



One-neutron knockout reaction of ^{17}C on a hydrogen target at 70 MeV/nucleon



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ABSTRACT

First experimental evidence of the population of the first 2^- state in ^{16}C above the neutron threshold is obtained by neutron knockout from ^{17}C on a hydrogen target. The invariant mass method combined with in-beam γ -ray detection is used to locate the state at 5.45(1) MeV. Comparison of its populating cross section and parallel momentum distribution with a Glauber model calculation utilizing the shell-model spectroscopic factor confirms the core-neutron removal nature of this state. Additionally, a previously known unbound state at 6.11 MeV and a new state at 6.28(2) MeV are observed. The position of the first 2^- state, which belongs to a member of the lowest-lying p - sd cross shell transition, is reasonably well described by the shell-model calculation using the WBT interaction.

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Much of our knowledge on quantum nature of atomic nuclei comes from studies of nuclear reactions in which an energetic beam of one nuclear species collides with a target made of another. Among various collision processes, the nucleon knockout reaction has become recognized as one of the most sensitive tools for spectroscopic studies, especially for nuclei away from the stability line, which include even those beyond the drip line. The knockout residue produced by removing a nucleon (or nucleons) from a fast moving beam particle, which impinges on a light target fixed in the laboratory, is observed in inverse kinematics by a detector placed in forward hemisphere efficiently. The removed nucleon(s) will be selected democratically from the valence space, allowing states with unique, often rarely accessible configurations

to be populated in this process. The final state in the residue is identified by tagging de-excitation γ rays [1–3] (see also references in Ref. [4]) and by observing decay neutrons and constructing the invariant mass [5–12]. For one-nucleon knockout case, the momentum spread of the residue reflects the Fermi motion of the nucleon suddenly removed, and is sensitive to the orbital angular momentum (the l value) of the struck nucleon. Furthermore, the cross sections leading to individual final states relate to the occupancy of single-particle orbits, providing a link to details of the nuclear structure.

The present study aims at exploring unbound states in ^{16}C through an application of the one-neutron knockout technique to a ^{17}C beam impinged on a proton target, for which simple reaction mechanisms are expected. Focus is placed in a search of lowest-lying cross shell transitions, the location of which reflects the shell gap between p and sd orbits. The neutron-rich carbon (C) isotopes have attracted attention as they often exhibit unique features: none of the odd mass C (heavier than ^{13}C) has the ground-state spin parity of $J_{g.s.}^\pi = 5/2^+$, the values which are expected from a naive shell model. There has been a debate about a reduced E2 transition strength (small proton collectivity)

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for the 2_1^+ state in ^{16}C [13–18]. There is evidence for neutron halo formation for ^{15}C [19], ^{19}C [20], and ^{22}C [21,22]. For some, if not all, of these features, nuclear deformation may play a key role, which occurs in this mass region due to near degeneracy of the $\nu d_{5/2}-\nu s_{1/2}$ orbits: neutrons in these orbits can gain energy by breaking spherical symmetry (the Jahn–Teller effect) [23]. The effect of nuclear deformation will further be signified by large quadrupole transition strengths [24,25] and by a reduction of the major p – sd shell gap [26–28]. A recent β -delayed neutron emission study of ^{17}B [29] has reported low-lying negative parity states in ^{17}C , among which the lowest one was the $J^\pi = 1/2^-$ state at the excitation energy of $E_x = 2.71(2)$ MeV. The energy of this state, reflecting the p – sd shell gap, turned out to be lower than those of neighboring odd mass C isotopes: $E_x = 3.10$ MeV for the $1/2_1^-$ state in ^{15}C and $E_x = 3.09$ MeV for the $1/2_1^+$ state in ^{13}C [30]. This might indicate an onset of the p – sd shell gap quenching towards heavier C isotopes. To examine this picture in more detail it is worthwhile to accumulate data on cross shell transitions in neighboring isotopes. This Letter reports on new relevant spectroscopic information on ^{16}C in its unbound E_x region. Besides, based on the parallel momentum distribution of the core fragment populated in a final state, it is demonstrated that the width of the distribution provides a good measure of the l value (and thus the parity) of the state populated; for neutron knockout involving a proton target, this has previously been shown based on the transverse momentum distributions in the $^1\text{H}(^{18}\text{C}, ^{17}\text{C}^*)$ [31] and $^1\text{H}(^{14}\text{Be}, ^{13}\text{Be}^*)$ [8] reactions with the aid of elaborate reaction mechanism calculations.

Despite relative proximity to stability, information on energy levels of ^{16}C , particularly that above the neutron threshold (the neutron separation energy of ^{16}C is $S_n = 4.250(4)$ MeV [32]), has been limited. This is partially due to ineffectiveness of β decay for this particular nucleus, as recognized by the absence of a parent nucleus (^{16}B is particle unstable). Early spectroscopic studies on ^{16}C utilized binary reactions involving transfers of neutrons. The $^{14}\text{C}(t, p)^{16}\text{C}$ two-neutron transfer studies [33–36] have investigated levels below 7 MeV, including six bound states and an unbound state at 6.11 MeV. Since the ground state of ^{14}C is characterized by neutron p -shell closure, the states populated mostly involved configurations with two sd -shell neutrons, $(1s0d)^2$. The $^{13}\text{C}(^{12}\text{C}, ^9\text{C})^{16}\text{C}$ three-neutron transfer study [37] has reported 14 more states up to $E_x = 17.4$ MeV, including states with more complex configurations. Due to kinematical matching [37] states with high angular momenta were favorably populated. Combining information from the recent $^{15}\text{C}(d, p)^{16}\text{C}$ reaction study using a radioactive ^{15}C beam [17], sound J^π assignments have been available for bound states. For unbound states only the 8.92-MeV level has received a firm assignment of 5^- [37]. Two earlier one-neutron knockout studies on ^{17}C using Be targets focused on transitions leading to bound final states in ^{16}C by means of in-beam γ -ray spectroscopy [3,38]. They provided information not only on excited states of ^{16}C but also on ground state properties of ^{17}C , e.g., the spin parity, $J_{g.s.}^\pi(^{17}\text{C}) = 3/2^+$, and no halo formation in spite of the remarkable low neutron separation energy of $S_n = 0.727(18)$ MeV [32] due to a high angular momentum of $l = 2$ for the valence neutron.

The experiment was performed at the RIPS facility [39] of RIKEN. Details of the setup are provided in Refs. [25,40], and a preliminary report of this work has been presented in Ref. [41]. The ^{17}C beam was produced from a 110-MeV/nucleon ^{22}Ne beam which impinged on a 6-mm-thick Be target. The typical ^{17}C beam intensity was 10.2 kcps with a momentum spread of $\Delta P/P = \pm 0.1\%$. The beam profile was monitored by a set of parallel-plate avalanche counters (PPACs) placed upstream of the experimental target. The target was pure liquid hydrogen [42] contained in a

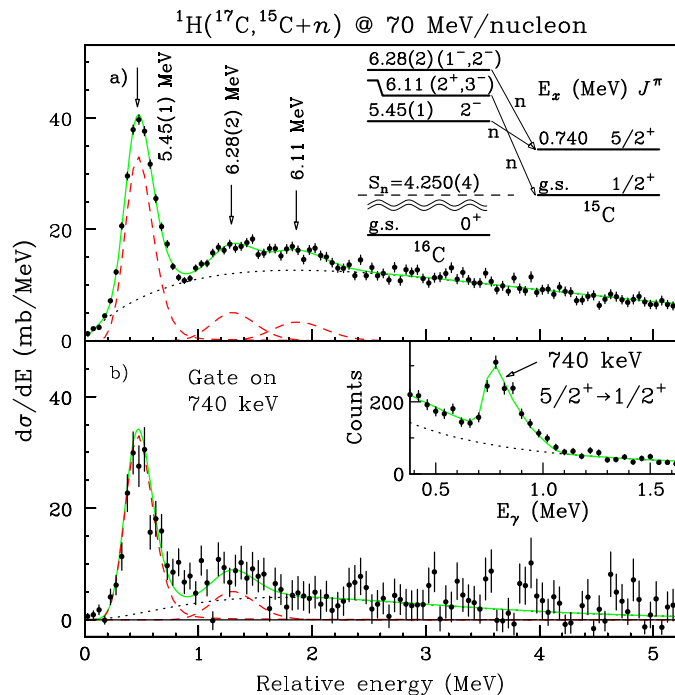


Fig. 1. (Color online.) Relative energy spectra for the (a) $^1\text{H}(^{17}\text{C}, ^{15}\text{C} + n)$ and (b) $^1\text{H}(^{17}\text{C}, ^{15}\text{C}(5/2^+; 0.74 \text{ MeV}) + n)$ one-neutron knockout reactions at 70 MeV/nucleon. Shown in the inset of panel (b) is the Doppler-corrected energy spectrum of γ rays emitted from ^{15}C . Neutron coincidence is required for this spectrum. Green solid lines represent the results of the fit; dotted lines assumed background; red dashed lines extracted individual resonances. A decay scheme for states populated is shown in panel (a).

cylindrical cell: 3 cm in diameter, 120 ± 2 mg/cm² in thickness, and having 6- μm -thick Havar foils for the entrance and exit windows. The average energy of ^{17}C at the middle of the target was 70 MeV/nucleon. The target was surrounded by a NaI(Tl) scintillator array used to detect γ rays from charged fragments. The fragment was bent by a dipole magnet behind the target, and was detected by a plastic counter hodoscope placed downstream of the magnet. The ΔE and time-of-flight (TOF) information in the hodoscope was used to identify the Z number of the fragment. The trajectory was reconstructed by a set of multi-wire drift chambers (MWDCs) before and after the magnet, which, together with TOF, gave mass identification. Neutrons were detected by two walls of plastic scintillator arrays placed 4.6 and 5.8 m downstream from the target. The neutron detection efficiency was $24.1 \pm 0.8\%$ for a threshold setting of 4 MeVee. The relative energy (E_{rel}) of the final system was calculated from momentum vectors of the charged fragment and the neutron. In deducing the fragment vector, information on the impact point on target in transverse directions (determined by the upstream tracking detectors) was taken into account together with hit information within the MWDC placed behind the target. Neutron coincidence events were classified in terms of E_{rel} and the Fermi momentum of the struck neutron k_3 . In the sudden approximation, the latter corresponds to the transferred momentum to the knockout residue (^{16}C). The detector acceptance was evaluated by a Monte Carlo simulation as a function of E_{rel} and k_3 .

Fig. 1 shows relative energy dependence of cross sections for the (a) $^1\text{H}(^{17}\text{C}, ^{15}\text{C} + n)$ and (b) $^1\text{H}(^{17}\text{C}, ^{15}\text{C}(5/2^+; 0.74 \text{ MeV}) + n)$ reactions at 70 MeV/nucleon. Background contributions measured by an empty target were subtracted. Error bars are statistical ones. Shown in the inset of Fig. 1(b) is the “Doppler-corrected” energy spectrum for γ rays emitted from the decay product nucleus ^{15}C . A peak around $E_\gamma = 0.8$ MeV arises from the decay of the

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