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Spectroscopy of ^{17}C via one-neutron knockout reaction

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Abstract. A spectroscopic study of ^{17}C was performed via the one-neutron knockout reaction of ^{18}C on a carbon target at RIKEN-RIBF. Three unbound states at excitation energies of 2.66(2), 3.16(5), and 3.97(3) MeV (preliminary) were observed. The energies are compared with shell-model calculations and existing measurements to deduce their spin-parities. From the comparison, the states at 2.66(2) and 3.97(3) MeV are suggested to be $1/2^-$ and $3/2^-$, respectively. From its decay property, the state at 3.16(5) MeV is indicated to be $9/2^+$.

1 Introduction

The unique features of neutron-rich nuclei, such as non-canonical shell structures differing from those near stability, have been a subject of intensive studies in both theory and experiment. Among the neutron-rich nuclei, neutron-rich carbon isotopes have attracted particular attention in recent years

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due to their anomalous level structures. For example, the ground state spin-parities (J^π) of ^{15,17,19}C nuclei, $1/2^+$, $3/2^+$, and $1/2^+$, do not follow naive shell-model expectations. The 2^+ excitation energy, $E_x(2_1^+)$ = 1588(20) keV, of $^{20}C_{14}$ turned out to be not much different from that of neighboring even-even $^{18}C_{12}$ of 1585(10) keV [1]. This migration of the 2_1^+ energy is distinct from that of oxygen isotopes, where $E_x(2_1^+)$ exhibits a sudden jump at $^{22}O_{14}$, signifying the emergence of the shell gap at the neutron number $N = 14$ [2]. The breakdown of the $N = 14$ gap in carbon isotopes has been ascribed to the near degeneracy of the $s_{1/2}$ and $d_{5/2}$ orbits and to the reduced neutron-neutron interaction when going from oxygen to carbon nuclei [1]. Detailed mechanisms and interplay of these effects, however, remain to be answered, requiring further studies. Here we present a spectroscopic study on a neutron-rich odd carbon isotope, ^{17}C, performed to furnish information on energy levels, especially above the neutron threshold. To populate neutron unbound states in ^{17}C, the one-neutron knockout reaction of ^{18}C on a carbon target was utilized.

2 Experiment

The experiment was performed at the Radioactive Isotope Beam Factory (RIBF) at RIKEN, operated by the RIKEN Nishina Center and the Center for Nuclear Study of the University of Tokyo, using the SAMURAI (Superconducting Analyser for MUlti particles from RAdio Isotope beams) spectrometer [3] during the first physics runs using the apparatus. For the spectroscopy of ^{17}C through the one-neutron knockout reaction from ^{18}C, beam particles were identified by the $B\rho$-TOF-ΔE method and the ^{18}C beam was selected. The ^{18}C beam with the mid-target energy of 245 MeV/nucleon and a momentum spread of ±3% impinged on a carbon reaction target having a thickness of 1.8 g/cm^2. The beam intensity was about 2300 pps and the mass resolution was $A/\Delta A$ = 770 in σ.

The unbound states in ^{17}C produced by one-neutron knockout of ^{18}C immediately decayed into a ^{16}C fragment and a neutron. Downstream of the target, the charged particles were bent by a superconducting dipole magnet having a central magnetic field of 3 T. They were also identified by the $B\rho$-TOF-ΔE method and the ^{16}C fragment was identified in terms of both charge and mass. The fragment mass resolution was $A/\Delta A$ = 250 in σ. The momentum vector of the neutron was obtained by the position and timing information from the neutron hodoscope, NEBULA, consisting of 120 modules of plastic scintillators for neutron detection (NEUT) and 24 modules of plastic scintillators for charged-particle veto (VETO). For NEUT, TOF resolution was 270 ps for a flight length of around 11 m. A γ-ray detector array, DALI2 [4], having 140 blocks of NaI(Tl) scintillators surrounded the target to measure γ rays emitted from the excited fragments.

3 Results and Discussion

The energies of the unbound states in ^{17}C were reconstructed by the momentum vectors of the ^{16}C fragment and neutron utilizing the invariant mass method. As preliminary results, three unbound states at the relative energies of 0.66(5), 1.92(1), and 3.23(3) MeV corresponding to the excitation energies (E_X) of 3.16(5), 2.66(2), and 3.97(3) MeV, respectively, were observed. The 3.16-MeV state was observed to decay into the 2^+ state in ^{16}C at 1.760(3) MeV [5]. The states at 2.66 and 3.97 MeV are associated with p-wave neutron knockout, as evidenced by their momentum distributions (both longitudinal and transverse ones) which are well described by the Glauber model calculations for L = 1 [6], and correspond well to the reported $1/2^-$ [2.71(2) MeV] and $3/2^-$ [3.93(2) MeV] states [7], respectively.

Fig. 1 compares the measured level energies with existing data [7–9] and shell-model calculations, separately for both negative (a) and positive (b) parity states. The J^π of the state at 3.16 MeV is not

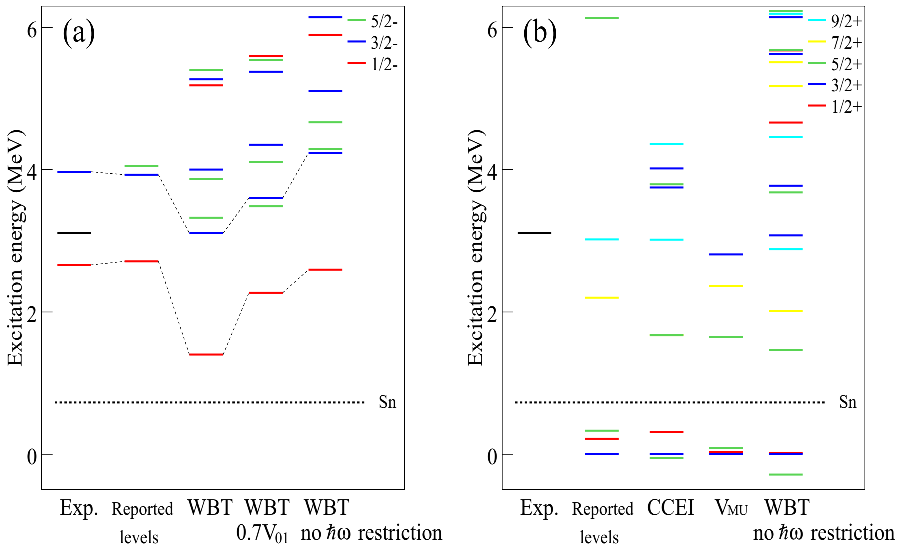

Figure 1. Negative (a) and positive (b) parity states in ^{17}C. "Exp." refers to the states observed in this study. For others see the text.

definitely known and this state is plotted in both panels of Fig. 1 in black. "WBT" and "WBT 0.7V$_{01}$" refer to the calculations using the WBT interaction [10] within the 1$\hbar w$ basis and the *p*-*sd* model space and those with reduced two-body matrix elements (by multiplying a factor 0.7) for the $J = 0$ and $T = 1$ channels [7], respectively. "WBT no $\hbar w$ restriction" provides energies from the NuShellX code [11] which can perform $\hbar w$ unconstrained calculations. Calculations utilizing the coupled-cluster effective interaction [12] and the monopole based universal interaction in the *p*-*sd* model space [13] are denoted as "CCEI" and "V$_{MU}$", respectively.

Ueno et al. [7] reported that the $1/2^-$ energy is underpredicted by about 1 MeV with "WBT", while such an underprediction is significantly remedied with "WBT 0.7V$_{01}$". The present "WBT no $\hbar w$ restriction" reproduces the energy of the $1/2^-$ state well together with that of $3/2^-$. Concerning the "WBT no $\hbar w$ restriction" predictions for negative parity states, there is no candidate for the 3.16-MeV state. This state, instead, has two candidate states, $9/2^+$ and $3/2^+$, in the positive parity state diagram, Fig. 1 (b). In an attempt to clarify the nature of this state, its decay property was examined within the shell model. This state has been observed to populate predominantly the 2^+ state of ^{16}C [5]. For the $3/2^+$ assumption, there are two routes for its decay, namely via *s*-wave and *d*-wave neutron emissions. From a simple estimate for the partial width (Γ), assuming that it is proportional to the product of the spectroscopic factor (C^2S) for decay, the wave number ($k = \sqrt{2\mu E_{\rm decay}}/\hbar c$), the radius of the decay daughter (R), and the transmission through the centrifugal barrier (v_l) [14] as

$$\Gamma \propto C^2S \cdot k \cdot R \cdot v_l, \tag{1}$$

we obtain that 97.5% of the decay is induced by *s*-wave. Here $E_{\rm decay}$ is the decay energy and μ is the reduced mass of the decay products. For this *s*-wave decay, the single-particle resonance width is predicted as 4.84 MeV [14]. A resonance having a width of this order will be hardly visible as a distinct peak structure. For d-wave decay, the single-particle width is calculated as 0.03 MeV [14]. The $9/2^+$ assignment for the 3.16-MeV state, thus, remains as a plausible solution (a $9/2^+$ state can decay to $^{16}C(2^+)$ only through the d-wave neutron emission). In one-neutron knockout from ^{18}C, the $9/2^+$ state is not populated via one-step processes; $9/2^+$ orbit occupancy of neutrons is expected to be zero. Multiple step processes, such as (a) inelastic excitation of ^{18}C followed by sequential decay into the $9/2^+$ state in ^{17}C and/or (b) initial population of $^{18}C(2^+)$ followed by $d_{5/2}$ neutron knockout, might be responsible for the population of the $9/2^+$ state.

4 Summary

Three unbound states at E_x = 2.66(2), 3.16(5), and 3.97(3) MeV in ^{17}C were observed by the one-neutron knockout reaction of ^{18}C using the SAMURAI spectrometer in RIBF at RIKEN. While the reported shell-model calculation with the WBT interaction had to be carried out using the two-body matrix elements of the particles within the *sd* orbits to obtain a proper excitaion energy spectrum for the observed negative parity states in ^{17}C, the calculation utilizing the WBT interaction without $\hbar w$ restriction in the model space provided an appropriate description of them. The state at 3.16 MeV is suggested to be a $9/2^+$ state from an examination of its decay property.

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