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Low-energy polarized-proton capture on ^{6}Li

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We have measured the thick-target yield and analyzing power for the $^6\text{Li}(\vec{p},\gamma)$ reaction to the ground and first excited state of ^{7}Be below $E_p = 80$ keV. High-purity-germanium detectors were used to acquire data at five angles from $\theta = 0°$ to 124°. For both states the yield, integrated from the beam energy of 80 keV down to 0 keV, is nearly isotropic and the integrated analyzing power shows only small deviations from zero. This is taken as an indication that, unlike the case of the $^7\text{Li}(\vec{p},\gamma_0)^8\text{Be}$ reaction, the p-wave-capture process is unimportant compared to the s-wave process. Transition-matrix-element analyses of the ground-state data yield p-wave contributions of a few percent. Under the assumption of a constant astrophysical S factor, consistent with direct s-wave capture, a value of $S = (2.69 \pm 0.54) \times 10^{-5}$ MeV b has been deduced.

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I. INTRODUCTION

Recently, a study [1] of the $^7\text{Li}(\vec{p},\gamma_0)^8\text{Be}$ reaction in which the yield and analyzing power as a function of photon-emission angle were measured at $E_p = 80$ keV revealed a strong p-wave contribution to the ground-state-capture cross section. Based on simple penetrability arguments and direct-model calculations, one expects almost no contribution from p waves. In the direct model the capture process is treated as a single-particle, one-step process. Its failure to reproduce the measured observables demonstrates the need to consider other mechanisms. The most obvious of these is the multistep mechanism of capture through the tails of nuclear resonances, as has been suggested by several authors [2–5]. Such a hypothesis implies that the observed p-wave strength is not a general feature of the capture process but is instead the result of nuclear-structure effects that can vary radically from nucleus to nucleus.

The observation of substantial p-wave strength in the $^7\text{Li}(\vec{p},\gamma_0)^8\text{Be}$ reaction at these low energies has direct bearing on the extrapolation of the cross section to astrophysically interesting energies because it is generally assumed that s-wave capture dominates the cross section in this energy regime. To better understand the nature of the observed p-wave strength and to ascertain whether this is a general feature of low-energy capture we have undertaken a systematic study of proton capture on light nuclei. We report on a thick-target study of the $^6\text{Li}(\vec{p},\gamma)^7\text{Be}$ reaction at a beam energy of $E_p = 80$ keV (lab). In this experiment, photon yields and analyzing powers were measured as a function of angle. The analyzing power for this reaction has not been measured at these energies before. Such measurements are important in studies where the goal is to determine the presence of various partial waves in the capture process.

II. EXPERIMENT

The $^6\text{Li}(\vec{p},\gamma)^7\text{Be}$ experiment was done using a beam of 80 keV, polarized protons directly from the Triangle Universities Nuclear Laboratory (TUNL) Intense Polarized Ion Source [6]. Because of the high intensity of positive ions available from the ion source, we ran this experiment with positive beam. Typically the beam current on target was about 30 μA.

We used a fast-spin-flipping technique in which one of the two polarization states was chosen every 0.1 s. Data were not acquired from 2 ms before to 5 ms after each polarization-state transition to allow beam of unknown polarization to drift out of the ion source and beam transport system. The fast-spin-flip method eliminates most potential systematic errors.

Prior to the start of the $^6\text{Li}(\vec{p},\gamma)^7\text{Be}$ experiment, we determined the values of the beam polarization transverse to the reaction plane to be $P_{y1} = -0.76 \pm 0.01$ and $P_{y2} = 0.64 \pm 0.01$ for the two polarization states by measuring the polarization asymmetry of the $^{12}\text{C}(\vec{p},p)^{12}\text{C}$ reaction at $E_p = 6$ MeV. We used the tandem accelerator with negative beam from the ion source to make this measurement. This method of determining the beam polarization has been shown [1] to be reliable. We made one other beam-polarization measurement using this method during the course of the experiment and found similar values. Additionally, we occasionally made polarization checks at the 20% level during short runs with a polarimeter [7] employing the reaction $^7\text{Li}(\vec{p},\gamma_0)^8\text{Be}$ at $E_p = 100$ keV. This polarimeter is installed just upstream of the scattering chamber used for the $^6\text{Li}(\vec{p},\gamma)^7\text{Be}$ reaction and the measurements were made with positive ions.

The target for the $^6\text{Li}(\vec{p},\gamma)^7\text{Be}$ study was a thick layer of ^{6}Li isotopically enriched to greater than 99% and evaporated on a 1.6 mm thick disk of aluminum. Because the beam stopped in the target material, the yields that we obtained were integrated from 0 to 80 keV (lab). As part of the experiment, we used a silicon solid-state detector to monitor the reactions $^6\text{Li}(p,\alpha_0)$ and $^7\text{Li}(p,\alpha_0)$ (from the residual ^{7}Li in the target). The target was changed whenever a fall off

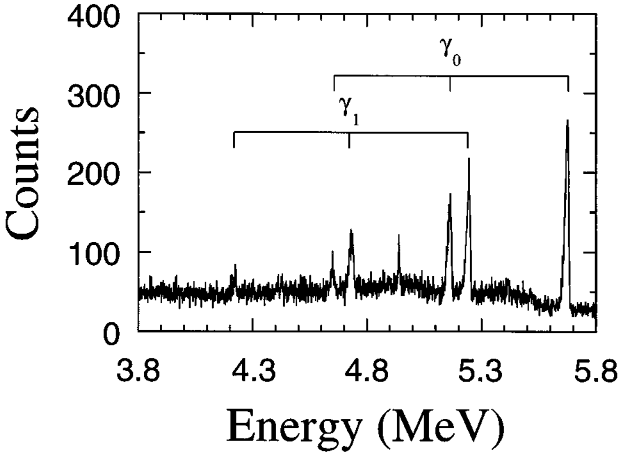

FIG. 1. Portion of the spectrum from the ^{6}Li(p,γ) reaction taken at $\theta = 90°$. The photo and escape peaks from capture to the ground and first excited state of ^{7}Be are visible.

in the monitor reaction rate was observed. The monitor rate can be reduced either by a reduction of the ^{6}Li on the target backing or by carbon buildup on the target surface which reduces the energy of the beam striking the ^{6}Li. Because of the rapid change of the cross section with energy, an energy loss of 1.5 keV in a carbon layer reduces the reaction yield by about 10%.

We used two large high-purity-germanium detectors to observe photons from the ^{6}Li$(\vec{p},\gamma)^7$Be reaction. The larger of the two detectors has a quoted relative efficiency at $E_\gamma = 1.33$ MeV of 1.4 times that of a 7.6 cm diameter, 7.6 cm length cylinder of NaI. This detector was kept fixed at a laboratory angle of $\theta = 90°$ throughout the experiment with the front face of the detector about 7 cm from the target center. The second germanium detector has a quoted relative efficiency of 1.28 and had its front face about 13 cm from the target center. This detector was placed inside of a 23 cm outer diameter cylindrical NaI detector, open at both ends, which was used as an anticoincidence shield. The assembly could be rotated about the target position and was used to acquire data at five angles from $\theta = 0°$ to $\theta = 124°$. The relative yields at each angle were normalized by the γ_0 yields acquired by the detector fixed at $\theta = 90°$.

III. RESULTS AND CONCLUSIONS

Figure 1 displays a portion of the spectrum taken with the detector fixed at 90° that includes the energy of the ground-state-capture γ ray. The energy of the outgoing γ ray depends on the energy of the proton that is captured by a target nucleus. Because the beam stops in the target, there is a range of γ-ray energies. The widths of the capture peaks in Fig. 1 are due mainly to this fact.

Figure 2 is a plot of the energy-integrated yield and analyzing power, A_y, as a function of angle for the ^{6}Li$(\vec{p},\gamma)^7$Be reaction for capture to the ground and to the first excited state. Unlike the results of the ^{7}Li$(\vec{p},\gamma_0)^8$Be reaction [1], the present angular distributions are nearly isotropic and the analyzing powers show little deviation from zero.

Yield asymmetries about $\theta = 90°$ and values of $A_y(90°)$ other than zero result from interference between amplitudes of opposite parity. No such interference is required to explain the present data from the ^{6}Li$(\vec{p},\gamma_0)^7$Be reaction. However, we have analyzed the ground-state data in terms of s-wave $E1$ and p-wave $M1$ transition-matrix elements (TME's) in order to set some limits on the p-wave contribution allowed by the data. In the following discussion, we use the jj angular-momentum-coupling scheme in which the TME's are labeled by the notation $^{2b+1}l_j$, where l is the quantum number labeling the orbital angular momentum between the proton projectile and the ^{6}Li target. The orbital angular momentum is coupled to the spin of the projectile and the result is labeled by j. The total angular momentum is the vector sum of j and the spin of the target nucleus and is labeled by b. In the analysis, we consider only s-wave $E1$ and p-wave $M1$ amplitudes. The allowed TME's are $^2s_{1/2}$, $^4s_{1/2}$, $^2p_{1/2}$, $^4p_{1/2}$, $^2p_{3/2}$, $^4p_{3/2}$, and $^6p_{3/2}$. Because there is no radial dependence in the single-particle $M1$ operator, matrix elements that connect continuum states (l_j) to single-particle states (L_j) having the same quantum numbers vanish due to orthogonality. In our analysis we assume that the ground state of ^{7}Be is well described as a $P_{3/2}$ single-particle state and we neglect the three M1-$p_{3/2}$ amplitudes. If we assume that the two s-wave $E1$ TME's have the same amplitude and phase and that the two remaining p-wave $M1$ TME's have the same amplitude and phase, then we have reduced the problem, effectively, to two TME's. There are three parameters left in this "reasonable model" of the capture process: an s-wave amplitude, a p-wave amplitude, and a relative phase.

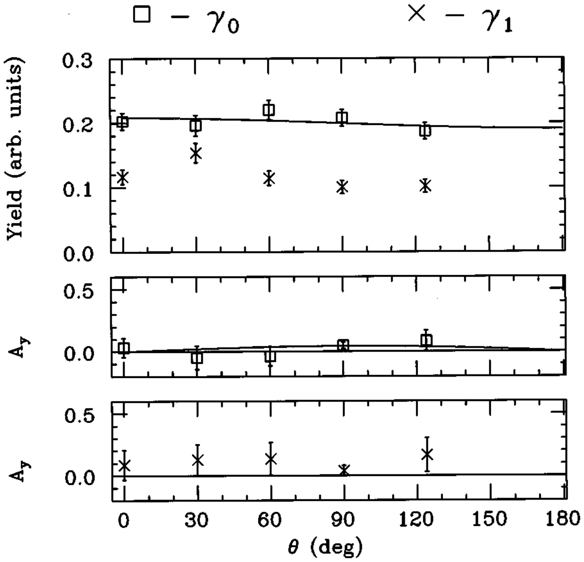

FIG. 2. Plots of yields and analyzing powers for proton capture to the ground and first excited states of ^{7}Be. The error bars represent the statistical uncertainties associated with the data points. The solid lines are the results of Legendre polynomial fits to the ground-state data as discussed in the text.

We parametrize the cross section and analyzing power as

$$\langle\sigma(\theta)\rangle = \sum_{i=0}^{i_{\max}} Q_i \langle A_i\rangle P_i(\cos\theta) \qquad (1)$$

and

$$\langle \sigma(\theta) A_y(\theta) \rangle = \sum_{j=1}^{j_{\max}} Q_j \langle B_j \rangle P_j^1(\cos\theta), \qquad (2)$$

where the $P_i(\cos\theta)$ and $P_j^1(\cos\theta)$ are Legendre and associated Legendre polynomials. The brackets on the left-hand side of the two equations indicate that observed values are averaged over detector acceptance and γ-ray energy. The Q_i are geometrical attenuation coefficients [8] that contain the effects of the finite detector acceptance. The $\langle A_i \rangle$ and $\langle B_i \rangle$ are therefore expansion coefficients for the energy-averaged observables. Elimination of the $p_{3/2}$ amplitudes reduces the maximum-order term in the above equations to $i_{\max}$, $j_{\max}=1$.

Using the formalism of Seyler and Weller [9], we find for this model:

$$\langle A_0 \rangle = \langle (|s|^2 + |p|^2) \rangle, \qquad (3)$$

$$\langle A_1 \rangle = \langle -1.961 |s||p| \cos\delta \rangle, \qquad (4)$$

and

$$\langle B_1 \rangle = \langle -1.961 |s||p| \sin\delta \rangle, \qquad (5)$$

where s and p represent the retained amplitudes and δ is the relative phase between them. The last two equations demonstrate that the observable effects of the interference between the s and p TME's are divided between the cross-section asymmetry and the analyzing power. Henceforth we neglect the energy averaging and treat s and p as effective amplitudes.

The solid lines in Fig. 2 are the results of fitting the data to Legendre polynomials using Eqs. (1) and (2) with $i_{\max}=j_{\max}=1$. The resulting coefficients are

$$a_1 \equiv \frac{A_1}{A_0} = 0.045 \pm 0.051 \qquad (6)$$

and

$$b_1 \equiv \frac{B_1}{A_0} = 0.045 \pm 0.021. \qquad (7)$$

Solving Eqs. (3)–(5) we find

$$f_p \equiv \frac{|p^2|}{|s^2| + |p^2|} = 0.0011 \pm 0.0013, \qquad (8)$$

where f_p is the fraction of the total cross section that comes from p-wave capture. There is a quadratic ambiguity between the s and p amplitudes, and we assume that the smaller solution corresponds to the p-wave contribution. This assumption is based on a direct model calculation where we find, using the parameters of Ref. [10], a predicted value of f_p of 3×10^{-6} at the top energy range of this experiment.

We have also analyzed the data using a two-amplitude "insensitive model" in which we assumed that only the ${}^2s_{1/2}$ and ${}^2p_{1/2}$ TME's contribute to the ${}^6\mathrm{Li}(\vec{p},\gamma_0)\,{}^7\mathrm{Be}$ reaction. These amplitudes were chosen because the observables are less sensitive to interference between these two amplitudes than to other combinations of the $s_{1/2}$ and $p_{1/2}$ amplitudes. This model leads to a large value of f_p for a given data set. From the Legendre coefficients listed in Eqs. (6) and (7), we obtain

$$f_p = 0.038 \pm 0.048. \qquad (9)$$

The energy dependence of the cross section at low energies is often parametrized in terms of the S factor:

$$\sigma(E) = [S(E)/E] e^{-(E_G/E)^{1/2}}. \qquad (10)$$

E_G has the value of 7606 keV for this reaction. In the absence of nuclear structure effects this definition results in a constant value of $S(E)$ for s-wave capture. Under this assumption the measured ${}^6\mathrm{Li}(\vec{p},\gamma_0)^7\mathrm{Be}$ yield taken with the calculated detector efficiency [11] and the calculated energy dependence of the target stopping power [12] implies $S = (2.69 \pm 0.54) \times 10^{-5}$ MeV b for this reaction. The uncertainty in this value comes mainly from uncertainties in beam-current integration. In a previous study [10] of this reaction using unpolarized beam, Cecil *et al.* assumed a linear S factor of the form $S(E) = S_0 + S_1 E$, and deduced values of $S_0 = 3.9 \times 10^{-5}$ MeV b and $S_1 = 2.4 \times 10^{-4}$ b. To compare our results to those of Cecil *et al.* we must assume that the S factor has this energy dependence. We then find that a renormalization of these parameters by a factor of 0.51 ± 0.10 reproduces the yield observed in the present experiment.

The fact that little p-wave strength is required to explain the ${}^6\mathrm{Li} + \mathrm{p}$ radiative-capture data is in contrast to the result of the ${}^7\mathrm{Li}(\vec{p},\gamma)^8\mathrm{Be}$ reaction in which large interference effects were interpreted as evidence for the presence of a significant p-wave contribution to the reaction. Several authors [2–4] suggested that the p-wave amplitudes observed in the ${}^7\mathrm{Li}(\vec{p},\gamma)^8\mathrm{Be}$ reaction are due to the tails of resonances. Barker [2] performed a two-level R-matrix calculation that included the $J^\pi = 1^+$ resonances at proton laboratory energies of $E_p = 0.441$ and 1.024 MeV as well as a direct component. He succeeded in finding a set of resonance parameters that yield a plausible fit to the data by adjusting the signs of the resonant reduced widths to produce as large a p-wave contribution as possible in the energy region below the resonances. Barker [2] notes that the choice of signs necessary to achieve this goal is at odds with those necessary to fit data [13] between the resonances and appears to be inconsistent with shell-model predictions.

In the case of the ${}^6\mathrm{Li}(\vec{p},\gamma)^7\mathrm{Be}$ reaction there are $J^\pi = 5/2^-$ levels [14] in the ${}^7\mathrm{Be}$ system at excitation energies of $E_x = 6.73$ MeV and 7.21 MeV that could provide a mechanism for p-wave capture. No proton branch has been observed for the first of these levels and we neglect its effects. The second level has a center-of-mass width of about 500 keV and its γ-ray branching ratio is unknown. We make an order-of-magnitude estimate of its effects by assuming a rather large $M1$ γ-ray width of one Weisskopf unit or $\Gamma_\gamma = 7.8$ eV and assuming that the level decays primarily into the p-wave proton channels. Including the energy dependence of the penetrability and proton shift function, we find that the tail of the resonance can produce about a 0.26 nb cross section at a center-of-mass energy of $E_p = 68$ keV. This is on the order of a few percent of the measured cross section. Although there are some large uncertainties in this estimate, it is clear that the known level parameters in ^{7}Be do not necessarily imply large resonant tails at the energies of this experiment.

The lack of interference effects in the current study of the $^6\mathrm{Li}(\vec{p},\gamma)^7\mathrm{Be}$ reaction indicates that the capture process at this energy, in this system, proceeds almost entirely by partial waves of a single parity. Based on the direct-capture model, we assume that this reaction proceeds by s-wave capture. This result suggests that the large p-wave contribution observed in the $^7\mathrm{Li}(\vec{p},\gamma)^8\mathrm{Be}$ experiment at low energies is specific to that particular system. From the known level structure of ^{7}Be, one does not expect a significant p-wave contribution to the capture cross section for the $^6\mathrm{Li}(\vec{p},\gamma)$ reaction at low energy. This, coupled with the fact that Barker [2] found a set of ^{8}Be level parameters that produces reasonable fits to the $^7\mathrm{Li}(\vec{p},\gamma_0)$ capture data, supports the conclusion that the source of the anomalous p-wave strength in that reaction is resonant tails in the ^{8}Be system.

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