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Unbound States in ^{17}C Probed via Single-Neutron Removal from ^{18}C at 245 MeV/u

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Abstract. A study of unbound states in ^{17}C by means of one-neutron knockout from a fast moving ^{18}C beam at an energy of 245 MeV/nucleon on a carbon target was performed at the RIKEN-RIBF laboratory utilizing SAMURAI. The energy spectrum of unbound ^{17}C constructed from momentum vectors of the forward going beam velocity ^{16}C fragment and neutron covered an energy range of the decay neutron below about 6 MeV in the center of mass of ^{17}C*. The relative energy $E_{\rm rel}$ spectrum was characterized by two resonances at about 1.92 and 3.24 MeV in $E_{\rm rel}$ and a possible multiplet at around $E_{\rm rel} \sim 0.7$ MeV. Momentum distributions of the knockout residue for the $E_{\rm rel}$= 1.92 and 3.24-MeV states well matched to those of p-wave neutron removal, providing a model independent confirmation of negative parity assignments for these states. The proposed level scheme of ^{17}C was compared with a range of different shell-model predictions; it turned out that the YSOX shell-model interaction, employing the monopole-based universal interaction for the cross-shell two-body matrix elements and incorporating larger $\hbar\omega$ excitations, gave a consistent account of it, including the locations of the $1/2^-_1$ and $3/2^-_1$ cross-shell states.

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INTRODUCTION

There is currently a wide interest in investigating the structure of very neutron-rich nuclei. It is anticipated that various exotic properties are induced by large excess of neutrons and weak binding of valence neutrons [1]. The nucleon density distributions are modified drastically, which causes isospin inhomogeneity: a nucleus tends to be enlarged or diluted, and the structures of neutron halo and skin as well as enhanced cluster formation emerge. The modified mean field promotes drastic changes in shell structure, which induces increased possibility of altering magicity and of emergence of nuclear deformation in the ground state: a consequence of spontaneous symmetry breaking phenomena. Elevated Fermi energy of neutrons far above that of protons would modify the effects of Pauli blocking, and those of proton core polarization on the effective nucleon-nucleon interaction among the neutrons in the valence orbits, and enhance the coupling with continuum states.

Obtaining predictive effective interactions for nuclear shell model is one of the main issues in nuclear structure physics. For neutron-rich carbon isotopes with mass numbers $A \geq 15$, Fermi surfaces of protons and neutrons are located in different major shells: *p* shell for protons and *sd* shell for neutrons. In such a proton-neutron asymmetric system, determining reliable effective interactions encompassing the two major shells remains of a special difficulty. This is partly due to scarcity of experimental constraints. In addition, describing cross-shell states built on top of the *pn* asymmetric system, whose parity is opposite to that of the ground state (negative parity states for the above mentioned carbon isotopes), requires knowledge of a specific part of the cross-shell interaction involving neutron (and proton) particle-hole excitations across the major shell gap. The often not well constrained character of the relevant interaction, together with the required larger model space for computation, leads to an extra difficulty in the shell-model description of such states.

It has been recognized that the conventional shell model encounters difficulties in reproducing precise positions of the 2_1^+ states in ^{16,18,20}C [2], known, respectively, at 1.766(10) [3], 1.585(10), and 1.588(20) MeV [2]: the WBT interaction [4] within the *spsdpf* model space allowing $0\hbar\omega$ excitations (from the ground state) predicts them at 2.37, 2.16, and 2.18 MeV, respectively. One observes that the 2_1^+ energies are over-predicted by about 600 keV. A quick remedy for this has also been discussed in Ref. [2]: reducing the neutron-neutron two-body matrix elements (TBMEs) by 25%, and it has been argued that this might be attributed either to (1) the general diffused surface character of the neutron-rich nuclei, which leads to a weakening of the inter-nucleon interaction at the periphery of the system or (2) the difference in core polarization contributions of the $p_{1/2}$ orbit protons, such as that represented by the sort of $3p-1h$ core polarization diagram at the second order (for ^{18}O) of Kuo and Brown [5, 6] (the contributions are stronger in oxygen than in carbon). A shell-model study [7] provides evidence in favor of the latter explanation.

As for the negative parity states, predicting their positions in the shell model represents a notoriously difficult task. The cross-shell $1/2_1^-$ states in the ^{15,17,19}C nuclei are calculated at 1.96 (4.00), 1.04 (2.60), and 0.58 (2.19) MeV, respectively, with the (0–1)$\hbar\omega$ WBT ($\hbar\omega$ unrestricted WBT^X) interaction. Here WBT^X refers to the WBT interaction as used in the NUSHELLX@MSU code [8] with the model space restricted into *psd*. [1] For these cross-shell states, a large dependence of the calculated energy on the range of allowed $\hbar\omega$ excitations is seen. Experimentally the $1/2_1^-$ states had been identified at 3.103(4) [10] and 2.71(2) [11] for ^{15,17}C, respectively, prior to the present study. [2] It is here mentioned that the cross-shell states might have implications to astrophysical radiative neutron capture processes, as the latter are strongly influenced by the presence of dipole resonances [13].

In this study we have examined spectroscopy of the neutron-rich ^{17}C nucleus, including the lowest-lying cross-shell states, by means of the one-neutron knockout reaction from the ^{18}C beam at an energy of 245 MeV/nucleon, in an attempt to provide data which can be used to better constrain nuclear structure calculations, especially of shell model. The results of an accompanying study of excited unbound states in ^{19}C utilizing the ^{20}C beam can be found in Ref. [12]. This study firstly aimed to extend the realm of known spectroscopy of ^{17}C beyond the neutron threshold (for the bound region, see, e.g., recent lifetime measurements of bound excited states in ^{17}C [14]). This includes an independent confirmation of the character of negative parity states reported in a β-delayed neutron spectroscopy (βn) study of ^{17}B [11], where respective J^π assignments of $1/2^-$, $3/2^-$, and $(5/2^-)$ have been given to the observed states at E_x=2.71(2), 3.93(2), and 4.05(2) MeV, with the respective $\log ft$ values of 4.8(1), 4.9(1), and 6.0(1). Secondly, the study aimed to revisit the shell-model description of the states in ^{17}C and to examine the predictive capability of recently available shell-model calculations on them. In this report preliminary results are presented.

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[1] Unless otherwise stated NUSHELL@MSU [9] was used.

[2] The (0–3)$\hbar\omega$ WBT shell model predicts the location of $1/2_1^-$ in ^{15}C at 2.988 MeV, in good agreement with the experiment. The accompanying study [12] identified the $1/2_1^-$ state in ^{19}C at 2.89(10) MeV.

One-nucleon knockout processes from a neutron-rich (or proton-rich) nucleus offer a unique spectroscopic means with the following favorable features [15]: (1) they often exhibit large cross sections on the order of tens of mb, (2) knocked-out nucleon is democratically selected from valence orbits or below; hole-like states (both bound and unbound) can be populated efficiently, (3) cross sections leading to individual final states can be translated to spectroscopic factors, which reflect the occupancy of single-particle orbits, (4) momentum distributions of the knockout residue reflect the Fermi motion of the nucleon suddenly removed, and are sensitive to the orbital angular momentum (the *l* value) of the struck nucleon (thus the parity of the state created), (5) knockout of minor nucleon species can be used to create further exotic nuclear systems, including those outside of the drip line, and (6) theoretical tools based on the eikonal approximation and Glauber model, such as MOMDIS [16] and CSC_GM [17], and that based on the quasifree nucleon knockout formalism [18] are readily available. Applications of this technique to populate neutron unbound states (or nuclei) can be found in Refs. [19, 20, 21, 22, 23].

EXPERIMENT

The secondary beam of ^{18}C was produced by the BigRIPS fragment separator [24] at the RIBF laboratory in RIKEN [25] at 245 MeV/nucleon (at the middle of the reaction target) from a primary ^{48}Ca beam at 345 MeV/nucleon. A carbon target with a thickness of 1.8 g/cm^2 was used as the reaction target, where the one-neutron knockout processes occurred. The charged fragments, ^{16}C, were momentum analyzed by the SAMURAI spectrometer [26] and the decay neutrons, emitted at forward angles with beam like velocities, were detected by the NEBULA plastic scintillator hodoscope [27]. De-excitation γ rays emitted from the fragments were detected by the DALI2 NaI(Tl) scintillator array [28] surrounding the target.

The excitation energy in ^{17}C was obtained by the invariant mass method, where the momentum vectors of the decay products, $(E_f, \boldsymbol{p}_f)$ and $(E_n, \boldsymbol{p}_n)$ for the fragment and neutron, respectively, are used to calculate the invariant mass $M_{\rm inv}$ and relative energy $E_{\rm rel}$ by

$$M_{\rm inv} = \sqrt{(E_f + E_n)^2 - |\boldsymbol{p}_f + \boldsymbol{p}_n|^2}, \quad (1)$$

$$E_{\rm rel} = M_{\rm inv} - (M_f + M_n). \quad (2)$$

Here $M_f(M_n)$ is the mass of the fragment (neutron). The excitation energy E_x was calculated by $E_x = E_{\rm rel} + S_n + E_\gamma$, with S_n(=0.735(18) MeV [29]) the one-neutron separation energy of ^{17}C, and E_γ the energy of γ rays emitted from the fragment. The adopted experimental scheme was characterized by (1) a high detection efficiency for decay neutrons which inherently acquire high velocities in the laboratory, (2) large coverage of phase space of the final decaying system due to kinematical focusing of decay products toward forward angles, (3) large geometrical acceptance down to vanishing $E_{\rm rel}$ ensured by magnetic separation of charged fragments and neutrons, and (4) maintained good $E_{\rm rel}$ resolution well suited for spectroscopy.

RESULTS

Figure 1 shows a preliminary relative energy spectrum in ^{17}C obtained via the ^{12}C(^{18}C,^{17}C$^*\rightarrow^{16}$C + n + γ) reaction at 245 MeV/nucleon. Contributions arising from material other than the secondary target are subtracted. Geometrical acceptances are corrected considering the kinematics of sudden removal of the struck neutron. The distribution was fitted by four responses located at $E_{\rm rel}$=0.57(4), 0.81(5), 1.92(1), and 3.24(2) MeV, of which the $E_{\rm rel}$=0.57-MeV state was identified to be in coincidence with the de-excitation γ ray from ^{16}C(2^+_1) (the arrows in the inclusive $E_{\rm rel}$ spectrum in Fig. 1 and in its inset indicate the position of this state). The excitation energy of the $E_{\rm rel}$=0.57-MeV state is calculated to be E_x=3.07(5) MeV, in good agreement with the $9/2^+_1$ state at 3.10 MeV observed by the ^{14}C(^{12}C, ^{9}C)^{17}C reaction [30]. The right shoulder of this state needed to be filled by, at least, a previously unknown strength at $E_{\rm rel}$=0.81 MeV (E_x=1.55(6) MeV), which we tentatively assign as $5/2^+_2$ from a comparison with shell-model calculations (later described). The $E_{\rm rel}$=1.92 and 3.24-MeV states (at E_x=2.66(2) and 3.98(2) MeV, respectively) most-likely correspond, respectively, to the $1/2^-_1$ and $3/2^-_1$ states reported in the βn study [11]. The longitudinal and transverse momentum distributions of these states were deduced and it turned out that they are consistent with p-wave neutron knockout. This provides a model independent confirmation of negative parity assignments for these states.

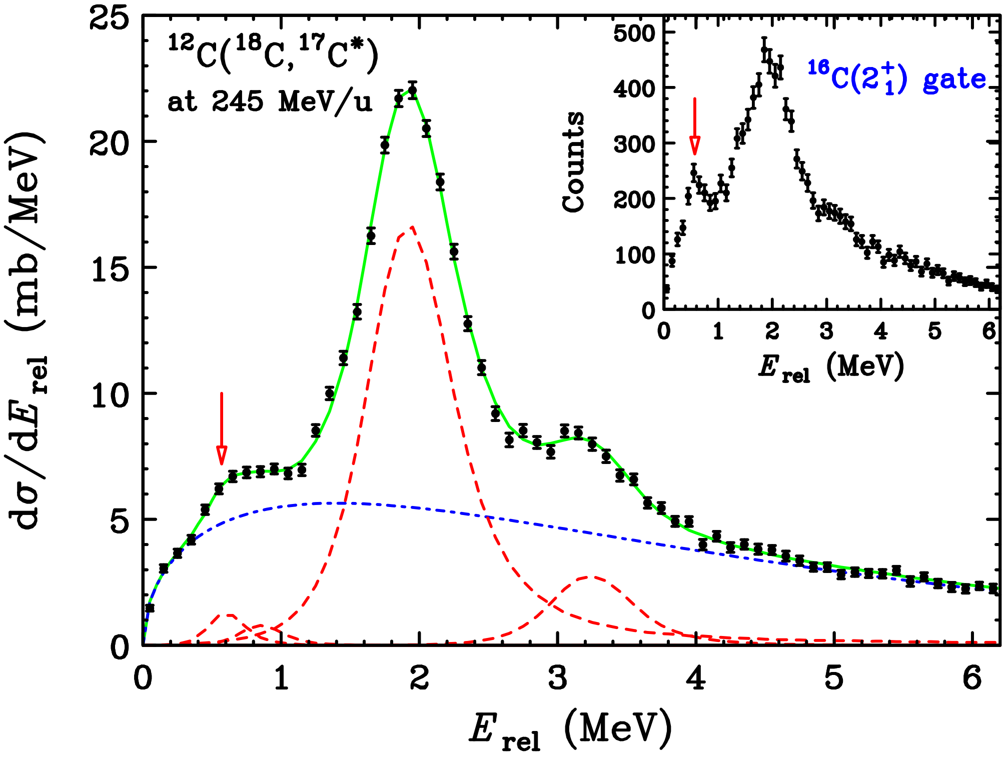

FIGURE 1. Preliminary relative energy spectrum of ^{17}C reconstructed by the momentum vectors of ^{16}C and neutron in the ^{12}C(^{18}C,^{17}C*) reaction at 245 MeV/nucleon. Inset shows the relative energy spectrum obtained in coincidence with γ rays forming the photo peak (E_γ = 1.4 – 2.0 MeV) of the de-excitation γ transition from ^{16}C(2_1^+). Red arrows indicate the position of the γ-ray emitting E_{rel}=0.57-MeV peak. A background shape of $aE_{\mathrm{rel}}^{0.53}\exp(-bE_{\mathrm{rel}})$ was adopted.

DISCUSSION

Figure 2 shows a comparison of shell-model spectroscopy in ^{17}C with the experiment. The theoretical excitation energy is taken to be the energy interval measured from the lowest-lying state whose J^π is the same as that known for the ground state of ^{17}C: $J^\pi_{\mathrm{g.s.}}$=3/2$^+$. WBM refers to WBP [4] with its USD part reduced appropriately [9]. YSOX is an interaction in full *psd* model space including (0 – 3)$\hbar\omega$ excitations [32], with its cross-shell part constrained by the monopole-based universal interaction V_{MU} [33]. The NUSHELLX@MSU code [8] was used for the calculations with this interaction. CCEI stands for Coupled-Cluster Effective Interaction and refers to the nonperturbative calculations of Ref. [34] based on chiral two-plus-three nucleon interactions and the Coupled-Cluster Model.

The 1.55-MeV state did not have any counterpart in the shell-model spectroscopy except for $5/2_2^+$; an assignment of $5/2_2^+$ to this state will be appropriate. The WBM interaction, which well explains the 2_1^+ energies of neutron-rich even carbon isotopes [2], fails in reproducing the positions of $5/2_2^+$, $7/2_1^+$, and $9/2_1^+$ in ^{17}C: calculated energies are compressed as compared to the experiment, and, in most cases, to the other calculations. The over-predicted 2_1^+ energies by the shell model, as mentioned above, may thus not be uniquely explained by the diffused surface character of neutron-rich nuclei (and thus by the weakened inter-nucleon interaction in such a system), because if this applies, we could observe a better agreement in predicted and experimental spectroscopy of positive parity states in odd carbon isotopes as well with WBM. The predicted energy of $1/2_1^-$ by WBM comes close to the experiment as compared to WBT, which is in line with the discussion of Ueno *et al.* [11]. It, however, is still inappropriate to fully explain the observed location of E_x=2.66 MeV. YSOX, on the other hand, provides a good account of it (and also of $3/2_1^-$). The good explanation of the locations of $1/2_1^-$ in ^{15,19}C by YSOX has also been noted in Ref. [12]. This is likely due to its reasonably tuned cross-shell parts, such as the off-diagonal cross-shell interaction, $\langle pp|V|sdsd\rangle$ [35], and to the adopted larger model space in terms of $\hbar\omega$ excitations. CCEI provides a good account of the spectroscopy of positive parity states. This approach, however, currently does not produce predictions on negative parity spectroscopy due to

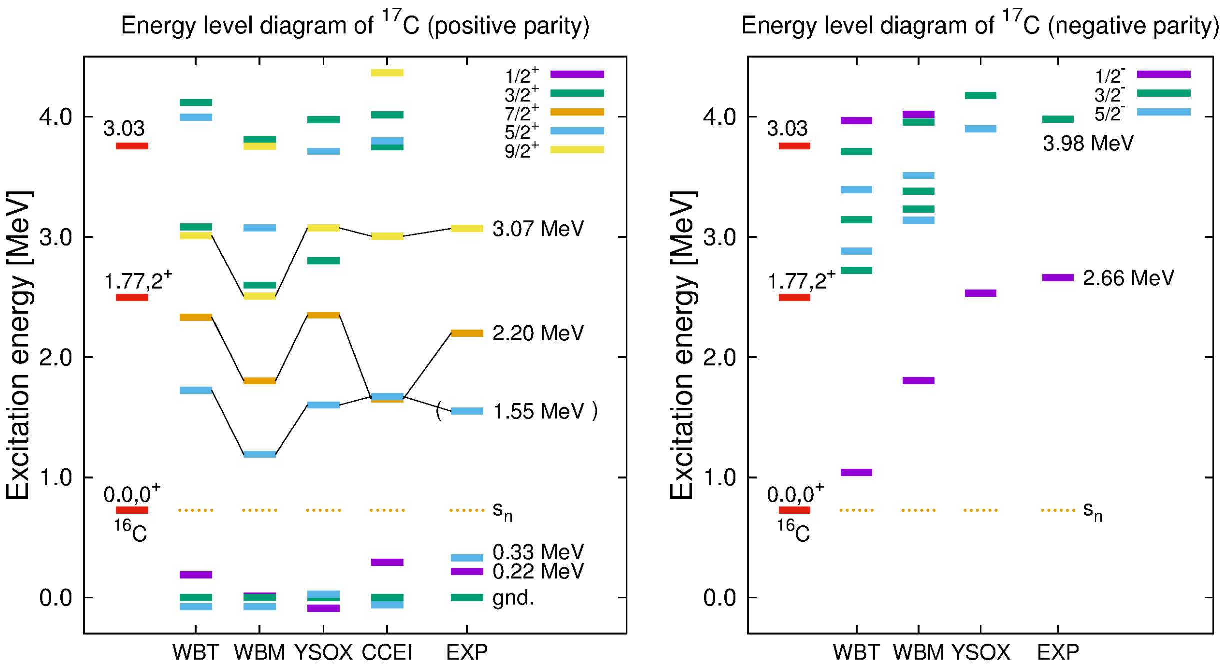

FIGURE 2. Shell-model excitation energy spectrum in ^{17}C as compared to the experiment. Left (right) panel is for positive (negative) parity states. Theoretical energies are taken to be the energy interval from the $3/2_1^+$ state. Experimental energies for bound states are taken from Ref. [14] and that of $7/2_1^+$ from Ref. [31], while others are from this study. The left most column in each panel displays the experimental spectrum of ^{16}C above the neutron threshold of ^{17}C. See text for details of the shell-model calculations.

computational limitations.

CONCLUSION

One-neutron knockout processes of a ^{18}C beam at 245 MeV/nucleon were exploited, taking advantages of the scheme of inverse kinematics, to populate several neutron unbound states in ^{17}C. The p-wave character of the E_x=2.66 and 3.98-MeV states, formerly reported as $1/2_1^-$ and $3/2_1^-$, respectively, from a βn study [11], was confirmed from the new measurement of momentum distributions of the knockout residue. Possible indication of the presence of the $5/2_2^+$ state at E_x=1.55 MeV was obtained for the first time. Known spectroscopy of the ^{17}C nucleus was compared with a range of shell-model predictions. The prescription to reduce the TBMEs of the USD part in WBT(P), introduced to explain the 2_1^+ positions in the neutron-rich carbon isotopes, had an effect to compress the calculated positive parity spectrum with odd spins, and seemed not to be fully supported by the present comparison in ^{17}C. The YSOX Hamiltonian, developed from the monopole-based universal interaction, provided a consistent account of the measured spectroscopy, including the locations of the cross-shell $1/2_1^-$ and $3/2_1^-$ states.

The energies of these cross-shell states reflect the shell gap at the neutron number of N=8. Identifying such states in the higher and lower Z nuclei nearby (such as ^{18}N [36] and ^{16}B [37, 38]) provides an idea about how the shell gap migrates along the isotonic chains in the vicinity of the relevant neutron drip line and beyond. The information provides stringent testing grounds of modern structure theories, forming an interesting subject of forthcoming investigations.

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