BRIEF REPORTS

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Spin parity of the 7.478 MeV state of ^{10}B and the S factor of the ^{9}Be($\vec{p},\gamma_0$)^{10}B reaction

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Polarized protons were used to measure the analyzing power of the ^{9}Be($\vec{p},\gamma$)^{10}B reaction for $E_p = 280-0$ keV. The analyzing power for the ground state transition compared to calculations leads to a spin-parity assignment of 2^+ for the 7.478 MeV state of ^{10}B. This 2^+ assignment is consistent with other observables for this reaction and is predicted by cluster and shell model calculations. It is found that the 2^+ assignment leads to a value for the astrophysical S factor for capture to the ground state of ^{10}B of $S(0) = 0.20$ keV b which is about 40% smaller than that obtained with a 2^- assignment. [S0556-2813(99)01706-9]

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In the most recent compilation for $A=10$ [1] the proton capture ^{9}Be(p,γ)^{10}B reaction data set evaluates the spin-parity of the state at 7.478 MeV to be 2^-, but a footnote gives $J^\pi = 2^+$ based on (e,e') work. The adopted energy levels of ^{10}B gives the corresponding state a 2^+ assignment. Since, as will be demonstrated in this paper, the extrapolation of the S factor in the capture channel is very sensitive to this assignment, it is important to resolve this difference. In this paper we seek to do so and to thereby determine a value of the S factor at $E=0$ for the ^{9}Be($\vec{p},\gamma_0$)^{10}B reaction.

The spin-parity for the $E_x = 7.478$ MeV resonance was recently evaluated by Zahnow *et al.* [2] by measuring and fitting cross-section data for the ^{9}Be(p,γ)^{10}B reaction. This experiment measured the cross section for capture to the ground and first three excited states of ^{10}B. Figure 1 shows the astrophysical $S(E)$ factor which is defined in terms of the cross section

$$S(E_{\text{c.m.}}) = E_{\text{c.m.}}\sigma(E_{\text{c.m.}})e^{2\pi\eta}, \tag{1}$$

where η is the Sommerfield parameter

$$\eta = \frac{1}{2\pi}31.29 Z_1 Z_2 \left(\frac{\mu}{E_{\text{c.m.}}}\right)^{1/2}. \tag{2}$$

The center of mass energy $E_{\text{c.m.}}$ is in keV, and the reduced mass μ is in u. In Zahnow's paper [2] the fit for $J^\pi = 2^-$ resulted in a smaller χ^2 value ($\chi^2 = 3.7$) than the assignment of $J^\pi = 2^+$ ($\chi^2 = 5.4$). These fits were obtained using an expression for the cross section which included direct, resonance, and interference terms.

In order to demonstrate the sensitivity of fitting the cross section to the details of such a model, we have used a direct capture plus resonance model [3] to calculate $S(E)$ under various assumptions, and compared the results to the data from Ref. [2]. In these calculations, single particle resonance amplitudes for dipole transitions are added to the direct capture amplitudes. The first calculation included three resonances: $E_x = 6.873(1^-)$, $7.478(2^+)$, and 7.560 MeV(0^+) which correspond to $E_p = 310$, 989, and 1083 keV, respectively. The energies and widths for these resonances were taken as those found in Ref. [4]. The strengths of the resonances were adjusted to fit the low energy part of the $S(E)$ data with the constraint that the contributions from each energy state at the resonance are related as given by the relative

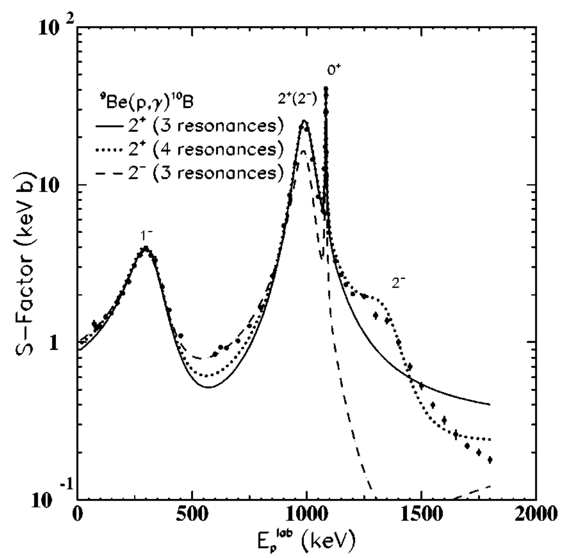

FIG. 1. Data from Ref. [2] are compared to direct-capture-plus-resonance calculations for two different parity assignments for the resonance at $E_p = 939$ keV. The solid (dashed) line is the result of calculations with $J^\pi = 2^+(2^-)$. The dotted line illustrates the effect at low energies of adding another higher resonance ($E_p = 1290$ keV, $J^\pi = 2^-$) to the previous 2^+ calculation.

intensities found in Table 10.11 of Ref. [1]. This fit was repeated for the case where the $E_x = 7.478$ MeV resonance has spin parity of 2^-. When the spin parity is 2^- the calculations fit the data better in the region around 500 keV. (This value of J^π allows the resonance to interfere with the direct capture amplitude in the angle-integrated cross section.) Unfortunately this region between resonances is very sensitive to the tails of higher resonances that have not been included and other assumptions in the model, so an exact fit with a limited model can be misleading. To illustrate this point, the dotted curve in Fig. 1 shows an example where a fourth resonance with $E_x = 7.75$ MeV(2^-,$E_p = 1290$ keV) is included in the first calculation with $J^\pi = 2^+$ for the 7.478 MeV state. As seen in Fig. 1, this improves the original fit in the region of the minimum without appreciably affecting the quality of the fit at lower energies. As other assumptions or higher resonances could also affect $S(E)$ in this region, it is helpful to consider another observable in evaluating the spin parity of this state.

In a recent paper by Wulf *et al.* [4], a study of the reaction $^9\mathrm{Be}(\vec{p},\gamma)^{10}\mathrm{B}$ suggested that the uncertainty in the spin parity of the $E_x = 7.478$ MeV state of $^{10}\mathrm{B}$ could be resolved by looking at the analyzing power. In the present study, we have followed this suggestion and made measurements of the analyzing power for the $^9\mathrm{Be}(\vec{p},\gamma)^{10}\mathrm{B}$ reaction using a 280 keV polarized proton beam. Increasing the beam energy from the previous value of 100 keV to the present value corresponds to an increase in yield by a factor of 300 for the same beam current.

The present measurement used a 280 keV polarized proton beam. The experiment was run in the Triangle Universities Nuclear Laboratory (TUNL) High-Voltage Chamber [5] which allowed the 80 keV beam from the Atomic Beam Polarized Ion Source (ABPIS) to be accelerated to an energy of 280 keV. The polarized proton beam from the ABPIS stopped in a 1 cm×1 cm×0.5 mm piece of 99.5% pure ^{9}Be. The polarization, measured using the spin-filter polarimeter in the source, was $P_\uparrow = 0.68 \pm 0.05$ and $P_\downarrow = 0.63 \pm 0.05$ and the direction of polarization was reversed at a rate of 10 Hz. Gamma rays were measured in two 60% HPGe detectors at a number of angles, in order to map out the angular dependence of the analyzing power. Because of spatial constraints the two detectors were oriented vertically, and γ rays impinged on the sides.

Polarization degrees of freedom allow a more sensitive study of the spin-parity of resonance states. The analyzing power $A_y(\theta)$ is sensitive to the interference of radiations of opposite parity, especially at 90°. The analyzing power at a given angle is defined by the expression

$$A_y(\theta) = \frac{Y_\uparrow(\theta) - Y_\downarrow(\theta)}{P_\downarrow Y_\uparrow(\theta) + P_\uparrow Y_\downarrow(\theta)}, \qquad (3)$$

where $Y_\uparrow(\theta)$ and $Y_\downarrow(\theta)$ are the yields of the proton spin up and down polarized states, respectively, and $P_\uparrow$ and $P_\downarrow$ are the beam polarizations for those states. With pure $E1$ or $M1$ radiation, $A_y(90°) = 0$. A finite analyzing power at $\theta = 90°$ requires the presence of radiations of opposite parity.

Figure 2 shows the analyzing power for capture to the ground state at six angles. A_y was extracted by comparing the yields for spin up and spin down within the same gate.

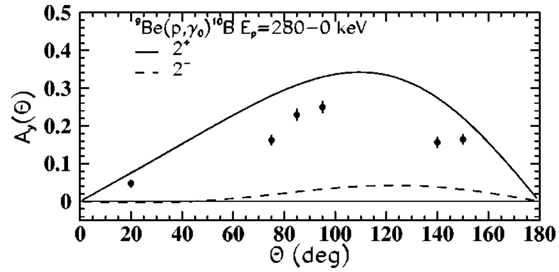

FIG. 2. Analyzing power from the ground state of $^9\mathrm{Be}(\vec{p},\gamma)^{10}\mathrm{B}$. The solid (dashed) line represents the direct-capture-plus-resonance calculation where the 7.478 MeV state in ^{10}B has a spin parity of $2^+(2^-)$.

This gate was set to include the photopeak and first escape peak of the ground state, but to exclude γ rays that could come from the first excited state. Background, measured in a gate of the same size at higher energies where there are no gamma rays from this reaction, was subtracted from each spin state. The error bars include statistical errors and the uncertainty in the beam polarization.

The analyzing power data were compared to the previously mentioned direct capture plus resonance model calculation [3]. To compare to the experimental data, obtained when the beam stopped in the target, calculations were done for a range of energies from 280–0 keV. These results were combined in order to simulate the experimental conditions, weighting them with the appropriate stopping power [8].

In the current reaction the direct capture is mostly $E1$. The small $M1$ direct capture contribution is not sufficient to produce an analyzing power at 90° comparable to the observed value [4]. Furthermore, if the spin parity of the 7.478 MeV state of ^{10}B is 2^-, the tail of this resonance will con-

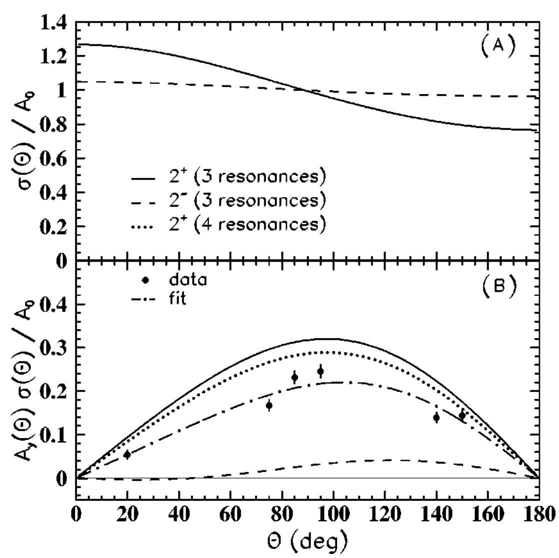

FIG. 3. (a) The calculated angular distribution of the differential cross section. The solid line is the prediction for $J^\pi = 2^+$ for the $E_x = 7.478$ MeV state and the dashed line is $J^\pi = 2^-$. (b) The analyzing power times the cross section. The solid points are the data times the average of the 2^+ and 2^- calculations with the fit shown by the dot-dashed line. The solid, dashed, and dotted lines are calculations with $J^\pi = 2^+$ with 3 resonances, 2^- with 3 resonances, and 2^+ with 4 resonances, respectively.

TABLE I. The b_k coefficients for Legendre fits to the data and theory.

	b_1	b_2
Data	0.215 ± 0.008	-0.020 ± 0.005
Theory (2^+) 3 resonance	0.319	-0.015
Theory (2^-) 3 resonance	0.0285	-0.0134
Theory (2^+) 4 resonance	0.288	-0.0137

tribute $E1$ strength in the case of capture to the ground state, and therefore does not provide any 90° analyzing power. The only way to produce a large analyzing power at 90° in the ground state channel is for this resonance to have a spin-parity of 2^+ and thus contribute $M1$ strength. This M1 strength interferes with the direct capture E1 strength in order to produce the observed value of $A_y(90°)$. The resonance parameters used to fit the cross section data in Fig. 1 were used to calculate $A_y(\theta)$ without further adjustment. $A_y(\theta)$ is quite sensitive to the tail of the $E_x = 7.478$ resonance in ^{10}B which contributes to the capture process leading to the ground state (3^+) with $E_\gamma = 6.838$ MeV. The solid line in Fig. 2 shows the results of the calculations for the assignment of 2^+, while an assignment of $J^\pi = 2^-$ is shown as a dashed line. The 2^- assignment leads to a value of A_y which is much too small compared to the observed analyzing power. The analyzing powers were also extracted for capture to the first three excited states of ^{10}B($E_{\gamma_1} = 6.120$ MeV, $J^\pi = 1^+$; $E_{\gamma_2} = 5.098$ MeV, $J^\pi = 0^+$; $E_{\gamma_3} = 4.684$ MeV, $J^\pi = 1^+$). Because of the small decay amplitude of the 7.478 MeV resonance to these states the analyzing power is small, and the difference between calculations for $J^\pi = 2^-$ and 2^+ cannot be distinguished within the accuracy of this experiment.

To quantify these results the data and calculations can be expanded in terms of Legendre and associated Legendre polynomials [6]:

$$\sigma(\theta) = A_0 \sum_{k=0} Q_k a_k P_k(\cos\theta), \tag{4}$$

where $Q_0 = a_0 = P_0 = 1.0$, and

$$A_y(\theta)\sigma(\theta) = A_0 \sum_{k=1} Q_k b_k P_k^1(\cos\theta). \tag{5}$$

The a_k and b_k coefficients are the normalized Legendre polynomial coefficients, Q_k are the finite geometry attenuation factors, and $P_k(P_k^1)$ are the Legendre (first associated Legendre) polynomials. Due to the unusual geometrical arrangement of the detectors, the Q_k's were calculated using a Monte Carlo simulation to assess the detector efficiency over the finite extent of the detector [7]. In this experiment it was impossible to normalize the yield between different runs, so $\sigma(\theta)/A_0$ could not be extracted from the data. In order to extract the b_k coefficients, theoretical values for $\sigma(\theta)/A_0$ were used to calculate $A_y(\theta)\sigma(\theta)/A_0$. The first panel of Fig. 3 shows the theory predictions for the angular distribution, $\sigma(\theta)/A_0$, for both the 2^+ and 2^- cases. The average of these values for the two spin-parity assignments was multiplied by the $A_y(\theta)$ from the data and used to obtain $A_y(\theta)\sigma(\theta)/A_0$ as shown by the solid points in Fig. 3. The b_k coefficients were

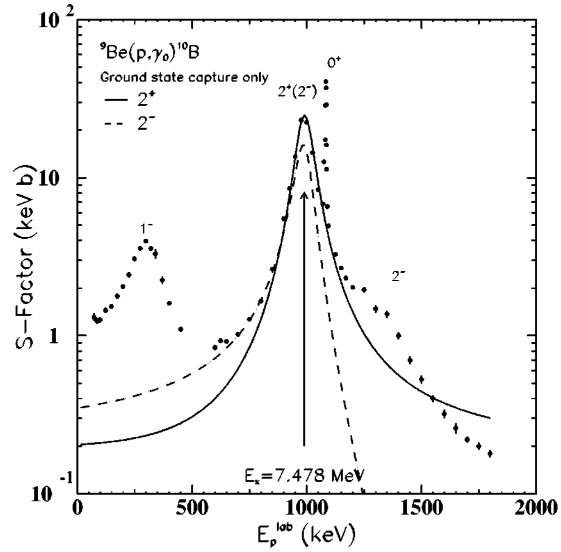

FIG. 4. Data are the same as in Fig. 1. The curves denoted as in Fig. 1 are the result of calculations for capture solely to the ground state of ^{10}B. The value of $S(0)$ is clearly sensitive to the J^π value of the 7.478 MeV state in ^{10}B.

extracted from these data points using a least-squares fit to Eq. (5) [9] (dot-dashed line in Fig. 3). The averaging for the $\sigma(\theta)/A_0$ theoretical values introduces an error of ± 0.002 to the b_1 values. The solid (dashed) lines show the theoretical predictions for the $2^+(2^-)$ case. The b_k coefficients for the data and the theoretical curves are given in Table I. The theory for the 2^+ case provides a better fit to the data. The dotted line shows the case when a fourth resonance ($E_x = 7.75$ MeV) was included and the $E_x = 7.478$ MeV state has a spin parity of 2^+. Higher resonances can affect the analyzing power, but as the difference in predictions is large the results from the analyzing power show that $J^\pi = 2^+$ for the $E_x = 7.478$ MeV state in ^{10}B.

Besides the evidence from experimental measurements, theoretical calculations have predicted a 2^+ state in ^{10}B at an appropriate energy. In Ref. [10] a cluster calculation was made to predict the energy levels in ^{10}B. The results were compared to adopted energy levels taken from the 1979 $A = 10$ data compilation [11] where the $E_x = 7.478$ MeV state was given a 2^- assignment. A predicted 2^+ state at about this energy was said to be unobserved so far. A more recent model calculation [12] using a shell-model also shows a 2^+ state at an energy which could correspond to this state.

In summary, the large 90° analyzing power observed for capture to the ground state of ^{10}B clearly indicates that the 7.478 MeV state of ^{10}B must have $J^\pi = 2^+$. These results resolve the discrepancy present in the literature regarding the parity of this state in the proton capture channel. The assignment of the parity of this state is important in extrapolating the $S(0)$ value for this reaction. When the direct capture-plus resonances model is used to calculate the energy dependence of the S factor for the case of capture to the ground state of ^{10}B, the results are as shown in Fig. 4. The value of $S(0)$ for the ^{9}Be($\vec{p},\gamma$)^{10}B reaction obtained using the correct $J^\pi = 2^+$ assignment for the 7.478 MeV state is found to be $S(0) = 0.20$ keV b, which is about 40% lower than the value obtained using a 2^- assignment.

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