic cross section and analyzing powers consistent with zero have led the authors to conclude that the ^{7}Li$(p,\gamma_3)^8$Be reaction essentially proceeds by either pure s-wave ($E1$) or pure p-wave ($j=\frac{1}{2};M1$) capture.

In a recently published paper [9] Barker attempts to account for the data of Zahnow *et al.* [6] and Chasteler *et al.* [2] simultaneously. The $M1$ strength is taken to arise from the two 1^+ levels (mentioned previously). The $E1$ strength is assumed to come from either s-wave direct capture, or (in the R-matrix two-level approximation) from the tails of two 1^- states. One of these states is the giant dipole resonance and the other ‘‘represents an actual $1^-,T=1$ level, or an isospin mixed $T=0$ level, or more generally some background contribution’’ [9]. Contrary to his earlier work [5], these recent fits (using an R-matrix approach and an $E1$ direct capture calculation) have signs in agreement with shell-model calculations (destructive interference between the two levels at 80 keV). Here the level parameters are the fitting parameters, rather than the transition matrix elements. However, even these solutions appear to have some problems. The R-matrix fit agrees with the 80–0 keV analyzing power data, but underpredicts the cross section at and below 200 keV, at least as reported in Ref. [6], by about a factor of 2. On the other hand, the direct capture calculation, although fitting the low-energy cross section data, underpredicts the analyzing power. In fact, the b_1 analyzing power coefficient (see Ref. [12] for a detailed discussion of these coefficients) at 80 keV is almost a factor of 2 lower than the experimentally measured value of Chasteler *et al.* [2]. It is important to note in this connection that the two calculations mentioned above, both of which are considered to be equally reliable, while giving similar cross sections at energies above 350 keV, yield cross sections (and therefore S factors) at very low energies (0–20 keV) which *differ* by about a factor of 2.

In order to investigate how the tails of the M1 resonances affect the astrophysical S factor below 80 keV we have performed extensive direct capture plus $M1$ resonances calculations for proton capture to the ground, first-, and third-excited states. Using these calculations we extrapolate the ground-state cross section to zero energy and compare this to previous measurements. We also present our measurement of the absolute cross section for the ^{7}Li$(p,\gamma_3)^8$Be reaction and the relative cross section for capture to the first-excited state (compared to the ground state). These calculations and their results are discussed below.

II. EXPERIMENTAL RESULTS

A. Angular distributions

The angular distributions of the cross section and analyzing power for proton capture to the ground, first-, and third-excited states of ^{8}Be are presented in Fig. 1. Note that some of these data have been previously published [2,7]. The curves are the results of direct capture plus $M1$ resonance calculations and will be discussed later. The details of the experimental setups used for these measurements have been previously discussed [2,7] and more details may be found in Ref. [13]. It is important to recall that all the data presented in this paper represent integrated yields of protons from 80 to 0 keV in the lab frame, but may be thought of as arising from a 70 keV beam since over 80% of the yield arises from 80–60 keV protons [13].

The analyzing powers for the ground state are observed to be nonzero (and quite large at 90°) and the cross section is clearly anisotropic. These data exhibit signatures of the presence of interfering multipolarities of opposite parity, most likely $E1$ and $M1$. However, both the first- and third-excited states show analyzing powers consistent with zero, and an isotropic cross section, within experimental error. As explained in Ref. [7] this result is consistent with both pure $E1$ s-wave capture and pure $M1$ p-wave capture if the p waves are captured only into a $j=\frac{1}{2}$ state.

B. Absolute cross section measurement

The angular distribution data presented in the previous section were obtained using the experimental setup described in Godwin *et al.* [7]. During the course of performing those experiments, it was determined that an accurate evaluation of the absolute cross section could not be obtained using the same procedure. In order to measure the absolute cross section, a different technique was developed; the details of this procedure are described below.

In order to extract information about the third-excited state we had to perform a coincidence experiment, detecting one of the two α particles from the decay of ^{8}Be (2^{+}, $T=0+1$, 16.6 MeV), such that the signal could be separated from the large cosmic-ray background. In our previous experiments [7] α particles passed through a thin lithium target (evaporated onto a 1.27×10^{-4} cm thick Ni backing foil) and were detected by a small plastic scintillator placed directly in back of the target. Although this procedure utilized a relatively simple design, the targets proved to be unstable. New lithium targets were made by evaporating lithium metal onto a 0.159 cm thick Al disc following the established procedures of other experiments [2,14]. The γ-ray yield per unit time was monitored and determined to be constant, thus demonstrating the target stability. Additionally, these targets were transferred to the beam line under an argon atmosphere and all precautions were taken to assure that they were not exposed to air. The fact that several different targets handled this way gave the same result provides additional evidence that no accidental exposures occurred. Since the distribution of the outgoing α particles is relatively isotropic at these energies [1,15], one α particle will be directed towards the target backing, while the other will emerge from the front face of the target. To detect the α particles in the present experiment we used thin plastic scintillators obtained from Bicron Corporation, placed in front of the target. Of course this suggests that larger scintillators needed to be used, in a more complicated configuration. This new arrangement is shown in Fig. 2, where the lithium target and the plastic scintillator array are indicated. The thickness of the lithium which the α particles must pass through is now determined by the range of the incident proton beam in the lithium, and not by the physical thickness of the target. γ-ray detection was performed using a large, high-purity germanium (HPGe) detector, as discussed previously [7]. An important benefit of this technique is that the energy distribution of the coincident α particles is, unlike the previous arrangement, a Gaussian-like distribution and so an energy cutoff can be established and reproduced.

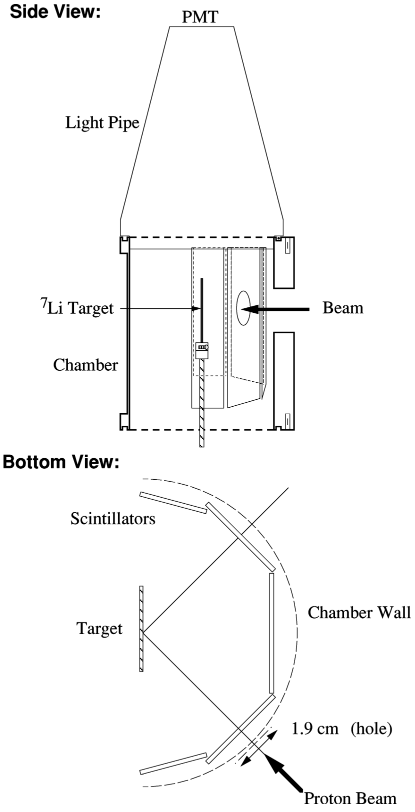

FIG. 2. Top view of the experimental setup used for the absolute cross-section measurement. Notice that the five plastic scintillator pieces surround the *front* of the lithium target.

The main goal of this procedure was to measure the absolute cross section for capture to the third-excited state of ^{8}Be. The results are displayed along with the results of direct capture plus resonances calculations in the next section.

III. DIRECT CAPTURE CALCULATIONS

Direct capture is expected to be the prevailing mechanism at these low energies. However, as mentioned in various papers [3,5,6,9], the tails of the well-known $M1$ resonances (at $E_p=441$ and 1030 keV in the laboratory frame) are expected to have an effect even at the low energies of this study. Therefore, in addition to direct $E1$ and $M1$ capture, our calculations also include these two $M1$ resonances. Although their contributions to the cross section are quite small, they may give rise to significant analyzing powers. Note that nonzero values for the analyzing power at 90° are an indication of interference between electromagnetic multipoles of opposite parity, e.g., $E1$ and $M1$.

To better understand the effects of these resonances, the following procedure was followed. First, direct capture calculations for the ground-state transition were performed over the proton energy range 0–1500 keV, and included the

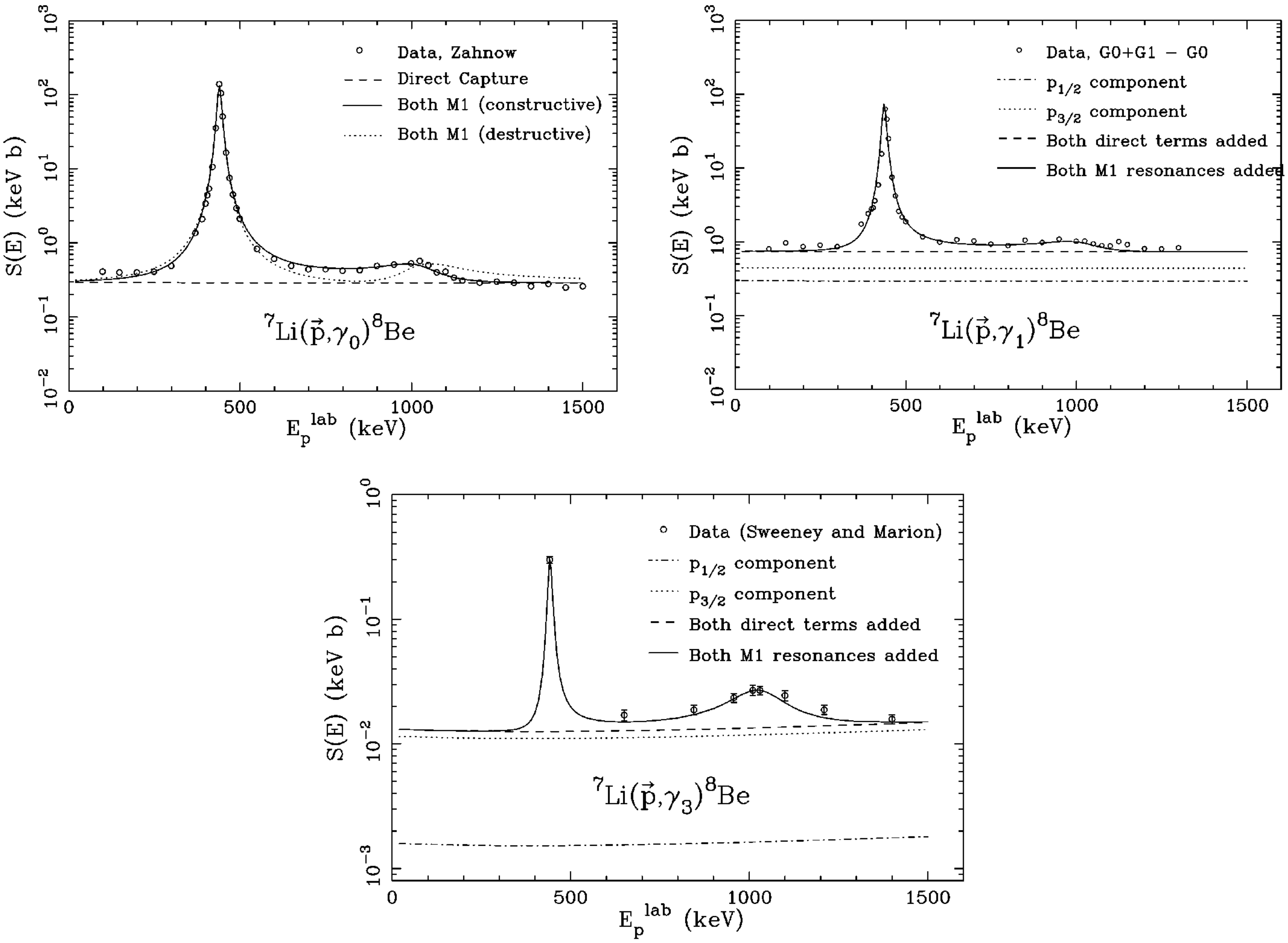

FIG. 3. Direct capture plus $M1$ resonance calculations for the $^7\mathrm{Li}(p,\gamma_0)^8\mathrm{Be}$, $^7\mathrm{Li}(p,\gamma_1)^8\mathrm{Be}$, and $^7\mathrm{Li}(p,\gamma_3)^8\mathrm{Be}$ reactions. The astrophysical S factor is plotted against the proton lab energy. Also displayed are the data of Zahnow (for the ground state and first-excited state) and the data of Sweeney (for the third-excited state).

known $M1$ resonances. The parameters for these resonances are well established and are taken from Ref. [16]. The strengths and phases of the resonances were varied until the cross section data of Zahnow *et al.* [6] were reproduced. With this established, the calculations were performed at 70 keV and the analyzing power and angular distribution of the cross section as a function of γ-ray angle were compared to the experimentally measured values. A similar procedure was followed for the γ_1 and γ_3 transitions. These calculations are discussed below.

A. Ground state

For the present calculations, the ground state of ^{8}Be was considered to be a pure single-particle $p_{3/2}$ state outside of a ^{7}Li core, with a spectroscopic factor of unity. Our first goal was to reproduce the extensive ground-state data of Zahnow *et al.* [6]. Including the two known $M1$ resonances (using resonance parameters from the $A=5-10$ data compilations [16]) and adjusting the strengths and phases of the resonances allowed us to fit the data fairly well, as shown in Fig. 3. Note that when we required the two resonances to interfere destructively in the region between the two levels (and therefore constructively in the energy range of the present study), the fit was much better. Barker [5] has come to the same conclusion and points out that this contradicts findings from shell-model calculations. The data and our fits are shown in Fig. 3. The calculations for the cross sections have been converted to astrophysical S factors using the following equation:

$$\sigma(E_{cm})=\frac{S(E_{cm})e^{-2\pi\eta}}{E_{cm}}, \tag{1}$$

where η is the Sommerfeld parameter.

The data we have obtained are for proton energies of 80–0 keV. As explained in Ref. [13], over 80% of the yield arises from protons of energy 80–60 keV and the ‘‘median energy’’ is $\approx$70 keV. Therefore we have performed calculations of the cross section and analyzing power at 70 keV, as a function of angle, and compared them with the data. These results are shown in Fig. 1. Note that the calculation does not reproduce fully the asymmetry in the $^7\mathrm{Li}(p,\gamma_0)^8\mathrm{Be}$ cross section reported by Chasteler *et al.* [2]. The remeasured analyzing powers for this reaction reported in Ref. [7] are also not predicted, although the calculation

TABLE I. Spectroscopic factors used in the ^{7}Li$(p,\gamma)^8$Be direct capture calculations.

State	Spectroscopic Factors $j=\frac{3}{2}$	$j=\frac{1}{2}$
γ_0	1.0	0.0
γ_1	1.119	0.751
γ_3	1.651	0.228

which requires destructive interference between the two levels is slightly better. The measured vector analyzing power (0.4 ± 0.014 at $\theta=90°$) is about a factor of 2 greater than the calculations predicts. Thus the $M1$ *amplitude* needs to be doubled, and (since $\sigma\sim$amplitude^2), we need four times as much $M1$ *strength* compared to what this direct capture calculation predicts. The direct capture plus $M1$ resonances calculations find a $\sim6\%$ ($\sim10\%$) $M1$ contribution to the cross section for the constructive (destructive) interference solution. Since the measured data imply that the $M1$ strength is under predicted by a factor of 4, a 24% (40%) $M1$ contribution would be required to fit our data.

B. First-excited state

The S factor for capture to the ground state and first-excited state together is reported by Zahnow *et al.* [6]. Following the same procedure as in the ground state, direct capture calculations were performed for the first-excited state with terms added in for the two $M1$ resonances. Unlike the ground state, the first-excited state is considered to be a mixture of $p_{1/2}$ and $p_{3/2}$ single-particle states. The spectroscopic factors have been previously determined [15,17,18] and are listed in Table I, along with the spectroscopic factors used in the γ_0 and γ_3 calculations. In this situation, the direct capture calculations needed to be performed twice, once for a $p_{1/2}$ single-particle bound state and once for a $p_{3/2}$ single-particle bound state. The total cross section was determined by adding these two pieces together. The angular distribution of the cross section and analyzing power calculations combine the results of both calculations weighted by the predicted value for A_0, the absolute cross-section normalization constant.

The overall normalization of the spectroscopic factors was allowed to vary until the direct capture only calculation agreed with the off-resonance data of Zahnow *et al.* [6]. Next, as in the γ_0 case, the strengths and phases of the $M1$ resonances were allowed to vary until a suitable fit to the cross-section data (reported in Ref. [6]) was found. As can be seen in Fig. 3, these direct capture plus $M1$ resonances calculations are in good agreement with the data.

Next the direct capture calculations were performed at $E_p=70$ keV over the angular range $\theta=0°-180°$. Figure 1 shows these calculations, the angular distribution of the cross section reported in Ref. [2], and the previously unpublished analyzing powers. The data, which display an isotropic cross section and analyzing powers consistent with zero, are well represented by the direct capture plus $M1$ resonances calculations.

C. Third-excited state

A direct capture plus resonances calculation has also been performed for the γ_3 state. As in the γ_1 case, the third-excited state is a mixture of $p_{1/2}$ and $p_{3/2}$ single-particle bound states. In the previous two sections the first step involved varying the strengths of the $M1$ resonances until the cross section was fit over a large energy range. The extensive data of [6] has been used in those cases, but, unfortunately, Zahnow *et al.* [6] do not report cross-section data for the γ_3 transition.

The data of Sweeney and Marion [15] was used in order to estimate the strength of the $M1$ resonances in the γ_3 transition. In this paper, the differential cross section for ^{7}Li$(p,\gamma_3)^8$Be at $\theta=120°$ was given for proton energies between 441 and 1400 keV. The astrophysical S factor was calculated from these experimentally determined cross sections assuming an isotropic angular distribution, and the strengths of the two $M1$ resonances were adjusted to match the resulting values. The calculated values for $S(E)$ are shown in Fig. 3 along with the result of the direct capture plus $M1$ resonances calculation. The contributions of each single-particle state ($p_{1/2}$ and $p_{3/2}$) are shown along with the total direct capture calculation and the DC plus $M1$ resonances calculation. Note that our direct capture calculations match those in Ref. [15] at $E_p=200$ keV.

Following the same procedure as before, the angular distributions of the cross section and the analyzing power are calculated at $E_p=70$ keV as a function of γ-ray angle. These calculations are displayed in Fig. 1 along with the experimentally measured values. The data measured for the ^{7}Li$(\vec{p},\gamma_3)^8$Be reaction are well reproduced by the direct capture plus $M1$ resonances calculations. There is no evidence of any $E1/M1$ mixing in this data, since $A_y(90°)$ is nearly zero. The slightly anisotropic cross section and small analyzing powers predicted by the model arise from the interference of s- and d-wave $E1$ amplitudes.

IV. EXTRACTION OF ASTROPHYSICAL S FACTORS

A. Ground state

In a previous study of proton capture to the ground state of ^{8}Be performed by Cecil *et al.* [1] the astrophysical S factor was *assumed* to be a constant. However, it is clear from the data presented here and elsewhere [2,7] that a significant portion of the capture strength is due to $M1$ radiation, which implies that the S factor will vary with energy. Previous experiments [19] have been able to use the excellent resolution of the TUNL HPGe detector to unravel the energy dependence of the cross section (or, equivalently, the S factor) and it was hoped that this procedure could be used here. Unfortunately, this was not possible, largely because of count-rate limitations. A direct experimental determination of the energy dependence of the ^{7}Li$(p,\gamma_0)^8$Be cross section below 100 keV is currently underway using a technique involving NaI detectors and a variable target bias voltage [20]. However, since a determination of this was not possible from the present data, the direct capture model was used to predict this energy dependence below 100 keV. These direct capture calculations predict that S_{E1} is constant in this energy regime (as expected). For the present analysis we shall use the value

TABLE II. Summary of the astrophysical S factors reported by various authors. The values given by Cecil *et al.* [1] and Zahnow *et al.* [6] are also listed for comparison. The values for γ_0 and γ_1 at 70 keV in the present study are normalized to the data of Cecil *et al.* [1] and the values at 0 keV are based on the extrapolations discussed in the text.

	Astrophysical S factors at $E_p=70$ and 0 keV Value for $S(E)$			
Reference	γ_0 (70 keV) keV barns	γ_0 (0 keV) keV barns	γ_1 (70 and 0 keV) keV barns	γ_3 (70 and 0 keV) eV barns
Present work				6.45 ± 1.54
Present work	0.25^{a}	$0.24^{b}/0.219^{c}$	$0.73^{a}\pm0.11$	
Cecil *et al.* [1] [d]	0.25 ± 0.05	0.25 ± 0.05	1.2 ± 0.2	
Zahnow *et al.* [6] [e, f]	0.4 ± 0.03	0.4 ± 0.03	0.9 ± 0.11	

[a] Data obtained by normalizing to the data of Cecil *et al.* [1].

[b] The $M1/E1$ strength ratio value given by the model is used to extrapolate from 70 keV.

[c] $4\times M1/E1$ strength ratio value is used to extrapolate from 70 keV.

[d] Values given by Cecil *et al.* [1].

[e] Values interpolated from the graphs of Zahnow *et al.* [6].

[f] Errors are taken from the lowest energy data points ($E_p=98.3$ keV) of Zahnow *et al.* [6].

of the S factor given by Cecil *et al.* [1] at $E_p=70$ keV and compare the method of extrapolating the astrophysical S factor to zero energy based on our direct capture plus resonances calculations with previous methods. A determination of the absolute cross section would require precise knowledge of the HPGe detector's efficiency. Although we were able to accurately evaluate this quantity, using a calibrated radioactive source, for capture to the third-excited state (where the γ-ray energy is 700 keV) no determination was made for the higher γ-ray energies of capture to the ground and first-excited states (17.3 and 14.3 MeV, respectively).

The energy dependence of the astrophysical S factor for the $^7\mathrm{Li}(p,\gamma_0)^8\mathrm{Be}$ reaction was parametrized as follows:

$$S(E)=k(1+aE+bE^2). \tag{2}$$

This functional form was fitted to the calculated values obtained from the DC plus $M1$ resonances model, and normalized to reproduce the value of the cross section for the $^7\mathrm{Li}(p,\gamma_0)^8\mathrm{Be}$ reaction obtained by Cecil *et al.* [1] at $E_p=70$ keV ($\sigma_T=54.3$ nb with an uncertainty of $\pm20\%$). The result is

$$S_{\gamma_0}(E)=(0.240\pm0.036)(1+0.000\,356\,E_p + 0.000\,003\,413\,E_p^2)\ \text{keV barns}, \tag{3}$$

where E_p is the energy of the proton in the lab frame and is measured in units of keV. Note that Cecil *et al.* [1] assume that S does not vary with energy, so $S(E)=S(0\ \text{keV})=0.25$ keV barns. As previously discussed, the experimentally determined analyzing powers indicate that the $M1$ strength is approximately four times larger than predicted by the direct capture plus $M1$ resonances model. Repeating the above procedure with the $M1$ strength enhanced by a factor of 4 gave an S factor (at 0 keV) of 0.219 keV barns. These results are compared with those of Cecil *et al.* [1] and Zahnow *et al.* [6] in Table II.

B. First-excited state

An independent measurement was performed which determined the ratio of the γ_1 to γ_0 yield. A large, anticoincidence shielded NaI detector was used to observe proton capture on ^{7}Li [20]. As Fig. 4 shows, the yield for capture to the ground and first-excited states are clearly resolved. An analysis of these data indicates that the ratio (r) of the first-excited state yield to the ground-state yield (at 90°) is 2.92 with a statistical error of 4.7% ($r=2.92\pm0.14$). This ratio is in excellent agreement with the earlier experimental results of Prior *et al.* [22]. We expect the efficiencies for γ-ray detection in this measurement to be the same for both the ground-state and first-excited state transitions [23]. Since the angular distribution of the γ rays are either isotropic (γ_1) or involve only a P_0 and $P_1(\cos\theta)$ term [the latter of which integrates out when determining the angle-integrated cross section from $\sigma(90°)$] the *ratio* of the total, angle-integrated cross section for proton capture to the first-excited state of ^{8}Be, compared

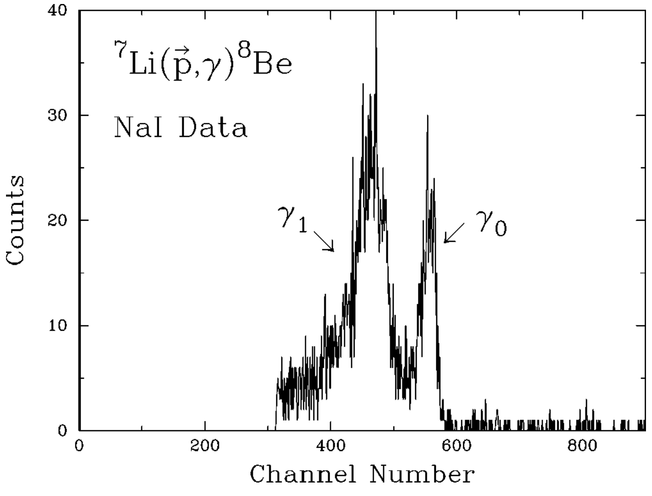

FIG. 4. NaI spectrum used for computing the γ_1 to γ_0 yield ratio. The two (full-response) peaks are well separated from each other. Cosmic-ray background is subtracted by normalizing to the yield above the γ_0 peak.

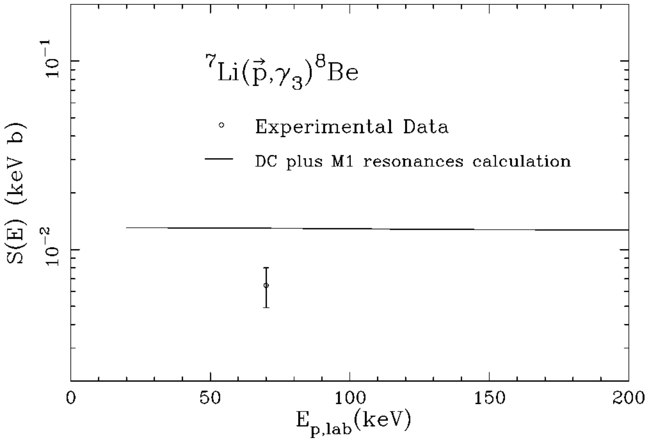

FIG. 5. Experimental measurement of the γ_3 astrophysical S factor shown with a direct capture calculation, which includes the $M1$ resonances. The vertical error bars represent statistical and systematic uncertainties. The data represents an *integrated* yield for proton energies of 80–0 keV. The reasons for displaying the data at 70 keV are discussed in the text.

to the ground state, at $E_p = 70$ keV, is the yield ratio mentioned above, 2.92±0.14. Previous studies [1,6,24] have established that the astrophysical S factor for proton capture to the first-excited state of ^{8}Be is constant at the low energies of the present study. Furthermore, our direct capture plus $M1$ resonance calculations also predict this behavior. Therefore we conclude that, based on a comparison to the ground state, the astrophysical S factor for the ^{7}Li$(p,\gamma_1)^8$Be reaction below $\sim$80 keV is $S_{\gamma_1}(E) = (0.73 \pm 0.11)$ keV barns. This measurement is compared with those of Cecil *et al.* [1] and Zahnow *et al.* [6] in Table II.

C. Third-excited state

The result of the direct capture plus $M1$ resonances calculation below 200 keV are displayed in Fig. 5, along with the data measured in this experiment. Again, the data represent an integrated yield from 80 to 0 keV. The astrophysical S factor is extracted from the data by integrating the cross section, expressed in terms of the astrophysical S factor, over the energy range of the experiment using the known stopping powers [25]. The S factor is assumed to be constant in this energy region ($E_p \leq 80$ keV). Since approximately 84% of the yield arises from the 60-to-80 keV region [2,13,25], the deduced S factor is displayed at an effective energy of 70 keV, but note that the value of the deduced S factor *does not* depend on this energy value in any way. However, although the systematic error in the value of the S factor which is introduced by the assumptions implicit in the procedure descibed above is difficult to estimate, our experiences with the γ_0 and γ_1 data suggest that it is less than 20%. This additional systematic error is included in the uncertainty for the S factor of the γ_3 channel given in Fig. 5. The measured astrophysical S factor for the ^{7}Li$(p,\gamma_3)^8$Be reaction below $\sim$80 keV is $S_{\gamma_3}(E) = (6.45 \pm 1.54)$ eV barns. The direct capture plus $M1$ resonance calculations yield a value of approximately twice this result.

D. Connection between the ^{7}Be$(p,\gamma)^8$B and the ^{7}Li$(p,\gamma)^8$Be reactions

The ^{7}Li$(p,\gamma_3)^8$Be reaction populates the third-excited state of ^{8}Be. This state lies at 16.63 MeV, has $J^\pi = 2^+$, and $T = 0+1$. Its isospin is almost totally mixed, so that it is basically a protonlike state. The $T=1$ component of this state is the analog of the ground state of ^{8}B, which has $J^\pi = 2^+$, $T=1$. It is this connection which relates the present reaction to the ^{7}Be$(p,\gamma)^8$B reaction.

An additional concern in considering the relationship between these two reactions lies in the fact that the energies are somewhat different: the γ rays in the ^{7}Be+p reaction for 80 keV protons would have $E_\gamma \sim 200$ keV, whereas they have $E_\gamma \sim 700$ keV for the ^{7}Li(p,γ_3) case. Although these differ, they are much closer than that obtained when comparing ^{7}Li$(p,\gamma_0)^8$Be ($E_\gamma = 17.3$ MeV) to ^{7}Be$(p,\gamma)^8$B ($E_\gamma = 200$ keV). It is also worth noting that the energy of the next highest resonance is more than twice as great for ^{8}B (704 keV) as ^{8}Be (320 keV), although the width is almost four times greater for ^{8}B (37 keV) as ^{8}Be (10 keV). This could be important since the tail of this resonance will give rise to p-wave capture and therefore influence the energy dependence of the S factor used in extrapolating to very low energies.

Isospin selection rules must also be considered for the $E1$ and $M1$ transitions in the two cases. For ^{7}Be+p, only $T=1$ states can be formed. The ground state of ^{8}B has $T=1$, so that the transition will be $T=1 \rightarrow T=1$. In the case of the ^{7}Li$(p,\gamma)^8$Be (16.6 MeV) reaction, both $T=0$ and $T=1$ states are formed. The final state's isospin (at 16.6 MeV) is ‘‘totally’’ mixed. So, although one expects only $\Delta T=1$ for $E1$ transitions and predominantly $\Delta T=1$ for $M1$ transitions in the self-conjugate nucleus of ^{8}Be, the fact that the isospin is not a good quantum number for the 2^+ (16.6 MeV) state implies that all of the continuum strength can decay to the final 2^+ isospin-mixed state at 16.6 MeV. Therefore, we do not expect isospin selection rules to play a significant role in the comparison of the two reactions being discussed.

V. CONCLUSIONS

Clearly the ^{7}Li$(p,\gamma_0)^8$Be reaction proceeds by both s-wave and p-wave capture. Since previous measurements of the astrophysical S factor and the extrapolation of this quantity to zero energy have assumed that only s-wave capture occurs, these values require revision. Chasteler *et al.* [2] calculate that previously extracted (s-wave only) astrophysical S factors may be 7–38% too high. Our calculations, which use the direct capture plus $M1$ resonances model in order to estimate values for the $M1/E1$ cross-section ratio, predict a zero-energy value only 4% lower than that which would be obtained assuming a pure $E1$ direct capture model. However, we estimate that the $M1/E1$ cross-section ratio is four times greater than the model predicts, which in turn gives a zero-energy S-factor value 12% lower than a pure $E1$ extrapolation. Values for the astrophysical S factor at 70 and 0 keV for the ^{7}Li$(p,\gamma_0)^8$Be, ^{7}Li$(p,\gamma_1)^8$Be, and ^{7}Li$(p,\gamma_3)^8$Be reactions are summarized and compared with other measurements in Table II. A direct experimental measurement of the slope of the S factor for the γ_0 and γ_1 cases at energies between 40 and 100 keV is underway [20]. Preliminary results [20] indicate a *negative* slope for the S factor in both of these channels. These results, if substantiated, could lead to an *increase* in the extrapolated value of the S factor by about 20% [21] compared to that obtained when a constant S factor is assumed in the 0–100 keV region. This implies that additional physics, not contained in the present model (which predicts a small but *positive* slope), must be included in a proper description of these reactions. Clearly, further experimental and theoretical effort is necessary before precise and reliable S factors can be specified for these reaction channels.

The similarities between the ^{7}Li$(p,\gamma_3)^8$Be and ^{7}Be$(p,\gamma)^8$B reactions are quite apparent, as previously discussed. Our study of the former reaction shows no evidence of interference between $E1$ and $M1$ radiation, and we conclude that the reaction proceeds by pure $E1$ capture on the basis of the direct capture model calculations. However, since relatively pure $p_{1/2}$ $(M1)$ capture would give identical results for the observed behavior of the angular distributions of the cross section and analyzing powers, a direct experimental determination is desirable and is being planned. This will consist of a measurement of the outgoing γ-ray polarization for this channel.

In conclusion, despite the discrepancies in the γ_0 measurements, and the uncertainties in the slopes of the S factors for both γ_0 and γ_1, the present results do not show any evidence that the essentially pure s-wave assumption is incorrect for the ^{7}Li$(p,\gamma_3)^8$Be reaction. It is therefore unlikely that the extrapolation of the nuclear cross section to zero energy in the ^{7}Be$(p,\gamma)^8$B case is in serious error, at least not as a result of the neglect of p-wave contributions. However, it is clear from our studies that the direct capture plus $M1$ resonances model is insufficient, or at least incomplete, at these energies. Before the direct capture model can be trusted to perform S-factor extrapolations to astrophysically significant energies more experimental and theoretical work needs to be performed.

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