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Study of ^{19}C by One-Neutron Knockout

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Abstract. The spectroscopic structure of ^{19}C, a prominent one-neutron halo nucleus, has been studied with a ^{20}C secondary beam at 290 MeV/nucleon and a carbon target. Neutron-unbound states populated by the one-neutron knockout reaction were investigated by means of the invariant mass method. The preliminary relative energy spectrum and parallel momentum distribution of the knockout residue, ^{19}C*, were reconstructed from the measured four momenta of the ^{18}C fragment, neutron, and beam. Three resonances were observed in the spectrum, which correspond to the states at E_x = 0.62(9), 1.42(10), and 2.89(10) MeV. The parallel momentum distributions for the 0.62-MeV and 2.89-MeV states suggest spin-parity assignments of $5/2^+$ and $1/2^-$, respectively. The 1.42-MeV state is in line with the reported $5/2^+_2$ state.

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1 Introduction

Neutron-rich nuclei exhibit exotic features such as quenching of a shell gap or advent of a new magic number. Such a structure is caused by ascending or descending single-particle orbits from their original location in stable nuclei, and cannot be explained by the conventional shell model. Recently, three-body forces [1] and tensor forces [2] have been introduced to shell model calculations for neutron-rich nuclei. The lack of spectroscopic information of near-drip-line nuclei, however, is an obstacle to verifying those state-of-the-art theories. In this study, the level structure of ^{19}C has been investigated via the one-neutron knockout reaction.

^{19}C is the heaviest odd carbon isotope. Its $1/2^+$ ground state has a one-neutron halo structure [3]. Two bound states, $3/2^+_1$ and $5/2^+_1$, were reported from an in-beam γ-ray spectroscopy study [4], while the $5/2^+_2$ state at $E_x = 1.46(10)$ MeV in neutron-unbound continuum was observed in a (p, p') experiment [5]. Recent knockout measurements left room for a conjecture that the $5/2^+_1$ state is unbound [6, 7]. The present study addresses the issue whether or not the $5/2^+_1$ state is bound.

2 Experiment and Analysis

The experiment was carried out at the RI Beam Factory [8] (RIBF) at RIKEN Nishina Center for Accelerator-Based Science. A ^{20}C beam, separated by the BigRIPS separator [9, 10], produced using a ^{48}Ca primary beam at 345 MeV/nucleon, had an average intensity of 190 cps and the momentum acceptance of $\Delta P/P = \pm 3\%$. It impinged on a carbon target with a thickness of 1.8 g/cm^2 and produced ^{19}C isotopes by the one-neutron knockout reaction. The mid-target energy was 290 MeV/nucleon.

^{19}C populated in a neutron-unbound state decayed into a charged fragment, ^{18}C, and a neutron, which were measured by the SAMURAI spectrometer [11]. The charged fragment, separated by the dipole magnet, was detected by a plastic-scintillator hodoscope and two drift chambers (FDCs) placed before and after the magnet. The $B\rho$-TOF-ΔE method was used for the identification of the fragment. Its momentum was determined with the $B\rho$ and the direction reconstructed by the drift chamber. Neutron Detection System for Breakup of Unstable Nuclei with Large Acceptance (NEBULA) was used to determine the momentum vector of the decayed neutron using the TOF method. The detection efficiency of NEBULA was 31.6% for a threshold of 6 MeVee, measured by using the ^{7}Li$(p, n)^7$Be(g.s.+0.43 MeV) reaction at $E_p = 250$ MeV. DALI2 [12], the γ-ray detector array, surrounded the secondary target to observe the de-excitation γ rays from the charged fragment.

The relative energy ($E_{\rm rel}$) of the knockout residue (^{19}C*) was reconstructed from the four momenta of the ^{18}C fragment and decayed neutron. The background was subtracted by using data taken with an empty target. The geometrical acceptance was estimated with a Monte Carlo simulation taking into account the beam profile and geometry of the setup. Single Briet-Wigner shape functions were used to extract the parameters of the resonances with an empirical distribution for the non-resonant continuum in the fitting analysis. Response functions were generated by a simulation to take into account the experimental resolution, which was estimated to be $\Delta E_{\rm rel} \approx 0.40\sqrt{E_{\rm rel}}$ MeV in FWHM. The excitation energy (E_x) of the populated state corresponding to a resonance centered at $E_{\rm rel}$ is obtained by the following equation: $E_x = E_{\rm rel} + S_n + E^*$, where S_n is the one-neutron separation energy of ^{19}C (0.58(9) MeV [13]) and E^* is the excitation energy of the daughter nucleus. Note that no γ rays in coincidence with any of the observed resonances were identified for the ^{18}C + n channel.

The parallel momentum ($p_{||}$) of ^{19}C* was reconstructed as well, which is a useful measure of the orbital angular momentum (l) of the knocked-out nucleon. By comparing the experimental distribution with the theoretical ones, the spin-parity of the populated state of ^{19}C was determined. The theoretical distributions for various l values were calculated by the code MOMDIS [14], which is based on the static density limit of the eikonal model. The core- and neutron-target S-matrices were obtained using the density-folding method using the NN profile function. The density of the carbon target was taken to be of a Gaussian form with a point-nucleon root-mean-square (rms) radius of 2.32 fm. The nucleon density distribution of the ^{19}C core was estimated from Hartree-Fock calculations using the SkX interaction [15]. For the nucleon-nucleon profile function, zero-range effective nucleon-nucleon interaction was used [16]. Neutron single-particle wave functions were calculated using the Woods-Saxon potential with a diffuseness $a_0 = 0.7$ fm and a reduced radius r_0 that was calculated to fulfill the relationship [17]: $r_{\rm sp} = \sqrt{A/(A-1)} r_{\rm HF}$ at the HF calculated binding energy of each orbit, where $r_{\rm sp}$ is the rms radius of the single-particle wave function and $r_{\rm HF}$ is the rms radius of the orbit deduced by the HF calculation for the beam nucleus. The calculated distributions were convoluted with an experimental resolution of 28 MeV/c in rms.

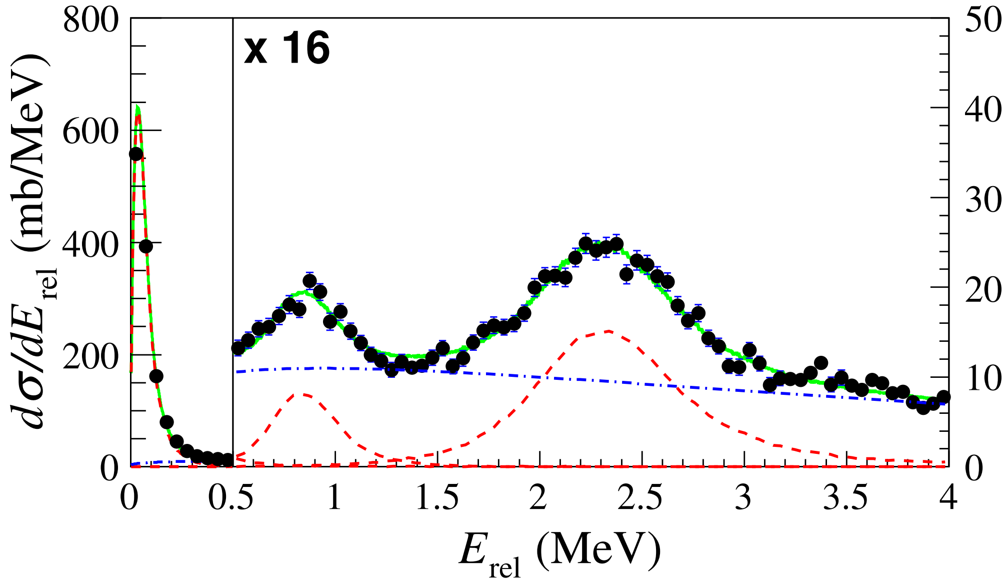

Figure 1. Preliminary relative energy spectrum of the ^{18}C + n system (*solid circle*) with statistical errors. The dashed and dot-dashed lines are the results of the fits for the resonances and a background component, respectively. The different scales for the y-axis are used below and above $E_{\rm rel} = 0.5$ MeV.

3 Results and Discussion

Figure 1 shows the preliminary $E_{\rm rel}$ spectrum for the reaction of C(^{20}C,^{18}C + n), which was described using three resonances at $E_{\rm rel} = 0.036(1)$, 0.84(3), and 2.31(2) MeV. The corresponding excitation energies are $E_x = 0.62(9)$, 1.42(10), and 2.89(10) MeV. While the first and second resonances are consistent with the $5/2^+_1$ and $5/2^+_2$ states reported by the knockout experiment [6] and the inelastic scattering measurement [5], respectively, the third one was observed for the first time in the present work.

The momentum distribution observed for the 0.62-MeV state was rather wide to be consistent with the $l = 2$ assignment, suggesting that the 0.62-MeV state was populated by the d-wave neutron knockout [18]. This is consistent with the suggested spin parity $5/2^+$ in Ref. [6]. For the 2.89-MeV state, the momentum distribution was found consistent with with the $l = 1$ distribution, which exhibits the p-wave knockout character. Considering the hierarchy of the orbits in the shell model, the 2.89-MeV state is likely to be the $1/2^-$ state [18]. This state is the firstly observed negative-parity state in ^{19}C.

4 Summary

The neutron-unbound states of ^{19}C have been investigated via a one-neutron knockout reaction with a carbon target. From the relative energy spectrum reconstructed by means of the invariant mass method, three states were identified at $E_{\rm rel}$ = 0.036(1), 0.84(3), and 2.31(2) MeV. They correspond to the states at E_x = 0.62(9), 1.42(10), and 2.89(10) MeV and the last one was observed for the first time. The spin-parity of the 0.62-MeV and 2.89-MeV states are determined to be $5/2^+$ and $1/2^-$, respectively, by comparing the parallel momentum distribution with the theoretical calculation. As a consequence, we provided direct evidence that the $5/2^+_1$ state is unbound. The analysis is still in progress, and more definitive results are expected to be obtained in the near future.

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