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Search for *p* waves in low-energy proton capture reactions relevant to the solar neutrino problem

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A previous study of the ground-state transition of the ^{7}Li($\vec{p},\gamma$)^{8}Be reaction at energies of E_p(lab)=80–0 keV indicated the possibility of a large p-wave capture amplitude in this reaction. A similar p-wave component in the ^{7}Be(p,γ)^{8}B reaction could seriously affect the extrapolation used to obtain the astrophysical S factor. The present work examines this possibility by observing the closely related ^{7}Li($\vec{p},\gamma_{16.6}$)^{8}Be* (2^+, T=0+1) reaction with polarized protons at and below 80 keV. Experimental data for $\sigma(\theta)/A_0$ and $A_y(\theta)$ for capture to the third (16.6 MeV) excited state of ^{8}Be are presented, and the implications discussed.

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Recently a detailed study of the ^{7}Li($\vec{p},\gamma$)^{8}Be reaction has shown large analyzing powers and an anisotropic cross section [1]. This is quite surprising considering that direct capture calculations predict almost pure s-wave ($E1$) capture at these low energies [2]. Previous experimental work [2] has suggested that the cross section is isotropic within 10%, supporting this model and the extrapolation of the astrophysical S factor to zero energy based on pure s-wave ($E1$) capture. However, the work of Chasteler *et al.* [1] has shown that the cross section possesses 30% anisotropy and, using polarized protons, an analyzing power at 90° of nearly 0.35, implying a significant p-wave ($M1$) admixture, as discussed below. The extrapolation to zero energy using p waves rather than s waves can affect the S factor by as much as a factor of 2 [1]. It would be quite intriguing if the same affect is present in the ^{7}Be(p,γ)^{8}B reaction, since this reaction creates most of the high energy neutrinos detected in ^{37}Cl based neutrino detectors [3].

A short summary of the work in Ref. [1] and recent developments is in order. As reported in Ref. [1], a transition matrix element (TME) analysis including s-wave $E1$ and p-wave $M1$ amplitudes produced four solutions with $M1$ strengths between 59 and 93%. If the energy dependence for $E1$ and $M1$ strength follow the direct capture model, this would imply a reduction of the astrophysical S factor by as much as 40%.

There has been considerable interest in these results [4–7]. Barker [6] has attempted to fit the data (using an R-matrix formalism) by allowing the $M1$ strength to arise solely from the tails of the two 1^+ levels in ^{8}Be (at 441 keV and 1030 keV proton energy). Searching on these resonance amplitudes and their relative phase, Barker's best fit gave 9.2% p-wave strength. However, contrary to shell model predictions and fits at higher energies, this result required constructive interference between the tails of the two resonances involved.

In order to further study this, a TME analysis of the data in Ref. [1] was performed with no constraints. Allowing both s-wave $E1$ and p-wave $M1$ transitions, the $M1$ percentage was varied from 0 to 100%, and in each case the best solution (i.e., lowest chi squared) was determined. We present the results of this study in Fig. 1. The broad minimum near 50% $M1$ strength stands out as the best solution in this view, although there is a 10% statistical chance that the correct solution contains less than 10% $M1$, as Barker's solution suggests. Of course Barker's solution may be preferred on the basis that it arises from a well-understood physical phenomena (the 1^+ resonances), although the previously mentioned discrepancies remain. It is interesting to note that when we replace the analyzing power data of Chasteler *et al.* [1] with the ground-state data obtained in the present experi-

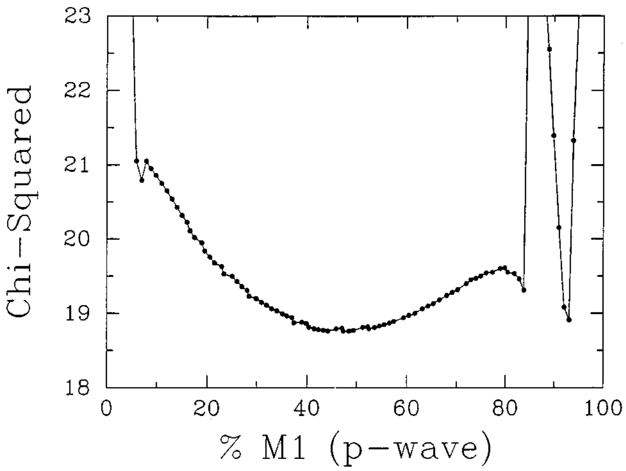

FIG. 1. The unnormalized χ^2 value plotted against $M1$ percentage obtained in a TME analysis of the data of Chasteler *et al.* [1]. There are 12 degrees of freedom present.

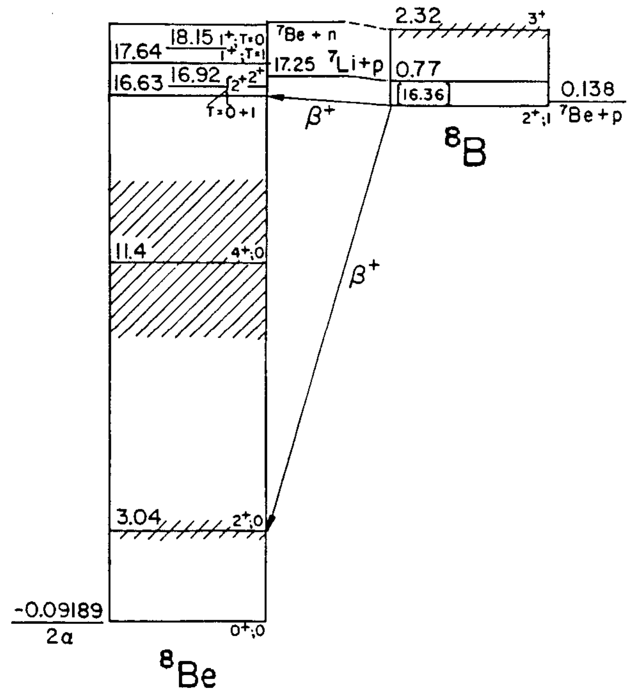

FIG. 2. A portion of the $A=8$ isobar diagram, showing the ground and low-lying states of ^{8}Be and ^{8}B. Notice the connection between the third excited state of ^{8}Be and the ground state of ^{8}B.

ment (see below), the structure of the plot does not change, but the chi-squared values do improve slightly.

We wish to examine the origin and importance of the p-wave strength in this reaction and others. To do this we are continuing our study of the ^{7}Li$(\vec{p},\gamma)^8$Be reaction at energies of E_p(lab)=80–0 keV using two large high purity germanium (HPGe) detectors. In addition to detecting γ rays corresponding to capture to the ground and first excited states we are most interested in examining γ rays leading to the $J^\pi=2^+$, $T=0+1$ states of ^{8}Be at 16.626 and 16.922 MeV. These two states are completely isospin mixed and collectively the $T=1$ portion is the analog of the ^{8}B ground state. This is clearly shown in Fig. 2, which depicts a portion of the $A=8$ isobar diagram. Note that the ^{7}Be$(p,\gamma)^8$B reaction is of extreme interest in that it is the key to at least a part of the solar neutrino problem. Unfortunately, target problems make that reaction quite difficult to measure and no experiments have been performed involving the direct detection of γ rays. The ^{7}Li$(p,\gamma_{16.6})^8$Be* reaction is closely related to the ^{7}Be$(p,\gamma)^8$B reaction since, as mentioned above, the 2^+, $T=1$ ground state of ^{8}B is the isospin analog of the $T=1$ part of the 2^+ states in ^{8}Be and must therefore possess the same space-spin wave function, so long as isospin is conserved. So, for example, if the ground state of ^{8}B possesses a significant halo, as suggested in Ref. [8], so would the 16.6 MeV state in ^{8}Be. This is significant here since the halo effect could cause the reaction to occur at a larger radius, thereby effecting the relative s- to p-wave ratio. In general, of course, any knowledge of the one will provide insight into the other.

Proton capture to the third excited state of ^{8}Be at $E_p=80$ keV yields γ rays of energy 698 keV (at 90° with respect to the beam direction). This is another reason for expecting this study to be closely related to the ^{7}Be$(p,\gamma)^8$B case (where $E_\gamma\approx200$ keV), especially in comparison to the previous ground-state capture experiment where $E_\gamma\approx17.3$ MeV. The 16.63 MeV state of ^{8}Be subsequently decays into two alpha particles virtually 100% of the time. In order to separate the capture γ ray from background we performed a coincidence experiment, detecting one alpha particle and the 698 keV γ ray simultaneously. The 80 keV polarized protons were directed at a lithium target, approximately 500 μg/cm^2 thick, which has been evaporated onto a very thin (0.00005 in.) Ni foil. A plastic scintillator was used in back of the target to detect the alpha particles and was wrapped with aluminized Mylar to keep out background light. The incident protons were stopped in the target. Gamma rays from the reaction were detected using two large (128% and 145% efficient) HPGe detectors and suffer only a small attenuation in their flight. The two alpha particles each possess a kinetic energy of about 8 MeV. They will be traveling in opposite directions in the center of mass, and so one will be directed toward the plastic scintillator. It will lose energy in the target, Ni foil and aluminized Mylar before being detected in the plastic scintillator. Alpha particles which are emitted perpendicular to the plane of the target will lose approximately 1.5 MeV. Those which emerge at ±70 degrees with respect to the target lose about 6.5 MeV. Based on the known angular distribution of these alpha particles [9] it is estimated that this angular range (20°–160°) corresponds to about 75% of the total angle integrated yield. The condition of the target was monitored by the use of a surface barrier detector to count alpha particles from the ^{7}Li$(p,\alpha)\alpha$ reaction. It should be noted that our data represent an integrated yield of proton energy from 80 to 0 keV, since the proton beam is stopped in the target. However, the cross section drops off drastically with decreasing energy (Coulomb barrier) and so the spectrum of coincident γ rays produced is dominated by the 108 keV width of the final state. A typical spectrum, showing a fit composed of an exponential background and a Breit-Wigner resonance line shape with previously determined resonance

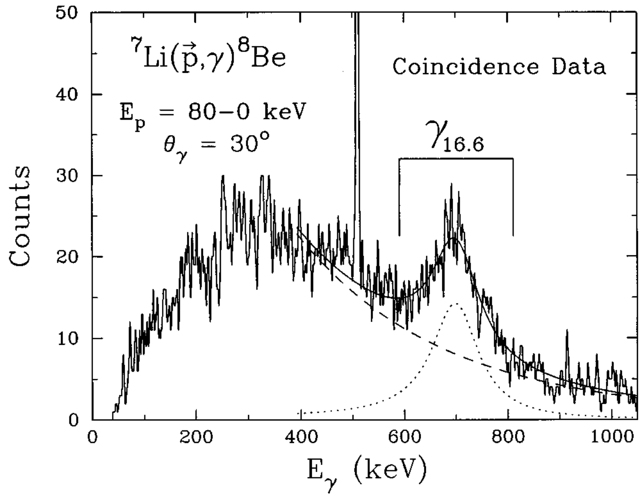

FIG. 3. A typical spectrum of γ rays obtained in coincidence with the alpha particle scintillator. The solid curve represents the fit to the pulse-height spectrum in terms of a background-plus-a-Breit-Wigner (BW) resonance. The background and BW components of this fit are also shown separately as a dashed and dotted curve, respectively.

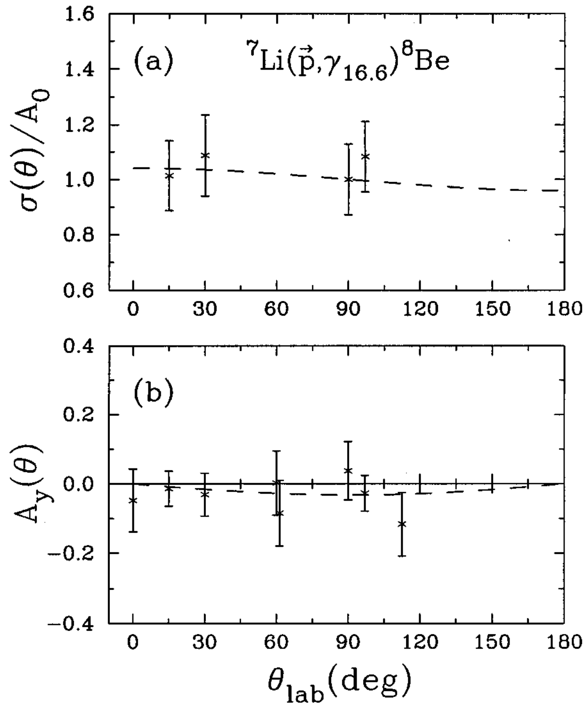

FIG. 4. Data obtained for (a) the relative cross section and (b) the analyzing power for the ^{7}Li($\vec{p}$,$\gamma_{16.6}$)^{8}Be* reaction at E_p(lab)=80–0 keV. The error bars represent the statistical uncertainties associated with the data points. The dashed curves represent the TME fit to the data, as described in the text.

parameters [10] is presented in Fig. 3.

The present work utilized the high intensity, polarized proton beam of the Atomic Beam Polarized Ion Source at TUNL [11]. The beam polarization was measured using a proton polarimeter based on the ^{12}C($\vec{p}$,p_0)^{12}C reaction [12]. Typical values for the polarization were ≈60–70 %, with errors of ≈2%. This process required changing the beam from a positive to a negative ion beam and accelerating it through the tandem to an energy of 6.18 MeV. It has been shown that the polarization of the positive and negative beams are equal, within experimental error [13]. In order to minimize target and instrumental asymmetries, the spin orientation (“up” or “down”) was electronically flipped at a rate of 10 Hz. Analyzing power measurements were performed at 7 angles. The large analyzing power reported in Ref. [1] for the ground-state transition, attributed to p-wave strength, is well reproduced in the present work, as is the unpublished data for capture to the first excited state. The coincidence technique described above allows us to separate the 698 keV capture γ rays from background. Figure 4(a) shows the relative cross section for capture to the third excited state, normalized to the ground-state yields, while Fig. 4(b) depicts the angular distribution of the analyzing power data. These data display an isotropic cross section and analyzing powers consistent with zero, which is indicative of pure s-wave, $E1$ capture. Nevertheless, a formal TME analysis of the data has been performed, including one effective s-wave $E1$ and one effective p-wave $M1$ transition amplitude. The results are shown as a dashed line in Fig. 4. Because of the quadratic nature of the equations involved, two solutions are found. One consists of 0.1% $M1$ admixture, the other 0.1% $E1$.

Chasteler *et al.*, have shown that the existing data for capture to the ground state of ^{8}Be can be explained only by including a significant p-wave amplitude. The present experiment (capture to the third excited state) was designed to see whether a similar p-wave capture strength is present in the transition to the ^{8}B-like third excited state, since this could have a serious impact on the extrapolated S factor in the ^{7}Be(p,γ)^{8}B reaction. The data of Fig. 4 do not show any nonzero analyzing powers. This result could arise from either a 99.9% $E1$ or a 99.9% $M1$ capture amplitude. Since the “traditional” direct capture model predicts a dominant $E1$ (s-wave) amplitude, the results suggest that p waves are unimportant in the present case and are therefore unlikely to be important in the ^{7}Be(p,γ)^{8}B reaction.

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