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LOW-LYING STRUCTURE OF ^{10}Li IN THE REACTION ^{11}B(^{7}Li,^{8}B)^{10}Li

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Abstract

Momentum spectra have been measured for the reaction ^{11}B(^{7}Li,^{8}B)^{10}Li at 130 MeV and laboratory angles of 5° and 3.5°. There is strong evidence for the existence of a broad state in the unstable nucleus ^{10}Li, corresponding to a single p–wave neutron resonance unbound to neutron decay by 538 ± 62 keV with width $\Gamma_{\text{lab}} = 358 \pm 23$ keV. There is also weak evidence that the ^{10}Li ground state may be either an s– or a p–wave resonance barely unbound to neutron decay with $S_n \geq -100$ keV and $\Gamma_{\text{lab}} < 230$ keV. The measured Q–values for the reaction leading to these states are -32908 ± 62 keV and greater than -32471 keV, respectively. A comparison is made with previous measurements and theoretical predictions of the of the low–lying structure of the neutron–unstable nucleus ^{10}Li.

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I. INTRODUCTION

Recent advances in accelerator and spectrometer design have made possible the production of intense radioactive nuclear beams. This has greatly expanded the region of experimentally obtainable nuclei to encompass both drip-lines. Experiments involving nuclei far from stability have revealed structures and dynamic systems very different from those previously studied. These new systems have presented a challenge to nuclear models which were developed to describe phenomena closer to the valley of stability.

One of the most interesting nuclei to exhibit these new phenomena is ^{11}Li. In an attempt to understand its structure, a large body of experimental work has been carried out, including measurements of parallel [1] and transverse [2] momentum distributions of ^{9}Li fragments from the breakup of ^{11}Li, measurements of neutrons observed in coincidence with the ^{9}Li fragments [3–5], and measurements of Coulomb dissociation cross sections [6,7]. These experiments have provided evidence that ^{11}Li consists of a ^{9}Li core with a "halo" of two loosely bound neutrons, the matter radius of which extends well beyond that observed in most nuclei. The fact that ^{11}Li is loosely bound while ^{10}Li, with one less neutron, is unbound also implies that the interaction between the valence neutrons plays a vital role in its stability and structure. With these ideas as a starting point, several calculations have been made by treating ^{11}Li as a three–body system comprising a ^{9}Li core and 2 neutrons [8–13]. Central to these models is the interaction of a single neutron and the ^{9}Li core. For this reason, there is considerable interest in the unbound nucleus ^{10}Li.

If the neutron configuration of ^{10}Li is taken to be that of other $N = 7$ nuclei, such as ^{11}Be and ^{12}B, then the lowest states should have 6 neutrons in their lowest shell model orbits and the seventh neutron in the $1p\frac{1}{2}$ or the $2s\frac{1}{2}$ orbits. This, combined with the proton in the $1p\frac{3}{2}$ orbit, should lead to four states of ^{10}Li having J^{π} values of 1^{+}, 1^{-}, 2^{+}, and 2^{-}. In the first measurement of the ^{10}Li neutron separation energy, Wilcox *et al.* [14] determined the energy of ^{8}B in coincidence with ^{9}Li (from the breakup of ^{10}Li) produced in the reaction ^{9}Be(^{9}Be,^{8}B)^{10}Li at 121 MeV. They observed a state with $S_n = -0.80 \pm 0.25$

MeV and $\Gamma_{c.m.} = 1.2 \pm 0.3$ MeV. It was assumed that this was the ground state of ^{10}Li. Soon thereafter, Barker and Hickey [15] argued that the ^{10}Li ground state should be a $\nu 2s\frac{1}{2}$ state which is narrow and much less unbound to neutron decay. They further suggested that the state observed by Wilcox *et al.* was an excited $\nu 1p\frac{1}{2}$ state.

In 1990, Amelin *et al.* [16] measured the inclusive spectrum of protons produced in absorption of π^- by ^{11}B nuclei and reported the observation of a state in ^{10}Li unbound to neutron decay by approximately 150 keV. In late 1992, Kryger *et al.* analyzed the relative velocity spectrum of neutrons collected in coincidence with ^{9}Li nuclei from the decay of ^{10}Li [17]. Their analysis indicates the presence of a very low energy neutron decay which could either be a low-lying ^{10}Li state decaying to the ^{9}Li ground state, or a ^{10}Li excited state at $S_n \simeq -2.5$ MeV decaying to the first excited state of ^{9}Li. Both Ref. [16] and Ref. [17] present evidence for a weakly unbound ^{10}Li ground state. However, Bohlen *et al.* [18] have recently reported their observation of a $\nu 1p\frac{1}{2}$ ground state unbound to neutron decay by 0.42 ± 0.05 MeV and an excited state, also a $\nu 1p\frac{1}{2}$ state, with excitation energy 0.38 ± 0.08 MeV. They believe that the higher state is that observed by Wilcox *et al.*. The experimental results published to date are summarized in Table I.

The existence of a weakly unbound $\nu 2s\frac{1}{2}$ ground state would be in agreement with the suggestions of Barker and Hickey, as well as the theoretical predictions of Warburton and Brown [19,20]. Also supporting the existence of this state is the observation by Abramovich *et al.* [21] of a $T = 2$ state in ^{10}Be which, with Coulomb energy systematics, gives $S_n = -60$ keV for ^{10}Li. Very recently, Thompson and Zhukov [22,23] have reported the results of calculations using several of the models described in Refs. [9–13]. They found that by assuming only $\nu 1p\frac{1}{2}$ states for the neutrons in ^{11}Li, it was not possible to reproduce simultaneously the experimentally observed neutron binding energy [24,25], the widths of the ^{9}Li momentum distributions from ^{11}Li breakup [1,2], and the energy of the 3–body breakup peak [5]. By including a dominant s–wave contribution to the n–^{9}Li interaction, the three measurements could be reproduced, but the predicted matter radius was significantly larger than the experimentally determined value. It is clear that the results of these calculations are very sensitive to the existence of a low-lying s-wave resonance.

In this paper we present the momentum spectrum from the reaction ^{11}B(^{7}Li,^{8}B)^{10}Li. Following a description of the experimental procedure in Sec. II, we discuss the general features of the spectra in Sec. III, and describe the calculations which have been performed to obtain the expected resonance shapes for s- and p-wave neutrons. It will be shown that the present data are best described by a single p-wave neutron resonance and possibly a narrow, low-lying neutron resonance which could be either an s- or a p-wave. In Sec. IV the conclusions are drawn.

II. EXPERIMENTAL PROCEDURE

The experiment was performed with an E/A = 18.8 MeV, ^{7}Li^{1+} beam from the K1200 cyclotron at the National Superconducting Cyclotron Laboratory. The beam energy was determined with the A1200 analysis device upstream of the target and is accurate to within 0.3%. Beam currents on target were approximately 50 nA. The target was a self-supporting ^{11}B foil 0.125 mg/cm^{2} thick. A ^{12}C (natural) target, 0.56 mg/cm^{2} thick, was used for the calibration runs. The reaction products were analyzed with the S320 magnetic spectrograph [26] with an overall resolution of 0.23 MeV. The focal plane detector consisted of two resistive wire position counters separated by two ionization chambers. The ions were stopped in a thick plastic scintillator. The energy loss signal from the ionization chambers and the time-of-flight, taken from the scintillator signal relative to the cyclotron rf, provided unambiguous particle identification.

The reaction data were taken at laboratory angles of 5° and 3.5°. The position counters at the spectrometer focal plane were calibrated by setting the magnetic elements to step elastically scattered beam particles across the active area of the detector array. These points were fit with a second-order polynomial. Also, spectra were collected for ^{12}C(^{7}Li,^{8}B)^{11}Be at the same angles and field settings as the reaction measurements. The resolved low-lying states in ^{11}Be were used to fix the calibration for the ^{10}Li spectrum.

III. RESULTS AND DISCUSSION

A. Spectra and Calibration

The momentum spectrum collected at 5° from the reaction ^{12}C(^{7}Li,^{8}B)^{11}Be is shown in the top part of Figure 1. The ground and first excited states of ^{11}Be were observed but not resolved. The 1.778 MeV second excited state of ^{11}Be, with a known Q-value of -29966 ± 12 keV was strongly populated, however. This state, combined with the second-order polynomial fit to the elastic scattering data, was used to calibrate the spectrometer. By comparing the known widths of the observed states of ^{11}Be with the measured widths, we found the (FWHM) resolution of the device to be 230 keV. The momentum spectrum collected, under identical conditions as above, from the reaction ^{11}B(^{7}Li,^{8}B)^{10}Li is shown in the bottom part of Figure 1. At 3.5°, the reaction cross section was smaller, and the resulting spectrum contains less than 75 events; however, the general features are consistent with those of the 5° spectrum.

The most striking feature of the 5° data is the broad peak corresponding to a neutron separation energy of approximately −500 keV. Also notable is a weak narrow peak in the spectrum at a neutron separation energy close to zero. While this is not as well pronounced as the broad peak, it does not appear to correspond to any likely target contaminants. As discussed in Sec. I, it is expected that the ^{10}Li ground state might have the valence neutron in the $2s\frac{1}{2}$ orbit and the first and second excited states should both have $1p\frac{1}{2}$ valence neutron orbits. Since an s-wave neutron resonances at $S_n \leq -500$ keV is expected to be too broad to observe, the broad peak in the data is believed to correspond to one or more p-wave resonances, while the narrower, less unbound peak could be an s-wave resonance belonging to the ^{10}Li ground state.

B. Line Shape Calculations

We have performed resonance scattering calculations to estimate the widths and line shapes of p–wave resonances. In the calculations, we assumed that a single neutron moves in the potential created by a ^{9}Li nucleus. The potential consisted of, in addition to a centrifugal term, a Woods–Saxon term

$$V_{\mathrm{WS}}(r) = \frac{-V_0}{1 + exp(r - r_0 A^{1/3})/a} = -V_0 f(r) \tag{1}$$

and a Thomas spin–orbit term

$$V_{\mathrm{SO}}(r) = W_0 \sigma \cdot \ell \frac{1}{r}\frac{df}{dr}. \tag{2}$$

The parameters r_0, a, and W_0 were taken to be 1.25 fm, 0.65 fm and 15.64 MeV fm^2 respectively. Holding V_0 constant, we found the wavefunction $\Psi_{\mathrm{E}}(r)$ for the neutron at a given kinetic energy E. We then normalized the wavefunction inside the nucleus [27]

$$S(E) = \int_0^\infty \Psi_{\mathrm{E}}^2(r) \frac{dV_{\mathrm{WS}}}{dr} r^2 dr. \tag{3}$$

The behavior of S as a function of the neutron kinetic energy E provided the single–particle resonance line shape. The energy at which S reaches a maximum, that is, the resonance energy, varies with the value chosen for V_0. By mapping $S(E)$ for different values of V_0 we were able to parametrize the line shape, and in particular the width, as a function of resonance energy for $p\frac{1}{2}$ neutrons. The resulting parametrization was folded with the experimental resolution of the spectrometer, which was taken to be a Lorentzian with a width of 0.23 MeV, and was used to fit the observed peak. The resonances for $s\frac{1}{2}$ and $p\frac{1}{2}$ neutrons below 100 keV were found to be substantially narrower than 0.23 MeV, so the device resolution shape was used in the fits. Also included in the fitting procedure was a three–body phase space distribution [28] from the reaction ^{11}B(^{7}Li,^{8}B)^{9}Li+n, and a constant background.

C. Fitting Procedure and Error Estimation

Since the statistics in the collected spectra are low, the standard least-squares fitting technique, which assumes that the measured number of events in a given channel has a Gaussian distribution about some "true" value determined by nature, is inapplicable. In reality, the measured number of counting events has a Poisson distribution about the "true" value. Only for a large number of events per channel, where the Poisson distribution approaches the Gaussian distribution, is the least-squares technique valid.

A general maximum-likelihood fitting technique, of which the least-squares method is one, seeks to fit a model function $f(x,a)$ to the data by adjusting the model parameters a to maximize the probability of obtaining the given data set. Typically, a figure of merit is defined as the negative natural logarithm of this probability. More convenient than (but equivalent to) maximizing the probability is minimizing the figure of merit. In the example of the least-squares method, the figure of merit is the χ^2 statistic [29]. With this prescription, if the data in a given channel, (x_i, y_i), have a Poisson distribution about a model $f(x_i, a)$ with parameters a, then the total probability of obtaining the measured data set is

$$P = \prod_i \frac{\{f(x_i,a)\}^{y_i}}{y_i!} e^{-f(x_i,a)}, \tag{4}$$

and figure of merit is

$$\mathcal{L} = -\ln P = \sum_i \{f(x_i,a) + \ln y_i! - y_i \ln f(x_i,a)\}. \tag{5}$$

The $\mathcal{L}$ statistic is similar to χ^2 in that it is a measure of the goodness-of-fit, and that its minimization over the space of model parameters is the objective of the fitting procedure. However, its analytical behavior is not as well known as that of the chi-squared statistic. More specifically, using $\mathcal{L}$ it is possible to compare fits with two different models and to determine whether one fit is better than the other; but it is not possible to assign to a given value of $\mathcal{L}$ a probability analogous to the chi-square distribution as described in Ref. [29]. The statistical uncertainties on the model parameters were determined, as described in Bevington [30], from

$$\sigma_{a_i}^2 = \frac{2}{\partial^2 \mathcal{L}/\partial a_i^2} \tag{6}$$

Additional contributions to the uncertainties in the measured Q-values came from experimental considerations. The beam energy was known to within 0.3%, and the spectrometer angle was known to within 0.05°. The target thicknesses, determined from the beam energy-loss, were known to an accuracy of about ±1%. The effect of each of these on the spectrometer calibration and subsequent Q-value measurement was found to contribute an additional uncertainty of σ = 53 keV. To estimate the overall uncertainty, this value was added in quadrature with the statistical uncertainties from the fitting procedure.

D. Results

The best agreement with the data was obtained with a single $1p\frac{1}{2}$ neutron resonance at a Q-value of −32908 ± 62 keV ($S_n(^{10}\mathrm{Li}) = -538 \pm 62$ keV) with a width $\Gamma_{\mathrm{lab}} = 358 \pm 23$ keV, and a narrow neutron resonance at a Q-value greater than −32471 keV ($S_n(^{10}\mathrm{Li}) \geq -100$ keV) with width Γ_{lab} substantially less than 230 keV. This fit, shown with as solid line in Figure 2 yielded a figure of merit $\mathcal{L}$ = 106. A fit was also performed with a single p-wave only. The resulting peak had a Q-value of −32858 ± 62 keV ($S_n(^{10}\mathrm{Li}) = -505 \pm 62$ keV) with a width $\Gamma_{\mathrm{lab}} = 401 \pm 21$ keV. The figure of merit $\mathcal{L}$ for this fit, which is shown as the dashed line in Figure 2, was 123. A probability cannot be assigned to a given value of $\mathcal{L}$ for a fit with a certain number of degrees of freedom, and therefore an exact quantitative comparison between the two models cannot be made. However, further tests with the fitting procedure have shown that, while the model with the narrow resonance has one more fit parameter and hence one less statistical degree of freedom than the model without the narrow resonance, this difference in the number of degrees of freedom of the two models is not sufficient to account for the difference in the values of $\mathcal{L}$. This indicates that the best fit was obtained with one p-wave resonance and one narrow resonance which could be a p-wave or an s-wave.

We also attempted to fit the broad structure near −500 keV with two p–wave resonances, as was done by Bohlen *et al.*. With this model, the best fit corresponded to a minimum $\mathcal{L}$ value of 124 and put both of the resonances at the same energy as the single p–wave fit described above. Further investigations found that it was possible to keep $\mathcal{L}$ within unity of its minimum value only by placing the resonances less than 170 keV apart and centered near −520 keV separation energy. It is important to note that under no circumstances could a reasonable fit be made with a resonance unbound by more than 650 keV. Both of these results, the possible existence of a low–lying neutron state, and the fact that the broad peak in the data can only be fit by a single $1p\frac{1}{2}$ neutron resonance or by two such resonances separated by less than 170 keV, do not corroborate the results of Bohlen *et al.*. A possible explanation for this is the fact that, although the spectrum collected by Bohlen *et al.* is very similar to that in the present work, the theoretical p–wave line shapes used in their paper are symmetric and relatively narrow ($\Gamma_{\mathrm{lab}} \simeq$200 keV) whereas the line shapes used here are asymmetric and fairly broad ($\Gamma_{\mathrm{lab}} \simeq$400 keV). It seems plausible that a peak at $S_n = -800$ keV is artificially necessitated in order to fit the high–energy tail of the data with narrow, symmetric p–waves. It is also clear that the evidence for the narrow, low–lying state is less than conclusive. It is also unclear whether this state, if it exists, is a $\nu 2s\frac{1}{2}$ state or a $\nu 1p\frac{1}{2}$ state. Clearly, further measurements are greatly needed to solve this puzzle.

IV. CONCLUSIONS

We have collected energy spectra for the reaction ^{11}B(^{7}Li,^{8}B)^{10}Li at 130 MeV and laboratory angles of 5° and 3.5°. The 3.5° data are too low in yield to allow precise structure determination. The 5° data shows a broad state which is best fitted by a single $1p\frac{1}{2}$ resonance unbound to neutron decay by 538 ± 62 keV with width $\Gamma_{\mathrm{lab}} = 358 \pm 23$ keV. We must stress that, while the best agreement with the data was found with one p–wave, the possibility that this peak comprises two p–wave states separated by no more than 160 keV cannot be ruled out. The state at $S_n = -0.80$ observed by Bohlen *et al.* could not be corroborated. There is also weak evidence for a narrow ($\Gamma_{\mathrm{lab}} < 230$ keV) resonance unbound to neutron decay by less than 100 keV. It is possible that this state, which seems to correspond to that observed by Amelin *et al.* [16], is the ground state of ^{10}Li. It is still unclear whether this state is an s–wave or a p–wave, although mounting expectations from systematic and theoretical considerations indicate that an s–wave contribution dominates the n–^{9}Li interaction. Evidence for the existence of this state is still inconclusive, however, and further experimental effort is needed to determine the true nature of the ^{10}Li ground state.

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FIGURES

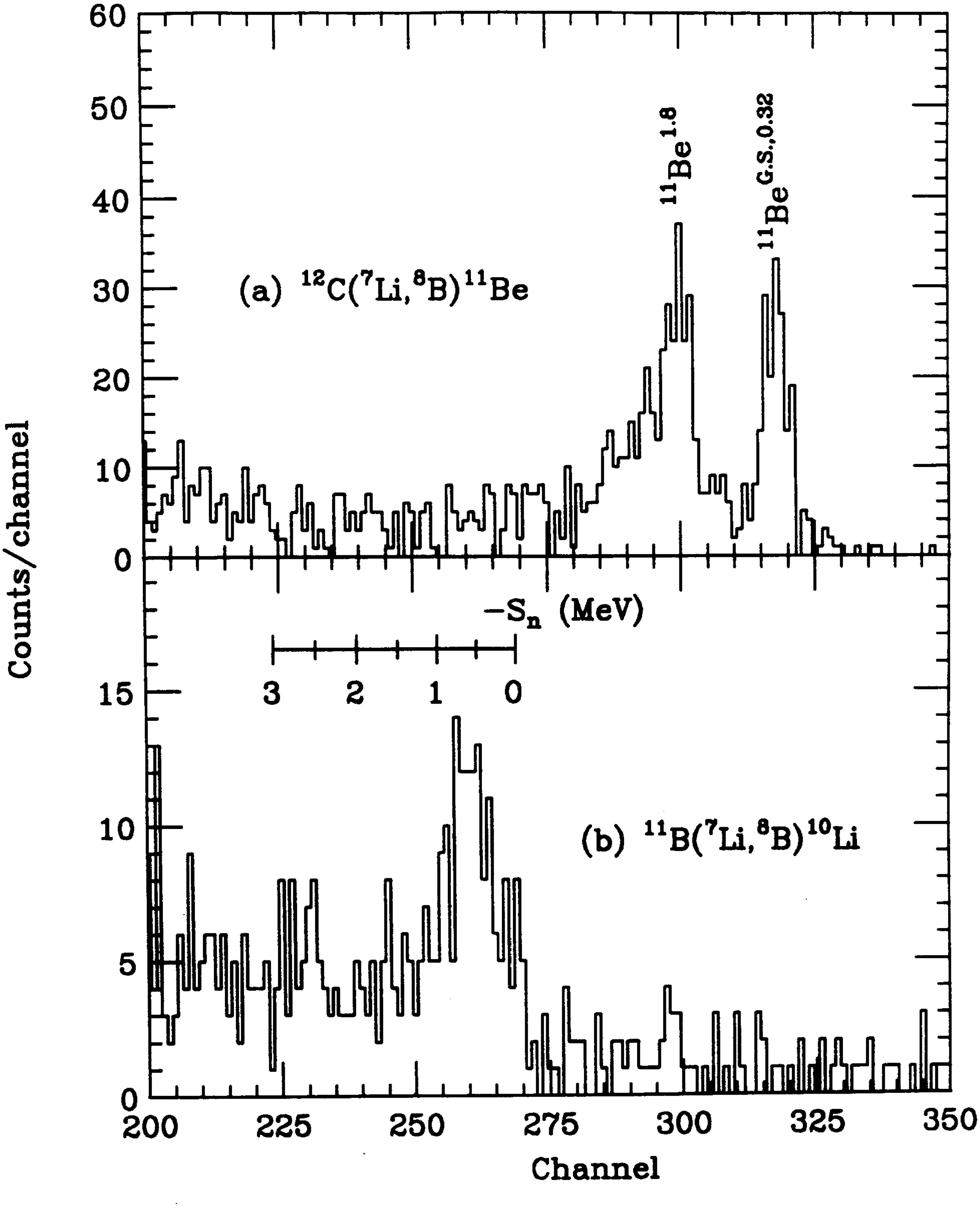
FIG. 1. Momentum spectra obtained under identical spectrometer settings but with different targets. (a) $^{12}C(^{7}Li,^{8}B)^{11}Be$. (b) $^{11}B(^{7}Li,^{8}B)^{10}Li$.

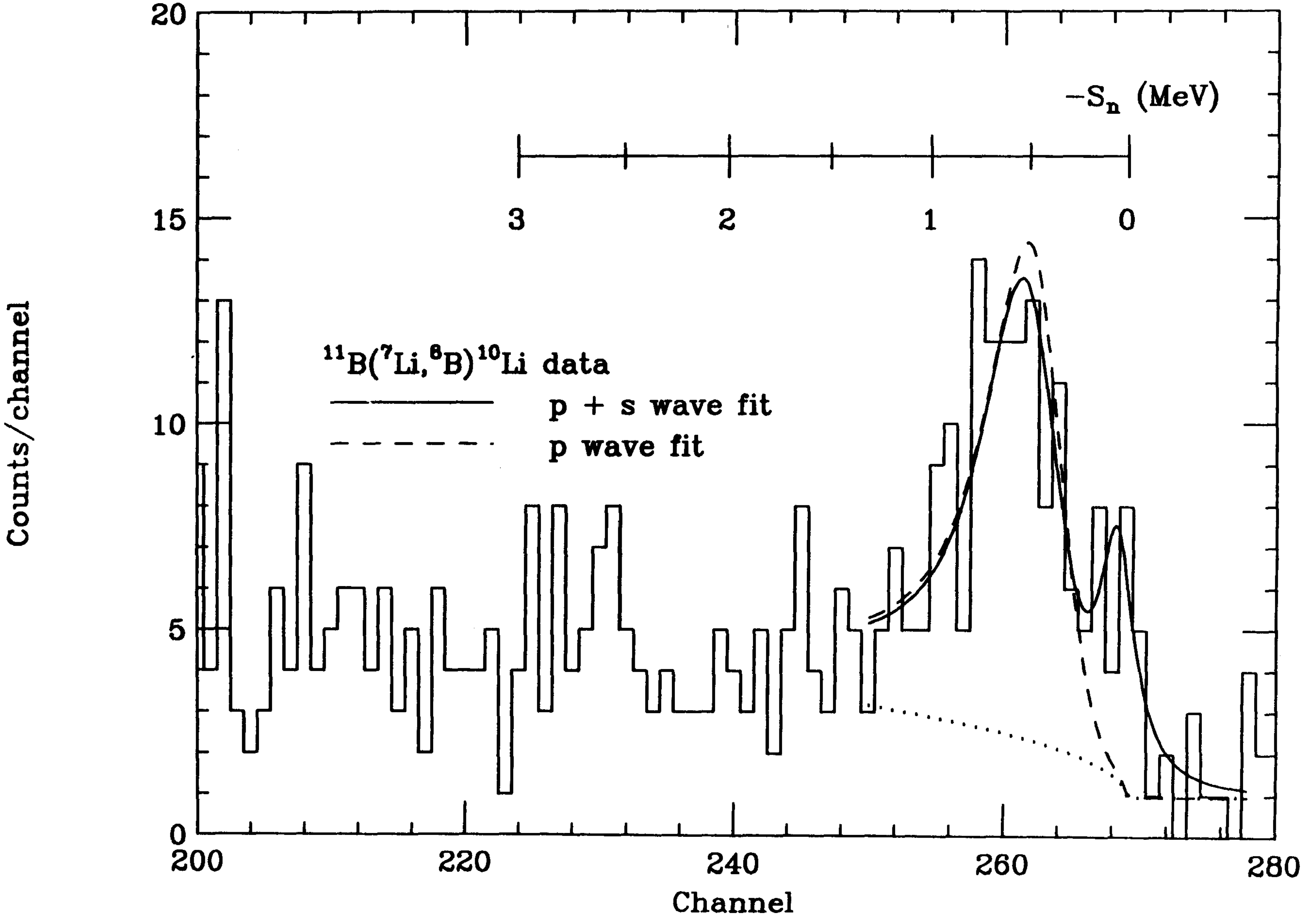
FIG. 2. Theoretical models fitted to the collected spectrum from the reaction $^{11}B(^{7}Li,^{8}B)^{10}Li$. The line shape for the broad peak is obtained from resonance calculations of a p–wave neutron. The narrow state is taken to be an s–wave neutron state, the line shape of which is assumed to be a Lorentzian with width 230 keV. The fitting procedure was a maximum likelihood technique described in the text. The best fit, shown with the solid line, was obtained with one p–wave resonance, one s–wave resonance, a 3–body background, and a constant background. The dashed line is the fit obtained with one p–wave, a 3–body background, and a constant background. Also shown, with the dotted line is the summed 3–body and constant background terms used in the above fits.

TABLES

TABLE I. Summary of experimental data on low-lying structure ^{10}Li published to date. The neutron separation energy and width are given for each state. Also given for each state is the identification (if any) claimed by the experimenters.

	S_n (MeV)	$\Gamma_{\rm lab}$ (MeV)	Identification
Wilcox *et al.* [14]	-0.80 ± 0.25	1.2 ± 0.3	G.S.
Amelin *et al.* [16]	-0.15 ± 0.15	≤ 0.4	$s\frac{1}{2}$, G.S.
Kryger *et al.* [17]	≥ -0.15 or		G.S.
	≈ -2.5		
Bohlen *et al.* [18]	-0.42 ± 0.05	0.15 ± 0.07	$p\frac{1}{2}$, G.S.
	-0.80 ± 0.06	0.30 ± 0.10	$p\frac{1}{2}$
Present Work	≥ -0.10	< 0.23	G.S.
	-0.54 ± 0.06	0.36 ± 0.02	$p\frac{1}{2}$


60
50
40
30
20
10
0
15
10
5
0
Counts/channel
(a) $^{12}C(^{7}Li,^{8}B)^{11}Be$
$^{11}Be^{1.8}$
$^{11}Be^{G.S.,0.32}$
$-S_n$ (MeV)
3
2
1
0
(b) $^{11}B(^{7}Li,^{8}B)^{10}Li$
200
225
250
275
300
325
350
Channel


$^{11}B(^{7}Li,^{8}B)^{10}Li$ data
p + s wave fit
p wave fit
$-S_n$ (MeV)
3
2
1
0
Counts/channel
0
5
10
15
20
Channel
200
220
240
260
280