$T = 3/2$ states in ^{13}C

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(Received 5 May 2008; published 6 October 2008)

Background: Experimental information on the structure of low-lying levels with isospin 3/2 in systems with 13 nucleons can be used to evaluate the quality of modern theoretical predictions for the light exotic systems. This level structure is poorly known at present. **Purpose:** Search for $T = 3/2$ states in ^{13}C was performed in this work. **Method:** These states were observed in the resonance elastic scattering of radioactive beam ^{12}B on protons using the thick target inverse kinematics technique. **Results:** Six new states in ^{13}C were identified as $T = 3/2$ states. Tentative spin-parity assignments are suggested. Comparison to the previous knowledge of the level structure of $T = 3/2$ $A = 13$ system and to shell-model predictions is given. **Conclusion:** The elastic scattering of neutron-rich beams on proton target is a convenient tool for isobaric analog states search. The observed ^{12}B+p excitation function is determined by the $T = 3/2$ states and no features associated with $T = 1/2$ states were found. Although the level scheme of $T = 3/2$ states in $A = 13$ systems is still far from being complete the emerging picture shows significant disagreements with predictions of contemporary shell models.

DOI: 10.1103/PhysRevC.78.044603 PACS number(s): 21.10.−k, 24.30.−v, 27.20.+n

I. INTRODUCTION

$T = 3/2$ levels in $A = 13$ nuclei are of interest to evaluate the predictive ability of contemporary shell-model calculations for the exotic nuclei in the *psd* valence space. All nucleons in these systems occupy the *p* shell in the ground state. However, most of the low-lying excited states correspond to cross-shell *p*-*sd* excitations. Several shell-model interactions that include the *p*-*sd* cross-shell matrix elements are available (see review article by B. A. Brown [1] and references therein). These matrix elements were determined from fits to experimental energies in the mass region $A = 10$–22 and their applicability for more exotic nuclei needs to be verified.

It can be expected that several low-lying $T = 3/2$ excited states in $A = 13$ nuclei should have substantial contributions from $2s_{1/2}$ and $1d_{5/2}$ single-particle configurations. However, little reliable experimental information is available for excited states in $T = 3/2$ $A = 13$ isobaric chain. Only recently has the first spin-parity assignment been made for the $1/2^+$ first excited state in ^{13}O [2]. Other levels with large predicted single-particle widths were not observed in this work, possibly due to the limited excitation-energy interval for ^{12}N+p elastic-scattering excitation function measured in Ref. [2].

In the present experiment, a search for $T = 3/2$ states in ^{13}C was performed using resonant elastic scattering of protons on ^{12}B. Only one $T = 3/2$ state is known with some degree of reliability: the $3/2^-$ state at 15.11 MeV that is the isobaric analog of the ^{13}B(^{13}O) ground state [3]. However, $T = 3/2$ isospin assignment has been proposed for four more states in ^{13}C (at 17.53, 18.08, 20.06, and 21.7 MeV) based on narrow width (<20 keV) of the structures at these energies observed in the isospin-forbidden ^{12}C+n channel [4].

The interaction of ^{12}B $(T = 1) + p$ can result in the population of both $T = 1/2(T_<)$ and $T = 3/2(T_>)$ levels in ^{13}C. This is why the interaction of neutron-rich nuclei on hydrogen presents a convenient new way to obtain data on $T_>$ states in isospin-allowed reactions. This possibility was considered about 10 years ago [5], but only a few experiments with very light nuclei ($A \leqslant 9$) have since been performed [6,7]. One of the reasons for this slow progress could be the involvement of the $T_<$ states. The interaction of the neutron-rich nuclei with a proton results in the population of highly excited states of the compound nuclei. For example, in the case of the ^{12}B+p interaction, states at over 17 MeV in ^{13}C are being probed and only a few of the $T = 1/2$ resonances in this region are known. However, although the specific structures of the possible $T = 1/2$ resonances in this region are unknown, it is evident that these states have many (more than 10) open decay channels, whereas the $T = 3/2$ states can decay only to the elastic channel because of isospin conservation. [At somewhat higher excitation energy, neutron decay through ^{12}C$(T = 1, J^\pi = 1^+) + n$ channel and proton decay to the first excited state of ^{12}B are also possible]. It is expected that the $T_<$ states should not contribute to the single specific elastic channel, as many other decay modes having much higher penetrability factors are allowed. Still, the properties of $T_<$ states at high excitation energies are not known. That is why the specific role of $T_<$ states in the experiments in question is under discussion. It was shown by a sample calculation for ^{7}Li that the contribution of $T_<$ levels is negligible [8]. However, additional experiments of this kind are needed to clear up the situation.

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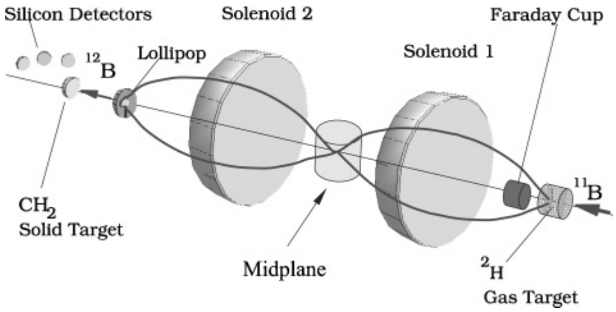

FIG. 1. The experimental setup with beam trajectories through TwinSol. The "lollipop" reduces contamination of the beam by intercepting ions that focus at a different location relative to ^{12}B.

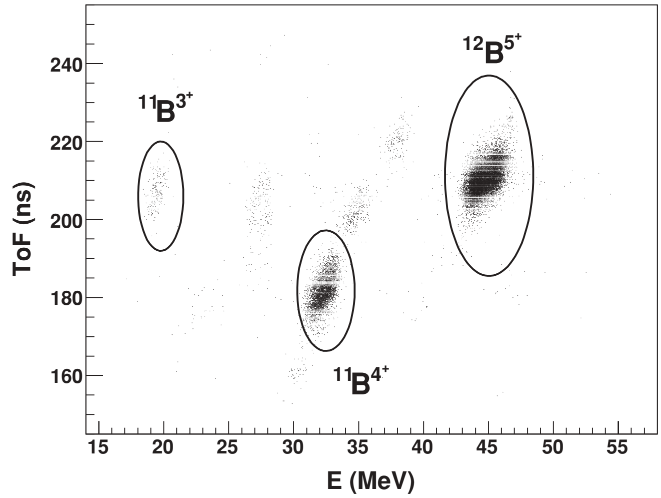

FIG. 2. Composition of the secondary ^{12}B beam obtained with a Si ΔE-E detectors at the secondary target position. The start signal for the TOF measurements was taken from the E detector, and the stop signal came from the RF of the buncher (reverse TOF). The $^{11}B^{3+}$ ions are from the preceding (with respect to ^{12}B) bunch.

II. EXPERIMENT

The experiment was carried out with the TwinSol radioactive nuclear beam facility [9] at the University of Notre Dame. The experimental setup is illustrated in Fig. 1. A radioactive beam of ^{12}B was produced via the ^{2}H(^{11}B,p)^{12}B reaction. A primary ^{11}B beam with intensity of about 80 electrical nA and energy 57 MeV was incident on the primary target, a 2.5-cm-long gas cell containing deuterium at a pressure of 1.2 atm. A Faraday cup placed after the gas cell was used to stop the primary beam. Two large superconducting solenoids act as thick lenses to separate ^{12}B from other reaction products and the scattered primary beam. The magnetic system of solenoids focused the reaction products into a 1-cm-diameter spot at the secondary target position. Under these conditions, a ^{12}B beam was obtained with an intensity of 2.8×10^6 particles per second. Its energy was 44.6 MeV, with an energy spread of 2 MeV full width at half maximum (FWHM). The composition of the secondary beam was ^{12}B: 70%, $^{11}B^{4+}$: 23%, $^{11}B^{3+}$: 4%. Other contaminants contributed ∼3%. The primary beam of ^{11}B was bunched into 2-ns bunches to allow for time-of-flight (TOF) separation between the events associated with ^{12}B and the contaminants of the secondary beam. The time between bunches was 100 ns. A two-dimensional TOF spectrum, plotted versus energy deposited in a Si detector placed at the target position, is shown in Fig. 2. The TOF was obtained in reference to the radiofrequency (RF) signal from the buncher. (The distance from the primary to the secondary target in TwinSol is 5.6 m). The intensity of the primary beam was reduced by a factor of 1000 to obtain this spectrum. It is clear from Fig. 2 that $^{11}B^{4+}$ events are very well separated in TOF from ^{12}B events. The presence of $^{11}B^{3+}$ ions in the time gate of ^{12}B was taken into account by subtracting protons in low-energy part associated with ^{11}B.

A polyethylene CH_2 target of 16.97 mg/cm^2 thickness was used to stop the ^{12}B ions, and a natural carbon target (thickness 23.3 mg/cm^2) was used for background measurements. (This carbon target thickness is nearly identical to the polyethylene target thickness in terms of energy loss.) Charged particles emerging from the secondary target were detected by two ΔE-E Si telescopes placed at 7.5° and 15.0° relative to the beam axis. The thicknesses of the ΔE detectors were 71 and 20 μm, respectively, and the Si E detectors were each 1000 μm thick. A spectrum of protons from the reactions of ^{12}B on the polyethylene target measured in the 7.5° telescope is shown in Fig. 3, in comparison with the background spectrum measured using the carbon target. It was found that carbon in the polyethylene target is responsible for only 5% of the total number of events in the proton spectrum. The "carbon" background was subtracted from the final spectra.

The excitation functions were then transformed to the center-of-momentum (c.m.) system on a bin-by-bin basis, using a computer code that takes into account kinematics, the geometry of the experimental setup, specific energy losses for ^{12}B and protons, and the total number of accumulated ^{12}B ions. The total number of ^{12}B ions accumulated during the run was evaluated using the following procedure. The ΔE-E telescope was placed at the secondary target location and the ratio between the number of $^{12}B^{5+}$ ions and the total charge accumulated by the Faraday cup (see Fig. 1) was measured.

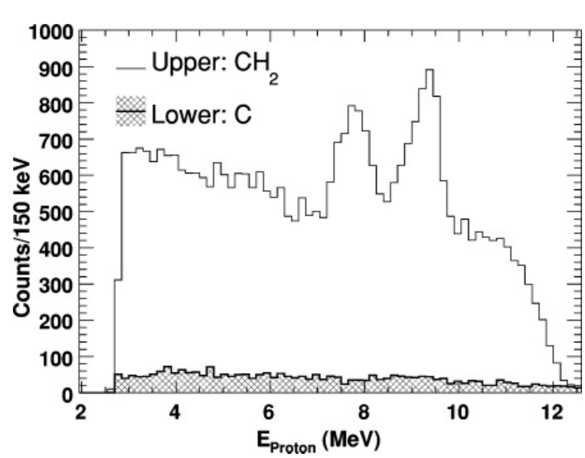

FIG. 3. Energy spectra of protons from the reactions of ^{12}B on polyethylene and carbon targets, measured in the 7.5° telescope.

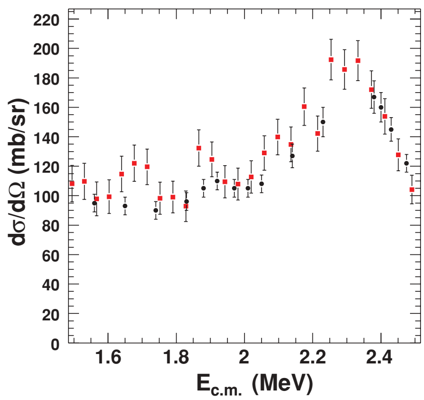

FIG. 4. (Color online) The excitation function for ^{11}B+p elastic scattering measured at 165° (c.m.). The round data points have been taken from Ref. [10], and the square data points are from the present experiment.

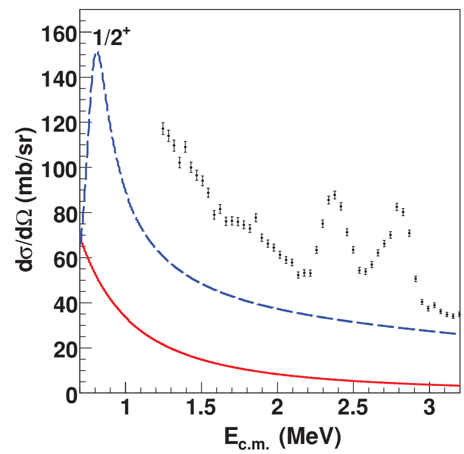

FIG. 5. (Color online) Excitation functions for ^{12}B+p elastic scattering from 1.25 to 3.2 MeV at 165° in the center-of-momentum reference frame. The solid line corresponds to the Rutherford cross section, and the dashed line shows the contribution of a $1/2^+$, $T = 3/2$ resonance at 0.87 MeV. This corresponds to a 18.4-MeV excitation energy in ^{13}C because the ^{13}C proton decay threshold is 17.53 MeV. The assumed width of this state was 190 keV.

Then, this ratio and the total charge accumulated during all production runs was used to calculate the total number of ^{12}B ions. To evaluate the accuracy of this procedure, we performed the same steps for the ^{11}B+p excitation function, which was measured automatically during the same production runs because there was a 23% admixture of ^{11}B ions in the secondary beam. [Clean separation between events associated with ^{12}B and ^{11}B^{4+} was achieved by gating on the time of flight (see Fig. 2).] Figure 4 shows comparison between the ^{11}B+p excitation function at 165° c.m. obtained in the present work and the same excitation function measured using conventional technique taken from the literature [10]. The two data sets are identical within error bars, indicating that the accuracy of the absolute normalization procedure is better than 15%.

III. ANALYSIS

Figure 5 shows the excitation function for ^{12}B+p elastic scattering in the center-of-momentum energy range from 1.25 to 3.2 MeV at 165°. The most striking feature of the measured excitation function is that even at center-of-momentum energy below 1.5 MeV the cross section is 5 times larger than the Rutherford cross section, shown as the solid line in Fig. 5. This clearly indicates that strong low-energy resonances are playing a dominant role in this spectrum. As an example, the contribution of a $T = 3/2$, $\ell = 0$, $1/2^+$ state at 0.87 MeV and a width of 190 keV, is shown in the Fig. 5 as the dashed curve. (The reason for the specific choice of these parameters is discussed below.) In addition to high overall cross section, there are two narrow peaks at $E_{\text{c.m.}} = 2.4$ and 2.8 MeV, which correspond to states at 19.9 and 20.3 MeV excitation energy in ^{13}C. (The ^{13}C proton decay threshold is 17.53 MeV.)

The analysis of the ^{12}B+p excitation functions was performed in the framework of the multichannel, multilevel R-matrix approach [11]. In agreement with the findings in Refs. [6] and [12], the first test calculations showed that, if all the relevant partial waves ($1/2^+, 3/2^+, 5/2^+, 7/2^+, 1/2^-$, $3/2^-$, and $5/2^-$) are included, the R-matrix calculations generate a significantly larger cross section of potential scattering at high energies than are observed in the experiment. In accordance with the main idea of this work, the $T = 1/2$ resonances are assumed not contribute to the elastic scattering. However, due to isospin coupling, the $T = 1/2$ resonances are populated with ratio 2:1 with respect to the $T = 3/2$ resonances and could be responsible for the absorption of the incoming flux of protons. $T = 1/2$ resonances at such high excitation energy (∼20 MeV) decay predominantly by neutron emission. The parameters of the ^{13}C $T = 1/2$ resonances at these excitation energies are mostly unknown. To take into account the absorption due to these resonances, we used a simple approach that had been previously discussed in Ref. [12]. Imaginary phase shifts were added to the phase shifts generated by the hard sphere in the R-matrix calculations. These imaginary phase shifts are calculated using the following phenomenological expression [12]:

$$\text{Im}\delta(k) = A\left[1 - \frac{1}{1 + e^{(kR-l)/A_1}}\right]\left[1 - \frac{1}{1 + e^{(kR-l_0)/A_2}}\right], \tag{1}$$

where $A = -0.31$, $A_1 = 0.15$, $l_0 = 1.75$, and $A_2 = 0.2$ are constants. This parametrization provides for an increase of the absolute value of the imaginary phase shifts from the very small values at energies less than 2 MeV up to a maximum of ∼0.1 at 3.2 MeV (for $\ell = 0$ partial waves). Validity of this approach can be justified by the fact that there are at least 20 $T = 1/2$ states per 1 MeV in ^{13}C at 20 MeV excitation energy (shell-model estimate with only 0, 1 and $2\hbar\omega$ excitations allowed) with typical width of more than 100 keV. (This estimate is based on the average spectroscopic factor predicted by the shell model for neutron decay of the ^{13}C $T = 1/2$ excited states at ∼20 MeV into the ground and low-lying ^{12}C excited states.)

To restrict the number of possible solutions, we used experimental data on the level scheme (see Fig. 6) of ^{13}B [3],

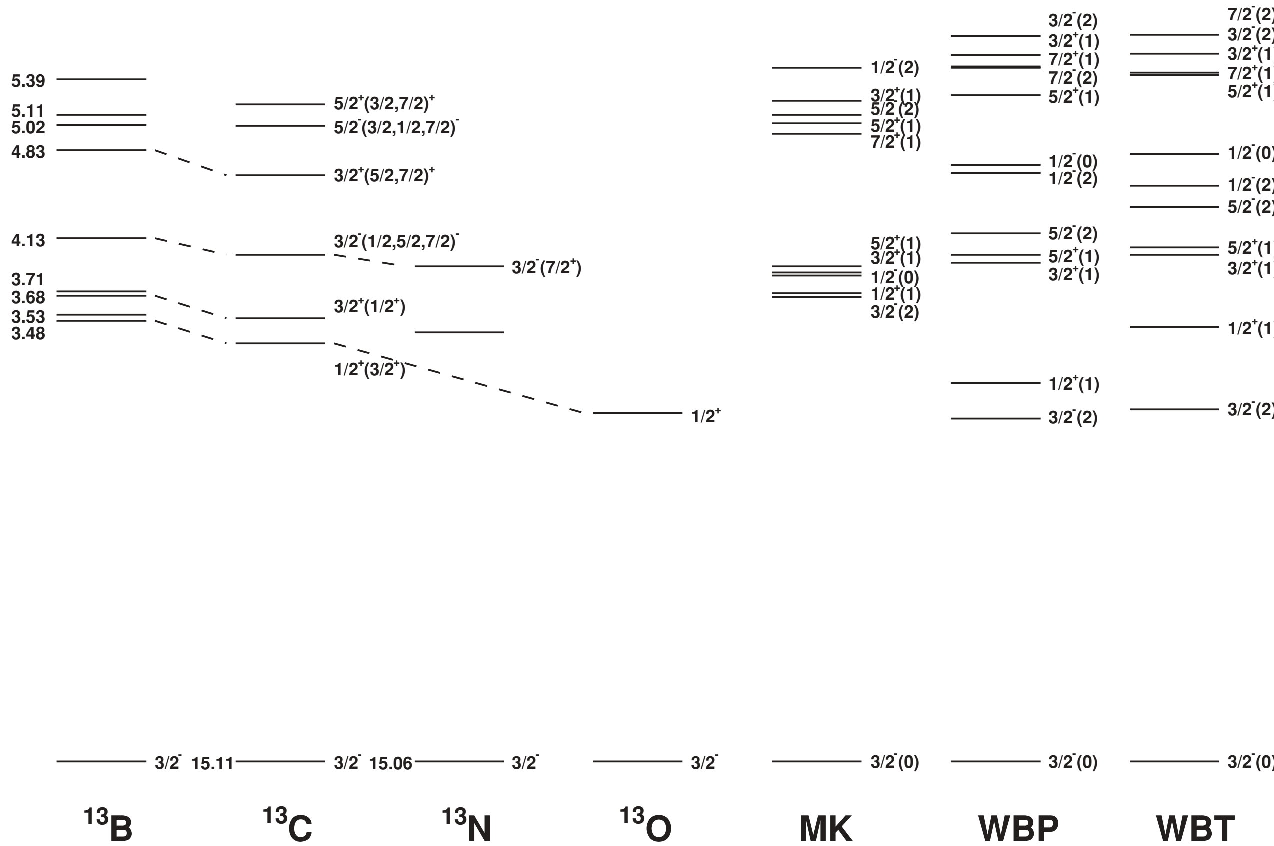

FIG. 6. The $T = 3/2$, $A = 13$ isobaric chain. Numbers shown in parentheses after the spins in the shell-model calculations are $\hbar\omega$. Only those $T = 3/2$ states that were observed in the present work are shown for ^{13}C.

and data on the first excited state in ^{13}O [2]. We also took into account qualitative features of the shell-model predictions for the lowest levels in ^{13}B. To address the large cross section, which exceeds the Coulomb scattering by a factor of 5 at the lowest energies, one should include a resonance (or resonances). It is natural to consider an $\ell = 0$, $1/2^+$ resonance that would be the isobaric analog of the first excited state in ^{13}O (identified as $1/2^+$ in Ref. [2]). To obtain the initial widths and energy for this ^{13}C resonance, we used the potential model with the parameters similar to those used in Ref. [2]. A Woods-Saxon potential having parameters $V_0 = -54.80$ MeV, $r_0 = 1.22$ fm, $a = 0.60$ fm produced the $\ell = 0$ state at the observed center-of-momentum energy of 1.20 MeV in ^{13}O (which corresponds to 2.7 MeV excitation energy in ^{13}O) and at 0.54 MeV in ^{13}C, considered as ^{12}B$+p$ system. The single-particle $T = 3/2$ states in ^{13}C have two components, ^{12}B(g.s.)$+p$ and ^{12}C($T = 1$; 15.11 MeV)$+n$ with statistical weights (1/3 and 2/3, respectively) determined by the square of the isospin-coupling Clebsch-Gordon coefficients. We assume that excitation energy of the $1/2^+$ first excited state in the ^{12}C($T = 1$; 15.11 MeV)$+n$ configuration is the same as in ^{13}B and that the first excited state in ^{13}B is $1/2^+$. Making use of the potential model result for the ^{12}B$+p$ configuration, and taking into account the statistical weights of the corresponding configurations, one obtains an expected excitation energy for the $T = 3/2$, $1/2^+$ state in ^{13}C of 18.4 MeV. This corresponds to a resonance at 0.87 MeV in the center-of-momentum reference frame. The width of this state can be estimated from the single-particle width of 700 keV, calculated using potential model mentioned above. The spectroscopic factor for the $1/2^+$ state in ^{13}O is 0.8 [2]. Taking into account the statistical weight of the ^{12}B$+p$ configuration (1/3) the total width of the $T = 3/2$, $1/2^+$ state should be $\sim$200 keV. The contribution of a state with these parameters is shown in Fig. 5 (dashed curve). Although introduction of the $1/2^+$ state significantly increases the calculated cross section, it was ultimately determined that reasonable variations of the position and width of the $1/2^+$ resonance alone cannot account for the cross section observed at low energies (see Fig. 5). The ^{13}B level scheme shows three more levels near the first excited state. The shell-model calculations indicate that one of these states should be $3/2^+$ with rather large $2s1/2(\ell = 0)$ spectroscopic factor. This level was included into the final fit because only $\ell = 0$ resonances can be broad enough to provide for the evident change in the cross section in the rather broad low energy region. The $3/2^+$ resonance should be placed 50–250 keV above the $1/2^+$ level in accordance with the ^{13}B level scheme and the Thomas-Ehrman shift that should be similar for both $\ell = 0$ states. The initial parameters of the $3/2^+$ resonance were taken from the shell-model calculations, and then some of the parameters of this state were varied slightly to obtain a better fit. It should be noted here that a

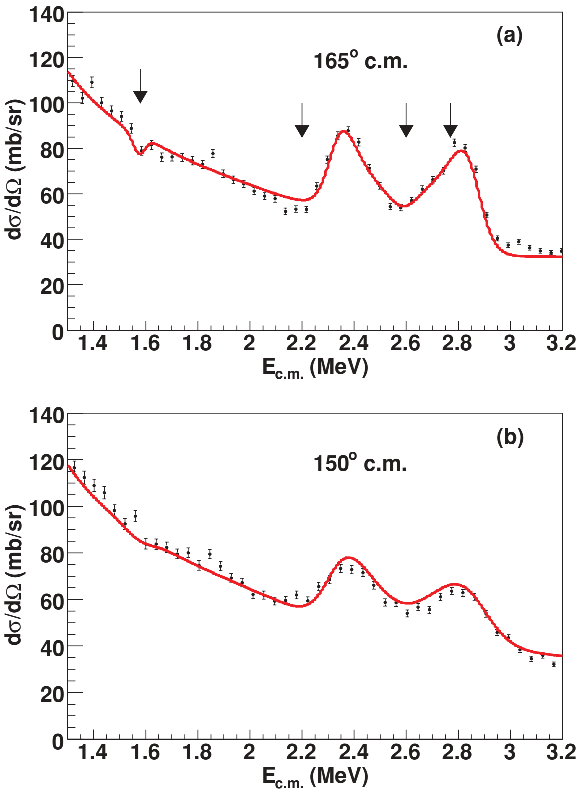

FIG. 7. (Color online) Excitation functions for ^{12}B+p elastic scattering measured at 165° (a) and 150° (b) in (c.m.). The solid line represents the best R-matrix fit that includes six $T = 3/2$ resonances and the absorption phase shift (see text). (a) Arrows indicate excitation energies of the high-lying resonances. The R-matrix fit was convoluted with the experimental resolution function.

$T = 3/2, 3/2^+$ state can also be constructed by coupling the ^{12}B, 1^+ ground state to a proton in $1d$ ($\ell = 2$) orbital. This configuration was also included for the $3/2^+$ state according to the predictions of the shell model.

The best R-matrix fit of the measured excitation functions is shown in Fig. 7. The two evident peaks at 2.4 and 2.8 MeV (19.9 and 20.3 MeV of excitation energy in ^{13}C) can be described only with a dominant d-wave ($\ell = 2$) component. Lower proton orbital momenta could not provide for the shapes of the resonances and for the falloff of the cross sections with angle. Higher orbital angular momenta resulted in unrealistically large spectroscopic factors (because the resonances were too narrow) and also gave the wrong shape. We therefore identify these two peaks as positive-parity states with possible spin-parity assignment $3/2^+$, $5/2^+$, or $7/2^+$. As it was pointed out above the $3/2^+$ state can have both $\ell = 0$ and $\ell = 2$ contributions. The R-matrix fit favors the $3/2^+$ spin-parity assignment for the first peak at 2.4 MeV due to specific interference pattern between the $\ell = 0$ components of the first and second $3/2^+$ states. However, this argument alone is not strong enough to make a final assignment. An irregularity in the vicinity of 1.6 MeV (19.1 MeV of excitation energy in ^{13}C) can be best described by the presence of a weak negative-parity $\ell = 1$ resonance. It was found that the low-energy shoulder of the 2.8-MeV peak can be better described if one more weak $\ell = 1$ resonance is introduced at a c.m. energy of 2.6 MeV. As will be clear from the discussion below, in addition to making the fit better, both weak $\ell = 1$ states agree well with the level scheme of ^{13}B. Nonetheless, due to weak manifestation of these states in the spectra, we consider our assignments for these resonances to be tentative. In addition to the states mentioned above, two narrow states at energies below the measured ones were included into the R-matrix fit, based on the level scheme of ^{13}B and the shell-model calculations. These are an $\ell = 1$ state at 1.1 MeV and an $\ell = 2$ state at 1.25 MeV. It was verified that these states are too narrow ($\sim$10 keV) to influence the behavior of the excitation function at the measured energies. These two states were introduced only to show that their presence does not ruin the fit.

The parameters of the resonances are given in Table I. (The two narrow resonances at 1.1 and 1.2 MeV are not shown.) All specific spin assignments in the table should be considered to be tentative. However, the parities and orbital angular momenta (with respect to the ground state of the ^{12}B core) of the observed states are reliable. Parameters shown in bold italic were not varied but were determined from the spectrum of ^{13}B and shell-model and potential-model considerations (see discussion above). In addition to elastic scattering, the following isospin-allowed decay channels were taken into account in the R-matrix fit: proton decay to the first excited state of ^{12}B (2^+ at 0.95 MeV), and neutron decay to the ^{12}C 1^+ $T = 1$ state at 15.11 MeV (this decay channel is open only for states above 2.55 MeV center-of-momentum energy). The initial values of reduced widths for all these channels were evaluated using shell model (Millener-Kurath interaction, see Sec. V) and isospin Clebsch-Gordon coefficients and then varied slightly to produce a better fit.

A remarkable feature of all the resonances is that no neutron decay into any $T = 0$ states in ^{12}C with favorable penetrability factors needed to be included. This serves as a strong argument for the $T = 3/2$ isospin assignment for the states in question. The combined effect of the $T = 1/2$ states (absorption) is taken into account by the imaginary phase shift.

IV. DISCUSSION

Consider the structure of ^{13}B using the shell-model approach. Eight neutrons fill the p shell in ^{13}B, and, considering

TABLE I. $T = 3/2$ resonances in ^{13}C from the best R-matrix fit. Parameters shown in italic were not varied (see text for details.) The excitation energy of the fourth state at 2.2 MeV depends on its assigned spin-parity due to interference and is 150 keV higher if this state is either $5/2^+$ or $7/2^+$.

$E_{c.m.}$(MeV)	E_{ex}(MeV)	J^π	Γ(keV)
0.87	*18.4*	$1/2^+(3/2^+)$	*190*
1.07	*18.6*	$3/2^+(1/2^+)$	90
(1.58)	(19.11)	$(3/2; 1/2; 5/2)^-$	<30
2.20(2.35)	19.74(19.90)	$3/2^+(5/2; 7/2)^+$	200
2.60	20.13	$5/2^-(1/2; 3/2)^-$	120
2.77	20.3	$5/2^+(3/2; 7/2)^+$	170

only $1\hbar\omega$ excitations, one would expect low lying $2s$-$1d$ excited states with large single-particle [^{12}B(g.s.)+n] reduced widths. The $1d5/2$ and $2s1/2$ states have lower excitation energy, whereas the $1d3/2$ states are at higher excitation energy (at least 3 MeV higher). Taking into account the 1^+ spin-parity of the ^{12}B ground state, one obtains the lowest single-particle states with spins $1/2^+$ and $3/2^+$ for a neutron in the $2s1/2$ shell, and $3/2^+$, $5/2^+$, and $7/2^+$ for a neutron in the $1d5/2$ subshell. The lowest possible proton excitation (from the $1p3/2$ to the $1p1/2$ subshell) results in a low-lying $1/2^-$ state. However, the structure of this state is rather different from ^{12}B(g.s.)+n configuration and the corresponding reduced width should be small. Due to similarities in the structure of the ground state and the first excited state (2^+, 0.95 MeV) in ^{12}B [both states have a $\pi(1p3/2)\otimes\nu(1p1/2)$ configuration], it is natural to expect that the ^{12}B(2^+, 0.95 MeV)+p reduced width for some low-lying states in ^{13}B can be significant. Finally, $2\hbar\omega$ excitations result in a large number of negative-parity states some of which, according to the shell-model predictions, may have rather low excitation energy (see Sec. V).

One can see in Table I that the states with positive parity manifest themselves in resonant scattering in accordance with these qualitative expectations. It is remarkable that the $T = 3/2$ states could be identified in the "sea" of many $T = 1/2$ states that should be present at this high excitation energy. This is about all we can deduce from qualitative structure considerations. A comparison with more-detailed shell-model calculations will be made in Sec. V, but first we compare the available information on the $T = 3/2$ states in ^{13}C and ^{13}N with the present results.

The study of analog states was one of the main directions in nuclear physics 20–40 years ago. Most of the $T = 3/2$ states in ^{13}C and ^{13}N were identified in resonant scattering of neutrons and protons on ^{12}C [3]. The $T = 3/2$ states are populated in these reactions through "isospin forbidden" channels due to isospin impurities. Very narrow resonances (5 keV in ^{13}C at 15.11 MeV and 1 keV in ^{13}N at 15.06 MeV), corresponding to the lowest $T = 3/2$ states (the isobaric analogs of the ^{13}B and ^{13}O ground states), were found in these studies. These lowest $T = 3/2$ states can decay only through T-violating channels, which makes these states very narrow. Their entrance-channel partial width is about 0.1 keV. It was possible to identify a resonance in this isospin-forbidden channel only if the partial width in the entrance channel (Γ_0) is more than 0.01 of the total width of the resonance [13]. Otherwise, the magnitude of the anomaly is too small. Therefore, only narrow $T = 3/2$ resonances could be found this way, and any narrow resonance identified at high excitation energy in resonant-scattering experiments was considered to be a candidate for a $T = 3/2$ state. In addition to the isobaric analog to the ground state of ^{13}B at 15.11 MeV, four narrow (~20 keV) resonances at 17.53, 18.08, 20.06, and 21.70 MeV [4] were identified as possible $T = 3/2$ resonances in ^{13}C. The excitation energies of the first two of these resonances are lower than the energy of the $1/2^+$ state of the present work. The 18.4-MeV $1/2^+$ state introduced in this work is the analog of the first excited state in ^{13}O observed in Ref. [2]. Also, no excited states below 3.48 MeV were observed in ^{13}B [3] (3.48 MeV in ^{13}B correspond to ~18.6 MeV excitation energy in ^{13}C). Therefore, it is very unlikely that the narrow state at 17.53 and 18.08 MeV observed in Ref. [4] are actually $T = 3/2$ state. Although one might argue that the 18.08-MeV state may be the isobaric analog of the first excited state of ^{13}B based on its seemingly close excitation energy, we note that the width of this state (12±7 keV [4]) is too small for single-particle $1/2^+$, $T = 3/2$ state at this excitation energy. No indication of the possible $T = 3/2$ state at 20.06 MeV was observed in this work. The nearest in terms of excitation energy is $\ell = 1$ state at 20.13 MeV but its width is 120 keV (Table I), not the 18 keV reported in Ref. [4], indicating that these are different states.

The study of the possible $T = 3/2$ resonances in ^{13}N was more extensive due to a very convenient beam-target combination. In addition to the lowest $T = 3/2$ state, resonances at 18.35 MeV ($\Gamma = 100$ keV, $\Gamma_0 = 25$ keV) and 18.96 MeV ($\Gamma = 15$ keV, $\Gamma_0 = 0.25$ keV) excitation energy in ^{13}N were observed. An analysis of the elastic $p+^{12}$C excitation functions [13] resulted in spin-parity assignments of $3/2^+$ for the 18.35 MeV state and $3/2^-$ or $7/2^+$ for the 18.96-MeV state. In spite of the fact that $\Gamma_0 = 25$ keV seems to be too large in comparison with the T-violating width found for the lowest $T = 3/2$ resonance, both these resonances were considered to have $T = 3/2$.

Excitation functions for the ^{12}C(p, $p'\gamma$) reaction were measured in Refs. [14,15]. The isospin-allowed proton decay of the $T = 3/2$ states to the 15.11 MeV ($T = 1$) state in ^{12}C was observed in these experiments. This reaction is more sensitive to $T = 3/2$ states than elastic scattering because of the isospin-allowed exit channel. It was found that the energy of the lower state appeared to be 18.45 MeV and not 18.35 MeV as in Ref. [13], whereas agreement on the excitation energy of the 18.97-MeV state was excellent. A large partial width for the proton decay of the 18.45-MeV state to the 15.11-MeV state in ^{12}C, as observed in Ref. [15], could be evidence for the $T = 3/2$ isospin (even though this decay is also allowed for $T = 1/2$ states), because the penetrability for this decay is rather low. Another important indication for a $T = 3/2$ isospin assignment to the state in question is the very low partial width for proton decay back to the ground state of ^{12}C. Unfortunately this partial width was not published. However, using data on the differential cross section for the ^{12}C(p, $p'\gamma$) reaction published in Ref. [15] we estimate that this partial width has to be less than 1 keV, in agreement with $\Gamma_0 = 0.24$ keV for the 15.06-MeV $T = 3/2$ state [13] and well below the Γ_0 partial width of 25 keV reported for the 18.35-MeV resonance in Ref. [13]. Consolidating all the above arguments, we conclude that the resonances at 18.35 MeV reported in Ref. [13] and at 18.45 MeV reported in Ref. [15] are two different resonances, and only the later one at 18.45 MeV is a good candidate for a $T = 3/2$ isospin assignment. This may be the isobaric analog state of one of the first four excited states in ^{13}B. The recommended width of this state reported in Ref. [3] is 66±8 keV, which makes it too broad for an $\ell = 2$ $T = 3/2$ state at this excitation energy in ^{13}N. However, both $\ell = 0$ and 1 orbital angular momenta are possible. Comparing the excitation energy of this state with the excitation energies of states used for the best fit to the ^{12}B+p data, and taking into account the fact that the excitation energy of the corresponding $T = 3/2$ states in ^{13}C should be slightly higher due to the Thomas-Ehrman shift, one can conclude that the $3/2^+$ state at 18.6 MeV can be considered as a good candidate for the isospin partner of the 18.45 MeV state in ^{13}N. However, the width of this state in our fit is 90 keV and it should be a factor of 2–3 larger for the corresponding state in ^{13}N due to a larger contribution of proton+^{12}C configuration and its higher energy above the isospin-allowed decay threshold (1.4 MeV in ^{13}N vs. 1.05 MeV in ^{13}C). Although it is not possible to make a definite conclusion based on the existing data, one may speculate that the 18.45-MeV state in ^{13}N corresponds to the $T = 3/2$, $\ell = 1$ negative-parity state.

The situation is more straightforward for the state at 18.97 MeV in ^{13}N. The excitation energies reported for this state in the ^{12}C$(p, p'\gamma)$ [15] and ^{12}C(p, p) [13] reactions are in good agreement. Its Γ_0 partial width is 0.22 or 0.30 keV [13], which agrees well with a $T = 3/2$ isospin assignment. A partial wave analysis made in Ref. [13] indicates that the spin-parity of this state is $3/2^-$ or $7/2^+$. The ^{12}B+p spectra (Fig. 7) shows a small irregularity that was described in our best R-matrix fit as a weak $\ell = 1$ $3/2^-$ state at 19.11 MeV. (Also identification of this state can only be considered as tentative.) Taking into account the Thomas-Ehrman shift for a state with $\ell = 1$, we can identify the $T = 3/2$, 19.11-MeV state in ^{13}C with the 18.97-MeV state in ^{13}N. The $7/2^+$ spin-parity assignment suggested as one of the possibilities in Ref. [13] cannot be made for the state because this would require $\ell = 2$, which does not produce the right shape of the excitation function.

Finally we should compare the present findings with the ^{13}B spectrum. Four states in the narrow excitation energy range from 3.48 to 3.71 MeV were found in the ^{11}B(t, p) reaction in Ref. [16]. Based on a plane-wave analysis of the angular distributions, positive parity was suggested for the 3.48- and 3.68-MeV states and negative parity for the 3.53- and 3.71-MeV states. (However, it was pointed out in Ref. [17] that it is difficult to obtain the values of the transferred orbital angular momenta from the practically similar angular distributions of the states in question, and additional data is needed to support the parity assignments in Ref. [16]. As will be clear from the discussion below our results agree with the positive parity assignment for the 3.48- and 3.68-MeV states made in Ref. [16].) The 3.48 MeV and 3.68 MeV states in ^{13}B were strongly populated in the single-neutron knockout reaction from ^{14}B [18]. No other states were observed, except for a possible state at 4.13 MeV with much lower cross section. It was suggested in Ref. [18] that this can be considered as evidence that the 3.48- and 3.68-MeV states have positive parity, as one would expect if one neutron is removed from the p shell in ^{14}B. (Removal of one neutron from the $1s$ shell would result in a higher excitation energy, and removal of a valence neutron from the sd-shell with unaltered core can only populate the ground state of ^{13}B.) One may also note that because the valence neutron in the ground state of ^{14}B is predominantly (89±3%) in the $2s1/2$ configuration [18], removal of a $1p1/2$ neutron, with subsequent coupling of the neutron hole to the $1p3/2$ proton hole in the 1^+ ground state of ^{12}B, would result in strong population of states with spin parities of $1/2^+$ and $3/2^+$. These considerations agree well with findings of this work which indicate presence of two strong $\ell = 0$, $T = 3/2$ states in ^{13}C at about 1 MeV above the proton decay threshold. We link these two states in ^{13}C with the 3.48- and 3.68-MeV states in ^{13}B, and suggest spin-parity assignment $1/2^+$ and $3/2^+$ for these states respectively.

As can be seen from Fig. 6, the 4.13-MeV state in ^{13}B and a group of four states at ∼5 MeV can be linked with the $T = 3/2$ states in ^{13}C observed in this work. (Although, only three $T = 3/2$ states were observed in ^{13}C at the excitation energy which corresponds to ∼5 MeV in ^{13}B.) We suggest a $3/2^-$ spin-parity to the 4.13-MeV state based on indirect arguments discussed above.

V. COMPARISON WITH THE SHELL-MODEL CALCULATIONS

To evaluate the quality of shell-model descriptions of the $T = 3/2$, $A = 13$ isobaric chain, we performed shell-model calculations using three different interactions: Millener-Kurath (MK, psd valence space) [19], WBT, and WBP ($spsdpf$ valence space) [20]. Pure 0, 1, and $2\hbar\omega$ excitations were considered. The calculations with the WBT and WBP interactions are identical to those performed in Ref. [18]. Shell-model codes COSMO [21] and OXBASH [22] were used. It is clear from Fig. 6 that the shell-model predictions depend strongly on the type of interaction used. However, there are some similar features. The first excited state appears to be a $2\hbar\omega, 3/2^-$ in all shell-model calculations, whereas experimental spin-parity assignment to this state, combining all available data, is most likely $1/2^+$. It is likely that the first $2\hbar\omega, T = 3/2$ state appears at 4.13 MeV in ^{13}B, at 19.11 MeV in ^{13}C (4.0 MeV above the 15.11 MeV analog of the ground state) and at 18.96 MeV in ^{13}N (3.9 MeV above the 15.06 MeV analog of the ground state). WBP and WBT interactions overbind this state by more than 1 MeV, but MK interaction overbinds it by only 0.5 MeV. All interactions predict two strong low-lying $\ell = 0$ states ($1/2^+$ and $3/2^+$). However, the splitting between these states is 160 keV, 1 MeV, and 570 keV for the MK, WBP, and WBT interactions, respectively. Again, the MK interaction seems to do a better job, as we find that the splitting between these states in ^{13}C is ∼200 keV. The group of states at 5.0 MeV (20.0 MeV excitation in ^{13}C), dominated by an $\ell = 2$ component, appears in all interactions but the MK interaction better describes the details of the level structure at this excitation energy. Although none of the shell-model calculations agree well with experiment it appears that the MK interaction produces more accurate results for the level structure of the $A = 13, T = 3/2$ system. However, it is worthwhile noting that it is still not possible to make a direct correspondence between shell-model and experimental levels even with the MK interaction.

VI. SUMMARY

A search for $T = 3/2$ states in ^{13}C in the 18.5–20.5 MeV excitation energy range was performed using the isospin-allowed ^{12}B+p elastic-scattering channel. Evidence for six new $T = 3/2$ states in this region was found, and tentative spin-parity assignments for these states are suggested. All these states have very small decay widths through isospin-violating channels, which supports the $T = 3/2$ isospin assignment. The dominant configurations of the levels are in qualitative agreement with shell-model predictions. However, there are significant disagreements with the relative excitation energies of the levels and level sequence compared with shell-model predictions. It was found that the Millener-Kurath interaction was the most adequate for the system studied.

Previous information on $T = 3/2$ states in ^{13}C and ^{13}N obtained in T-violating resonance scattering was discussed. We point out that none of the $T = 3/2$ states previously suggested in ^{13}C can be considered as such, except for the 15.11-MeV analog of the ^{13}B ground states. In ^{13}N, however, all three known $T = 3/2$ states are viable candidates for $T = 3/2$ isospin assignment (with some reservations discussed in the text).

We did not observe any evident anomalies which could be related with a manifestation of the $T = 1/2$ states. The collective influence of the $T = 1/2$ states was taken into account by an additional absorption, introduced through an imaginary phase in the R-matrix calculation. This result supports the idea that exotic nuclei can be studied through their isobaric analog states in resonant reactions induced by beams of neutron-rich nuclei.

Better experimental information on the level structure of the $T = 3/2$, $A = 13$ system is still needed. Although orbital angular momentum and parity assignments for the observed states are reliable, it was not possible to make a unique spin identification, which is a significant handicap of the present data. The most straightforward way to solve this problem is to measure the ^{12}N+p elastic and inelastic excitation function over a wide range of energies and angles. This approach would allow unique spin-parity assignments based on the angular distributions and the absolute values of the cross sections, as was demonstrated in Ref. [2].

It is reasonable to expect that application of *ab initio* approaches, such as Green's function Monte Carlo method (GFMC) [23] and large-scale no-core shell-model (NCSM) calculations [24,25] for a system of 13 nucleons may become possible in the near future. In fact, the excitation energy of the first $T = 3/2, 3/2^-$ state in ^{13}C has already been calculated using NCSM approach [26]. Another exciting theoretical development that seems to be applicable to a system of 13 nucleons is the coupled-cluster calculations [27,28]. It would be of great interest to evaluate the quality of predictions of these modern theoretical approaches for the light, relatively exotic $T = 3/2$, $A = 13$ system in which the cross-shell excitations determine the low-energy spectrum.

ACKNOWLEDGMENTS

The authors are very grateful to Alexander Volya and Alex Brown for useful discussions related to shell-model calculations and for their assistance in running shell-model codes COSMO and OXBASH. This work was supported by the National Science Foundation under grant numbers PHY03-54828, PHY04-57120, PHY04-56463, and PHY06-52591.

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