Astrophysical S factors for the ^{9}Be$(\vec{p},\gamma)^{10}$B reaction

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Analyzing powers for the ^{9}Be$(\vec{p},\gamma)^{10}$B reaction were measured by stopping a 100 keV polarized proton beam in a ^{9}Be target. The measured vector analyzing power is $A_y(90°)=0.18\pm0.03$ for capture to the ground state, with smaller values at 90° for the first three excited states. Astrophysical S factors were calculated for each of the final states using a direct capture plus resonance model which fit both the present analyzing power data and the previously reported cross section data. The calculated S factors at $E_p=0$ keV for capture to the ground state and first three excited states were 0.25, 0.34, 0.27, and 0.10 keV b, respectively, which are considerably smaller than previously reported. The observed analyzing powers are explained, within experimental uncertainty, as arising from the interference of the $E1$ direct capture amplitude with the tails of nearby p-wave and s-wave resonances. [S0556-2813(98)00407-5]

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I. INTRODUCTION

The analyzing power $A_y(\theta)$, especially at 90°, is a sensitive measure of interference between radiations of opposite parity. The quantity $A_y(\theta)$ can be obtained from polarized proton beam measurements using the expression

$$A_y=\frac{Y_\uparrow-Y_\downarrow}{P_\downarrow Y_\uparrow+P_\uparrow Y_\downarrow}, \tag{1}$$

where $Y_\uparrow$ is the yield of the reaction with a proton of polarization spin up and $Y_\downarrow$ is the yield for spin down proton beam. The quantities $P_\downarrow$ and $P_\uparrow$ are the absolute values of the polarizations of the spin down and up proton beam, respectively. Nonzero values of $A_y(90°)$ require that radiations of opposite parity are simultaneously present in the capture reaction [1]. For example, pure $E1$ or $M1$ radiation would give $A_y(90°)=0$, while an admixture of the two could result in finite values of $A_y(90°)$.

A previous study of the ^{7}Li$(\vec{p},\gamma)^{8}$Be reaction at $E_p=80$ keV found a substantial vector analyzing power at 90° for capture to the ground state. This was partially explained by nearby p-wave ($M1$ radiation) resonances interfering with the direct capture s-wave ($E1$) component. The $M1$ strength due to the resonance tail had to be enhanced by a factor of 4 in order to fit the observed A_y data [2]. This difficulty in accounting for the measured A_y led to the present investigation of the ^{9}Be$(\vec{p},\gamma)^{10}$B reaction at $E_p=100$ keV to see if it exhibited similar behavior.

The result of the present measurements indicates that $A_y(90°)=0.18\pm0.03$ for capture to the ground state of ^{10}B, with smaller values of $A_y(90°)$ for capture to other excited states. This nonzero value of $A_y(90°)$ indicates that the standard assumption of pure s-wave capture used in extrapolating (p,γ) cross sections to low energies cannot be precisely true. These extrapolations are done using the astrophysical S factor defined in terms of the cross section [3]

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

where η is the Sommerfeld parameter which is related to the center-of-mass energy

$$\eta=\frac{1}{2\pi}31.29Z_1Z_2\left(\frac{\mu}{E_{\text{c.m.}}}\right)^{1/2}, \tag{3}$$

where $E_{\text{c.m.}}$ is in keV and μ is the reduced mass in amu. The S factor removes the energy dependence of the cross section due to the Coulomb barrier. The nonzero 90° analyzing powers observed in our measurements indicate that in addition to s-wave ($E1$) capture, some p-wave ($M1$) capture must be present. Direct capture calculations including known s- and p-wave resonances have been performed in an attempt to determine the origin of this p-wave capture strength and its effect on the extrapolation of the S factor.

There are two previous measurements of the ^{9}Be$(p,\gamma)^{10}$B reaction at low energies by Cecil *et al.* [4] and by Zahnow *et al.* [5]. The former measured branching ratios between the α particle and γ-ray channels and used this information to determine astrophysical S factors for the ground state and first three excited states. They measured the γ rays from the ground state and first three excited states separately by using a high-purity germanium (HPGe) detector. Determinations of the S-factor values at $E_p=0$ were obtained by extrapolating the experimentally determined γ ray to charged particle branching ratios from 68 down to 0 keV. The second group [5] measured the cross section as a function of energy integrated over the four final states by using a NaI detector system with nearly 4π coverage. This yielded the astrophysical S factor as a function of energy for capture to the four final states combined down to an energy

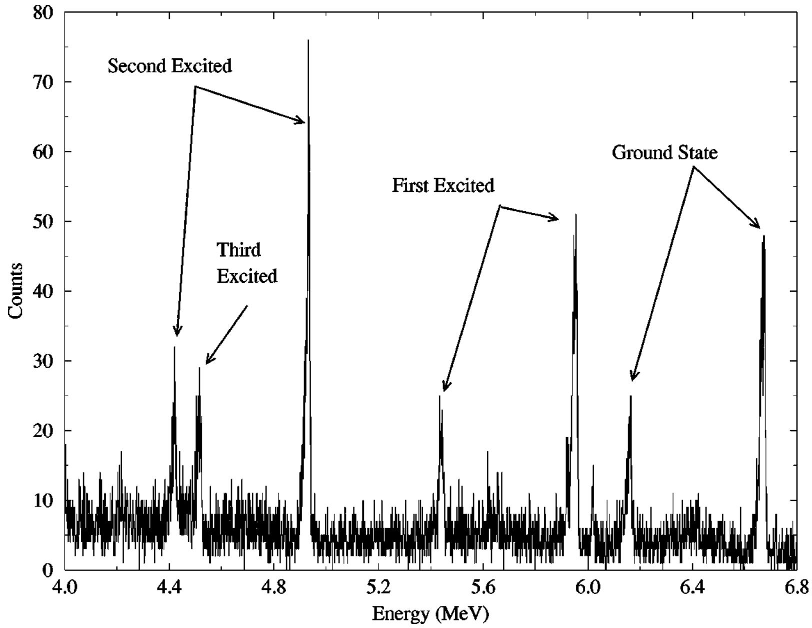

FIG. 1. Energy spectrum of γ rays obtained at $E_p = 100$ keV using a 128% HPGe detector and an anticoincidence shield. Full energy and first escape peaks are indicated where present.

of $E_p = 73$ keV. The authors performed a direct capture plus resonance calculation using an approximate expression to fit their data and determine the energy, width, and strength of three of the four resonances below $E_p = 1800$ keV. They were able to extrapolate the S factor to $E_p = 0$ keV for capture to the four final states combined. The analyzing power data in the current experiment was combined with the data and analysis from Ref. [5] in order to extract the individual S factors for capture to each of the four final states.

II. EXPERIMENT

In the present experiment, γ rays from the ^{9}Be$(\vec{p},\gamma)^{10}$B reaction were produced using an 80 keV polarized proton beam from the TUNL Atomic Beam Polarized Ion Source (ABPIS). The source switched the polarization of the protons at a rate of 10 Hz in order to minimize systematic errors. Capture γ rays from the reaction were detected in two (128 and 142%) HPGe detectors whose front faces were 12.7 cm from the target at $\theta_{\rm lab} = 62°$, 90°, and 120°. The smaller detector's background was reduced by surrounding it with a NaI annulus that was used as an anticoincidence shield. A spectrum from this detector is shown in Fig. 1. Events from the HPGe detector were stored in three different spectra: one for each spin state of the proton beam and one for the indeterminate spin state which is present during the time when the ABPIS is switching the spin of the beam.

The ABPIS produced a 30 μA polarized beam with $E_p = 80$ keV which, combined with the ^{9}Be$(p,\gamma)^{10}$B reaction cross section [4], the solid angle, and efficiency of the detectors, gave a predicted count rate of ~ 5 counts/h. This was deemed unacceptably low especially because this count rate is divided between the two spin states. The count rate expected at 100 keV, however, was estimated to be ~ 15 counts/h. Therefore, the ABPIS was run at 80 keV and the ^{9}Be target was biased to -20 kV to accelerate the positively charged beam to 100 keV. Direct measurements of the beam spot size and the intensity distribution on the target showed that neither was affected by this procedure. The target was biased by attaching it to a high voltage feed-through on top of the target chamber held at -20 kV by a high voltage power supply. The target was a 1 cm$\times$1 cm$\times$0.5 mm thick sheet of 99.5% pure ^{9}Be, which stopped the beam. Although the data represent the integrated yield from a proton beam with energy ranging from 100 to 0 keV, we can effectively view the data as arising from a beam with $E_p = 92 \pm 8$ keV. This is because 80% of the cross section yield arises from beam energies between 84 and 100 keV.

A direct measurement of the beam current was complicated by the target bias of -20 kV. Instead, a silicon surface barrier detector was placed in the target chamber to measure the count rates of the ^{9}Be$(p,d)^8$Be and ^{9}Be$(p,\alpha)^6$Li reactions. The detector was placed at the end of a tube coming out of the target chamber lid at an angle of 130° in order to minimize the flux of 20 keV secondary electrons reaching the detector. A 1 μm thick Ni foil was placed at the entrance of the tube in order to stop the backscattered protons. The counting rates of these two reactions provided a relative measure of the luminosity. The charged particle counting rate also provided information on the intensity of the beam and the quality of the target (see Fig. 2).

III. ANALYSIS

A. Resonance effects

Since the spin and parity of the ground state of ^{9}Be is $3/2^-$ and that of the ^{10}B ground state is 3^+, pure s- or d-wave capture can give rise to $E1$, $M2$, $E3$, $M4$, and $E5$ radiation, while p-wave capture can give rise to $M1$, $E2$, $M3$, $E4$, $M5$, and $E6$ radiation. If we assume that the dipole terms contribute most of the transition strength in the ^{9}Be$(p,\gamma)^{10}$B reaction, then s- and d-wave capture will result in $E1$ radiation, while p-wave capture will generate $M1$ strength. This also follows for capture to the first three excited states of ^{10}B at 0.72, 1.74, and 2.15 MeV, which have $J^\pi = 1^+$, 0^+, and 1^+, respectively [6].

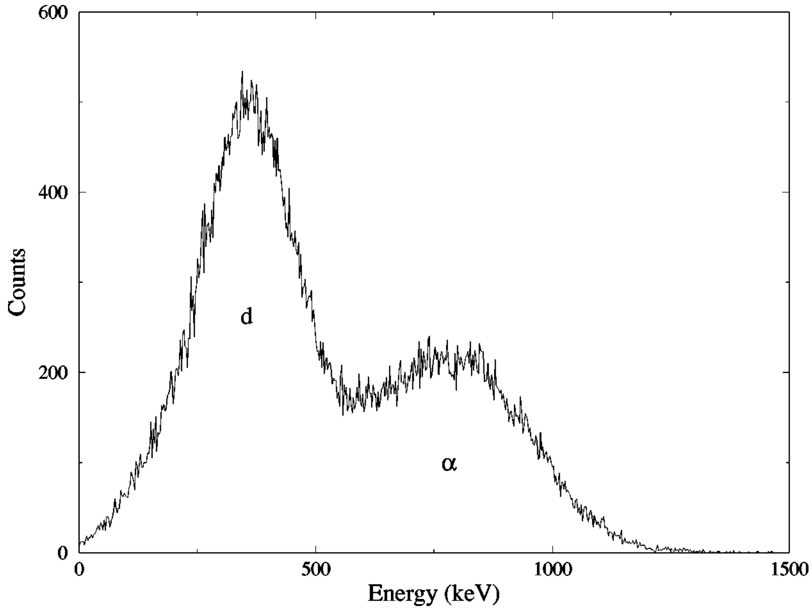

FIG. 2. A charged particle spectrum at $E_p = 100$ keV with $\theta = 0°$ and $\phi = 130°$. The energy of the deuterons and α's for this reaction are 0.65 and 2.2 MeV, respectively, but their measured energies are much lower after passing through the Ni foil.

There are four known resonances in the capture cross section between $E_p = 73$ and 1800 keV. They are located at $E_p = 319$, 992, 1083, and 1290 keV with $J^\pi = 1^-$, 2^+, 0^+, and 2^-, respectively [6] (see Table I). The analyzing power obtained at 90° for capture to the ground state was the largest of the four final states. This analyzing power indicates that p-wave capture is present along with the dominant s-wave $E1$ strength. The 2^+ resonance at 989 keV in ^{10}B [6] can be formed via p-wave capture and can decay to the ground state by $M1$ radiation. At 1350 keV there is a 2^- resonance which can decay to the ground state by $E1$ radiation. In principle, the low-energy tail of the 2^+ resonance could interfere with the direct s- and d-wave ($E1$) capture and the tail of the 2^- ($E1$) resonance in order to produce the observed A_y values for the ground state. In a similar manner, the 2^+ and 0^+ resonances can be formed by p waves and can decay by $M1$ radiation to the first and third excited state while the 1^- and 2^- resonances can decay by $E1$ radiation. Finally, the second excited state has only the 1^- resonance that can decay to it by $E1$ radiation.

B. Direct capture plus resonance calculations

To test whether these resonance tails could quantitatively explain the observed analyzing power, a series of direct $E1$ and $M1$ capture plus $E1$ and $M1$ resonance calculations were performed using the computer program HIKARI [7]. This code uses the jj-coupling scheme and adds single particle resonance amplitudes to the direct capture amplitudes. This is a complete calculation that includes all of the allowed interference terms between different resonances. These calculations were done with the radius and diffuseness of the Woods-Saxon potential used to generate the bound state wave functions set to 1.25 and 0.65 fm, respectively. The well depth was varied to reproduce the experimental binding energies of the four final states. The same real Woods-Saxon well was used to calculate the scattering state. The resulting well depths, along with the other parameters of the calculation, are given in Table II.

Zahnow *et al.* [5] calculated the direct capture S factor summed over the four final states (S^{dc}_{tot}) using their direct capture plus resonance model to be $S^{dc}_{tot}(E_p = 92$ keV$) = 0.374$ keV b. The relative spectroscopic factors for the four final states of ^{10}B have been measured using the ^{9}Be$(d,n)^{10}$B reaction [6]. The calculated total direct capture S factor (S^{dc}_{tot}) and the experimentally determined relative spectroscopic factors were used to calculate the direct capture S factor at $E_p = 92$ keV for capture to each of the four final states. The spectroscopic factors used for this calculation were set equal to the experimentally determined relative spectroscopic factors, but were renormalized by a factor of 0.2 while keeping their ratios fixed in order to reproduce the value of $S^{dc}_{tot}(E_p = 92$ keV) previously determined by Zahnow *et al.* [5] (see Table II).

These spectroscopic factors were then used to calculate the analyzing power allowing only s- and d-wave ($E1$) direct capture. That produced the dashed lines seen in Fig. 3

TABLE I. The energy and width of the ^{9}Be$(p,\gamma)^{10}$B resonances from two previously published sources and those used in the current calculations.

Resonance	Compilation [6]		Zahnow *et al.* [5]		Present work	
(J^π)	Energy (keV)	Width (keV)	Energy (keV)	Width (keV)	Energy (keV)	Width (keV)
1^-	319±5	133±6	380±30	330±30	310	161
2^+	992±2	80±4	989±2	90±3	989	90
0^+	1083±4	2.65±0.18	not fitted	not fitted	1083	3
2^-	1290	233±60	1405±20	430±30	1350	211

TABLE II. The parameters used to calculate the analyzing power and S factors for $^9Be(\vec{p},\gamma)^{10}B$ shown in Figs. 3, 4, and 5. The energy and width of the resonance are given in the lab frame. The $\Gamma_p\Gamma_\gamma$ terms were calculated using our calculated energy and width. These numbers were combined with previous Γ_p measurements [6] to yield Γ_γ except for the 2^+ resonance which did not have Γ_p measurements.

Final state (J^π)	Spec. factor	Binding energy (MeV)	Well depth (MeV)	Single particle state	Resonance J^π	Energy (keV)	Width (keV)	$\Gamma_p\Gamma_\gamma$ (keV^2)	Γ_γ (eV)
Ground (3^+)	0.1857	6.5857	54.70	$p_{3/2}$	2^+	989	88	2.400	
					2^-	1350	211	0.610	4.448
First (1^+)	0.3658	5.8673	53.23	$p_{3/2}$	1^-	310	161	0.015	0.311
					2^+	989	88	0.014	
					0^+	1083	3	0.021	7.000
					2^-	1350	211	0.108	0.787
Second (0^+)	0.2526	4.85	51.09	$p_{3/2}$	1^-	310	161	0.052	1.077
Third (1^+)	0.07614	4.44	50.21	$p_{1/2}$	1^-	310	161	0.012	0.248
					2^+	989	88	0.045	
					0^+	1083	3	0.002	0.666
					2^-	1350	211	0.071	0.518

which fit the measured analyzing power for the second excited state, but not the other final states. Next, p-wave ($M1$) direct capture was allowed and that produced the dot-dashed curve in Fig. 3. This led to another good fit for the second excited state and a close fit for the first and third excited state, but gave a result for the ground state that was too small.

The direct capture calculations were not able to completely fit the observed analyzing powers, so calculations were performed which included the four resonances described above. The initial width and energy of each resonance [5,6] were fine-tuned to fit the data of Ref. [5] using the present direct capture plus resonance formalism (see Table I). The total S factor reported in Ref. [5] at energies corresponding to the peaks of the resonances was split between the different final states using previously published relative strengths [6] (see Table III). The absolute strength of the resonance's decay to each final state was varied until the calculated S factor for each final state equaled these values (see Table II). The S factors as a function of energy were calculated for each of the four final states (see Fig. 4), and these were then summed and compared to the data taken by Zahnow *et al.* [5] (see Fig. 5). The fit is quite good at low energy, despite a small discrepancy between the first and second resonances, at about 600 keV. There are also some deviations above 1500 keV. This appears to be due to the resonances destructively interfering in the first, second, and third excited states as seen by the dips below the direct capture calculations (see Fig. 4). The energy and widths of the 1^- and 2^- resonances used in the calculations do not agree

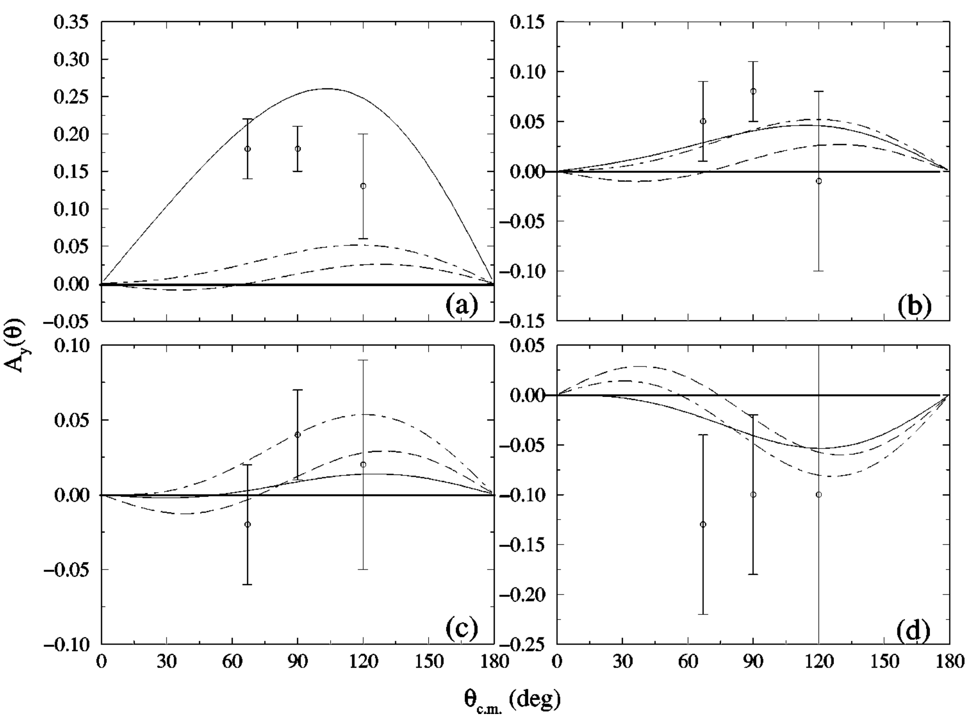

FIG. 3. The analyzing power $A_y(\theta)$ data for capture to (a) the ground state (3^+), (b) the first excited state (1^+), (c) the second excited state (0^+), and (d) the third excited state (1^+) are compared to the calculations assuming direct $E1$ (dashed line), direct $E1+M1$ (dot-dashed line), and direct $E1+M1$ plus resonances (solid line).

TABLE III. The relative intensities of the decay of each resonance to the ground and first three excited states taken from [6].

Resonance		Relative intensity		
(J^{π})	Ground	First	Second	Third
1^-		0.23	0.62	0.15
2^+	0.97	0.01		0.02
0^+		0.89		0.11
2^-	0.85	0.12		0.04

with the previous determinations. Since these two resonances are quite wide, the neglect of the energy dependence of the resonance parameters in our model could account for some of this discrepancy. The discrepancy is also partly due to the different calculations used here versus that of Zahnow *et al.* [5]. Whereas the present calculation is a straightforward sum of single particle resonance amplitudes using all of the interference terms, the resonance parameters from Zahnow *et al.* [5] were calculated using an abbreviated formula that left out the narrow 0^+ resonance. Nevertheless, our extrapolated S factor at $E_p=0$ keV agrees with Zahnow *et al.* [5] (see Table IV).

To check the consistency of the above procedure used to obtain the four individual S factors, the ratios of the S factor for each final state divided by the S factor summed over all four final states at $E_p=92$ keV was calculated. These ratios were then compared to the relative strengths obtained directly from the relative intensities of the spectral lines in the current experiment (see Fig. 1), and to those previously published [4]. The ratios at 92 keV agree within experimental uncertainty (see Table V) which lends further support to the assumptions made in obtaining the four S factors.

After these checks, calculations were performed to investigate the effects of the resonant tails on the analyzing power. For the ground state, there was a factor of 5 increase in the value of $A_y(90°)$ over the pure s- and d-wave direct capture calculation (see solid curve in Fig. 3). This result is further evidence that the resonance at $E_p=990$ keV has a J^{π} of 2^+ as is suggested in [6] while Zahnow *et al.* [5] argue that the resonance is a 2^- state. If the resonance were a 2^- state, there would be no resonant tail to contribute $M1$ strength for capture to the ground state. With a 2^+ resonance the maximum analyzing power is 0.26, whereas with a 2^- resonance the maximum analyzing power is 0.04, compared to a maximum measured value of 0.18 ± 0.03. This change contributes to the discrepancy between Zahnow *et al.* [5] and our calculations because it changes the J^{π} of the resonance as already discussed.

There are two resonances that can $M1$ decay to the first excited state (1^+) at 1083 keV and at 1290 keV [6]. The other two resonances can both decay by $E1$ radiation to this final state. This final state, according to Cohen and Kurath [8], is a two-component single-particle state with spectroscopic factors of 0.469 for $p_{3/2}$ and 0.8764 for $p_{1/2}$. If the calculation is performed with these two different single-particle components present, it yields an analyzing power that is too small since the two components tend to cancel each other out. The solid curve in Fig. 3 is the calculation using a pure $p_{3/2}$ state; this increased the analyzing power slightly over the direct capture so that it nearly agrees with the measured values.

There is no known resonance that can $M1$ decay to the second excited state (0^+). However, the resonance at $E_p=380$ keV can decay by $E1$ radiation, and its addition reduced the predicted analyzing power while maintaining a good fit to the data (see Fig. 3).

Finally, the third excited state (1^+) has the same J^{π} as the first excited state, so the resonances decay by the same transitions. The calculation was first performed using a pure $p_{3/2}$ single-particle state to describe this state, but this only fit

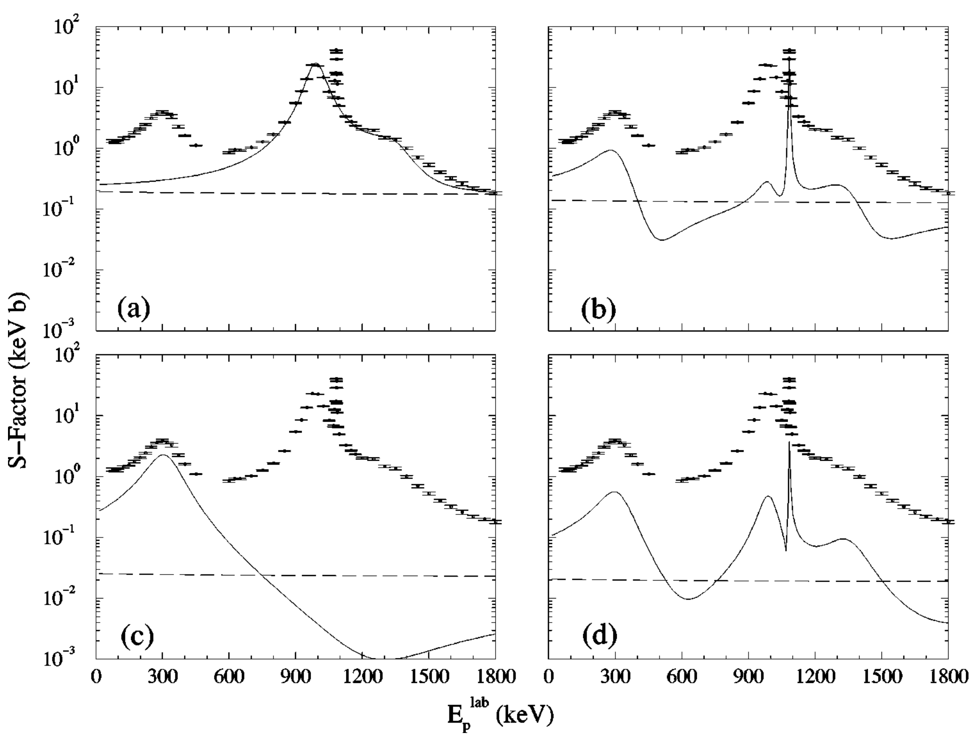

FIG. 4. The calculated astrophysical S factors for direct capture (dashed line), direct capture plus resonances (solid line) to (a) the ground state (3^+), (b) the first excited state (1^+), (c) the second excited state (0^+), and (d) the third excited state (1^+) are shown along with the data from Ref. [5].

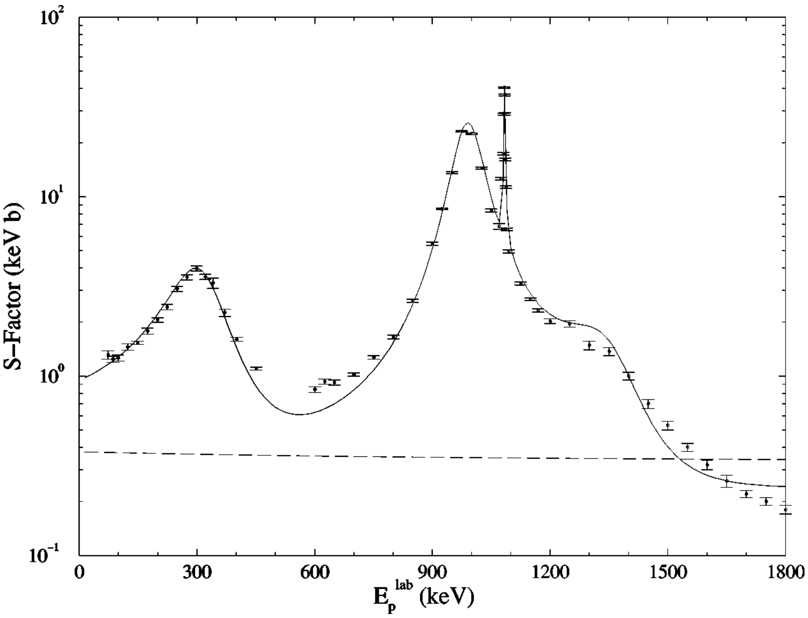

FIG. 5. The calculated astrophysical S factor for direct capture integrated over all final states (dashed line), direct capture plus resonances (solid line), and the data from Zahnow *et al.* [5].

the data at 120°. Changing to a pure $p_{1/2}$ single-particle state reversed the sign of the calculated analyzing power at all angles and gave better overall agreement with the data, as shown in Fig. 3. The assumption of pure $p_{1/2}$ strength contradicts the results obtained in the shell-model calculation of Cohen and Kurath [8]. Capture to this state has a rather small cross section which leads to large statistical uncertainties in the measured analyzing powers. Any definite conclusion about the single-particle structure of this state must await a more accurate set of measurements.

IV. CONCLUSIONS

The previously determined S factors published by Cecil *et al.* [4] are greater than the results of the current analysis by a factor of 4.2 (see Table IV). Their results are based on extrapolations from branching ratios between the α- and the γ-channel decays performed under the assumption that there is only direct s-wave capture at these low energies. The results of the present work indicate that this assumption is not valid. However, correcting their extrapolations for the resonance effects, as described in this paper, would increase their S factors even more. Therefore, it seems that their absolute S factors are off by some overall normalization. Zahnow *et al.* [5], on the other hand, measured the γ-ray channel directly, though without any sensitivity to the different final states. These authors included three of the four resonances in a direct capture plus resonance type analysis and determined the S factor integrated over all four final states. The resonances increase the extrapolated $(E_p=0)$ S factor, summed over the four final states, by a factor of 2.6 over that obtained using pure $E1$ direct capture. The S-factor analysis of the present work expands upon the results of Zahnow *et al.* [5] in two ways. First, the present analysis decomposes the previous integrated S factor into four individual S factors, and second, the direct capture plus resonance model is now constrained to fit the new analyzing power data of our experiment in addition to the cross section data of Ref. [5]. Our results indicate that there is a large difference in the values of the extrapolated S factors at $E_p=0$ between pure direct capture and direct capture with resonances for all of the final states. The validity of our analysis is substantiated by the fact that we were able to use previously determined relative spectroscopic factors and resonance parameters to obtain relative intensities for capture to the four final states at $E_p=92$ keV which agreed with measured values.

The nonzero analyzing powers observed for capture to the ground and first three excited states of ^{10}B in the ^{9}Be$(\vec{p},\gamma)^{10}$B reaction can all be accounted for, within ex-

TABLE IV. The astrophysical S factors (keV b) at $E_p=0$ keV for ^{9}Be$(p,\gamma)^{10}$B obtained by Cecil *et al.* [4], Zahnow *et al.* [5], using a pure direct capture model, and using a direct+resonance capture model which fit the present analyzing power data and the previous cross section data [5].

Final state	Cecil *et al.* [4]	Zahnow *et al.* [5]	Direct capture	Direct+resonant capture
Ground	0.92±0.25		0.19±0.01	0.25±0.01
First	1.4±0.4		0.14±0.01	0.34±0.01
Second	1.4±0.4		0.03±0.01	0.27±0.01
Third	0.47±0.15		0.02±0.01	0.10±0.01
Total	4.19±0.64	1.0±0.1	0.38±0.02	0.96±0.02

TABLE V. The ratios of the yields (Y_i) or S factors (S_i) for each of the final states, at $E_p=92$ keV, measured in the current experiment (experimental), published previously (Cecil), and calculated using the direct capture plus resonances model described in the text (calculated).

Final state	Experimental $Y_i/Y_{\rm tot}$	Cecil *et al.* [4]	Calculated $S_i/S_{\rm tot}$
Ground	0.24±0.01	0.22	0.21
First	0.31±0.01	0.33	0.34
Second	0.33±0.01	0.33	0.33
Third	0.13±0.01	0.11	0.12

perimental uncertainties, by known p-wave ($M1$) resonance tails interfering with the $E1$ direct capture (s- and d-wave) terms and known s-wave ($E1$) resonance tails. These resonance tails also have a large effect on the $E_p = 0$ keV extrapolated values of the astrophysical S factors. The present results, unlike the case of the $^{7}Li(\vec{p},\gamma)^{8}Be$ reaction [2], indicate that the observed analyzing powers can be explained as arising from the interference of the direct $E1$ capture amplitude with the tails of nearby p-wave resonances. The effect of these resonances on the extrapolated S-factor values for the final states measured in this experiment is extremely large, raising the ground and first three excited states S factor by a factor of 1.3, 2.4, 9, and 5, respectively.

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