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γ-ray spectroscopy of ^{19}C via the single-neutron knock-out reaction

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The one-neutron knock-out reaction ^{1}H(^{20}C,^{19}Cγ) was studied at RIKEN using the DALI2 array. A γ-ray transition was observed at 198(10) keV. Based on the comparison between the experimental production cross section and theoretical predictions, the transition was assigned to the de-excitation of the $3/2_1^+$ state to the ground state.

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I. INTRODUCTION

Construction of radioactive ion beam facilities opened new ways in nuclear structure studies. Neutron-rich nuclei far from the valley of stability became experimentally reachable in the past two decades. The neutron-rich carbon isotopes showing interesting phenomena like one- [1] and two-neutron halo [2,3], neutron decoupling [4,5], weakening of the neutron-neutron effective interaction [6], development of the $N = 16$ subshell closure, and disappearance of the $N = 14$ one [7] was in focus for a long time.

Since its identification by Bowman *et al.* [8], ^{19}C was one of the most investigated nucleus in the lower mass region of isotopes. It attracted attention as a candidate of a one-neutron halo nucleus because of its low binding energy and spin $1/2^+$ ground state suggested by shell model calculations. The large interaction [9] and Coulomb dissociation [1] cross sections supported this assumption. The momentum distribution probed in different ways by several groups [10–15] was consistent with the halo nature and the ground-state spin $1/2^+$ assignment, but $3/2^+$ and $5/2^+$ spins were not completely excluded as discussed in Refs. [12,13]. Even though there is a consensus that the dominant structure of the ^{19}C ground state is $1s_{1/2} \otimes 0^+$ on the basis of the observed spectroscopic factors and the absolute break-up cross sections. The halo nature and the spin $1/2^+$ ground-state assignment was confirmed in a recent experiment, too [16].

Concerning the excited states of ^{19}C, two γ rays in the ^{19}C (p,p$'$) reaction were observed at 72(4) keV and 197(6) keV energies [17], which were assigned to the $5/2^+ \to 3/2^+ \to 1/2^+$ decay sequence. The existence of the higher energy transition was confirmed in a multinucleon removal reaction [7], where a 201(15)-keV transition was observed. An unbound excited state was revealed at 1.46(10) MeV in the (p,p$'$) process via detection of the emitted neutrons [18]. Recently, another unbound state was observed at 653(95) keV in a multiproton removal reaction via detection of the emitted neutrons from the unbound ^{19}C states [19]. The state at 1.46-MeV excitation energy was assigned to a $5/2^+$ state on the basis of an angular distribution measurement [18]. It may have an $s_{1/2} \otimes 2^+$ core excited configuration according to shell model calculations [19]. On the other hand, the presence of three low energy excited states contradicts the shell model expectations. To resolve this contradiction, we studied the single-neutron knock-out reaction from ^{20}C because, according to shell model + Glauber model calculations for this reaction, only the $s_{1/2}$ and $d_{5/2}$ single-particle states were expected to be excited with a large cross section [3,20].

II. EXPERIMENTAL DETAILS

The experiment was performed at the Nishina Center for Accelerator-Based Science located in RIKEN, Japan [5]. As a first step, a stable ^{40}Ar beam of 700 pnA was produced by using the RILAC linear accelerator coupled to the RRC cyclotron. This ion beam, the energy of which was 63 MeV/nucleon, hit a target made of ^{181}Ta with a thickness of 0.2 mm. The ^{40}Ar particles were fragmented in the target. The reaction products were purified by the RIPS radioactive ion separator [21]. This purification was performed on the basis of the different magnetic rigidity (Bρ) of the isotopes by applying two dipole magnets between which a wedged-shape aluminum degrader of 221-mg/cm^2 thickness was placed for inducing dispersion at the first focal plane (F1). The momentum acceptance of the fragment separator was set to the maximum 6%. The total intensity of the radioactive ion beam was about 100 particle/s (pps). The following main species were included in the beam ^{17}B (11.32%), ^{19}C (18.02%), ^{20}C (9.77%), ^{21}N (45.76%), and ^{22}N (12.63%). These were identified by their energy loss (ΔE), time-of-flight (ToF), and Bρ [22]. ΔE was determined by a silicon detector with an area of 5 cm $\times$ 5 cm and a thickness of 0.1 mm located at the second focal plane (F2) while the ToF was measured between two plastic scintillators put 6 m away from each other at the F2 and F3 focal planes. The beam trajectory was also monitored on an event-by-event basis by parallel plate avalanche counters (PPAC) at F2 and F3. A complete separation of the beam constituents could be achieved.

The radioactive ion beam was transported to a secondary target of liquid hydrogen of 190 mg/cm^2 cooled down to 22 K [23]. The mean energy of the ^{20}C particles in the middle of the target was around 50 MeV/nucleon. The isotopes created by neutron knock-out reactions were identified by their ToF, ΔE, and total energy (E). A plastic scintillator of 1-mm thickness was put 80 cm downstream of the target which served two purposes: It measured ΔE and gave the start signal for ToF. The stop signal for ToF was provided by an array of 16 plastic scintillators of 6-cm thickness. The length of each bar was 1 m, thus a total area of about 1 m $\times$ 1 m was covered, which ensured a full coverage (6.5° in the laboratory system) of the outgoing reaction products. Because the isotopes fully stopped in the scintillators, they were also used to determine E.

The Z identification was complete and based on the combination of ΔE and ToF presented in Fig. 1. The mass separation was performed by using the two-dimensional plot of ToF and E. The resolving power was enough for a complete distinction between mass values differing by two units, however, we had some leakage between adjacent isotopes. This can be seen in Fig. 2. Nevertheless, this did not imply a problem because the odd carbon isotopes have low energy γ rays (below 600 keV) while even ones emit relatively high energy γ's (above 1 MeV).

The de-excitation γ rays were observed by an array of scintillators called DALI2 [24] arranged in a ball-like structure around the target. The DALI2 detector system contained 160 NaI(Tl) crystals in 16 layers, thus the setup covered a range of polar angles in the laboratory frame between 15° and 160°. To determine the detection efficiency for γ rays between 100 and 250 keV a GEANT4 simulation was constructed which provided 54% efficiency at 200 keV. The simulation showed good agreement with experimental data available by radioactive sources at around 1 MeV.

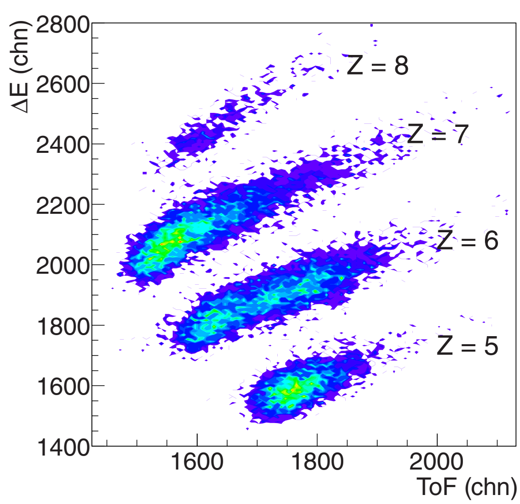

FIG. 1. (Color online) Energy loss and time-of-flight of the reaction products plotted against each other.

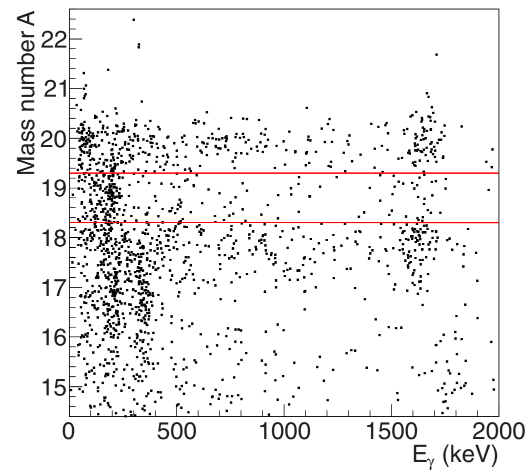

FIG. 2. (Color online) Mass number and $M=1$ Doppler-corrected γ-ray energy plotted against each other. The red lines indicate the range of projection for ^{19}C.

The energy of the γ rays were corrected for the Doppler effect by using the known average velocity of the beam constituents in the middle of the target and the position of the NaI(Tl) detectors. The time signals for each of the members of the DALI2 setup as well as the hit multiplicity of the array (M) were recorded.

III. RESULTS AND DISCUSSION

The $M=1$ γ-ray spectrum for ^{19}C from the neutron knock-out reaction obtained by use of the prompt time gate is presented in Fig. 3. A peak can be seen at 198(10) keV. The indicated uncertainty of the peak position is the square root of the sum of the squared uncertainties including two main errors namely the statistical one and the one from the

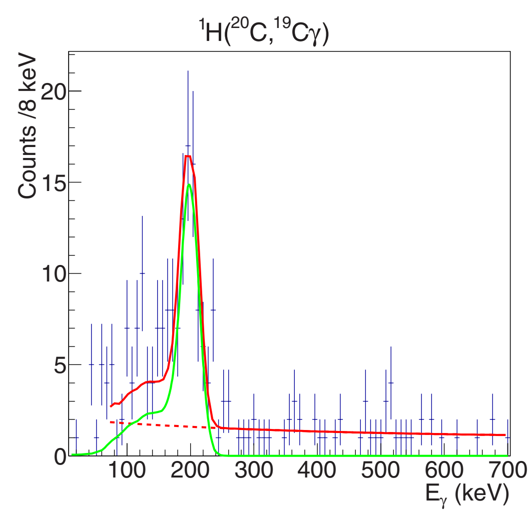

FIG. 3. (Color online) Doppler-corrected spectra of γ rays emerging from the neutron knock-out reaction ^{1}H(^{20}C,^{19}Cγ). The solid red line is the final fit including the spectrum curves from GEANT4 simulation indicated with a solid green line and an additional smooth first-degree polynomial background plotted in dashed red line.

uncertainty in Doppler correction. We took into account the uncertainties of the average velocity of the beam and detection angle of γ rays. The obtained energy is in accordance with the ones observed in earlier studies: 197(6) keV [17] and 201(15) keV [7].

The spectrum was fitted with the response of the array from a GEANT4 simulation [25] plus a smooth polynomial background. First, the function of peak width versus γ-ray energy was derived based on known γ rays at 217(7) keV and 342(10) keV of ^{17}C and 1601(47) keV of ^{18}C. Using this function, a GEANT4 simulation of the $M = 1$ spectrum was created, the simulated response curve at 198 keV with the smooth first-degree polynomial background fitted the experimental data points well and provided the peak height. The net counts in the peak for the spectra with liquid hydrogen were obtained from the fit.

The total cross section for the production of this γ ray was deduced taking into account the DALI2 efficiency. It was found that in the ^{1}H(^{20}C,^{19}Cγ) reaction the neutron removal cross section to the first excited state is $\sigma(198, \mathrm{H}) = 4.54(76)$ mb, much smaller than the 24(4) mb inelastic scattering cross section for the ^{20}C (p,p′) process [5], and much smaller than expected for the neutron removal cross section for such a weakly bound system. According to the calculation of Ozawa *et al.* [20] the total cross section for the one-neutron removal reaction from ^{20}C on a proton target is 127 mb, which is shared mainly between the $s_{1/2}$ and $d_{5/2}$ states produced with 52 mb and 75 mb cross sections, respectively. The production cross section for the $3/2^+_1$ state was calculated to be 3.6 mb, which is consistent with the experimental cross section obtained in the present study for the 198-keV state. This finding confirms the spin assumptions made in Refs. [17,19]. On the other hand, there is no sign for a much stronger transition which should feed the 198-keV state if we had a higher energy bound $5/2^+$ state. If we assume that the γ ray at 72 keV exists and connects the $5/2^+_1$ state to the $3/2^+_1$ one then the peak at 198(10) keV from the present experiment should be roughly an order of magnitude larger than the observed peak area because of the cascade feeding. Furthermore, we should see the 72-keV line in the $M = 1$ γ-ray spectrum with about 5 times larger intensity than the 198-keV line in the present spectrum considering the difference of the production cross section [20] for the $3/2^+_1$ state (3.6 mb) and the $5/2^+_1$ one (75 mb), the efficiency of DALI2 at 72 keV (approximately 20%) and 198 keV (approximately 54%), and the fact that a significant part of the intensity would be shifted to the multiplicity 2 part of the spectrum. Even a weak second gamma ray can be ruled out up to the neutron threshold as it is seen in Fig. 3. The slight increase in the spectrum around 110 keV could correspond to a peak at the level of significance of 1.22. Thus, it is regarded as a statistical fluctuation in the background. Thus, we can completely exclude the possibility of the existence of the bound $5/2^+$ state above the $3/2^+$ one. Having a lower energy $d_{5/2}$ state would result in an isomeric state, the existence of which was expelled by Kanungo *et al.* [13]. The experimentally observed cross sections given in Refs. [3,16,20] for the production of ^{19}C from the ^{20}C − n reaction are much lower than they would be if both single-particle states were bound.

By means of the spectroscopic factor from the absolute Coulomb cross-section measurement [11] the ground-state spin and parity of ^{19}C is well established to be $1/2^+$. As it was pointed out by Kanungo *et al.* [13], the decay of the $5/2^+_1$ state to the ground state is expected to be strongly hindered (about 2 μs half-life for a 200-keV transition), while that of the $3/2^+_1$ is prompt. Observation of the prompt 198-keV γ line also supports the spin 3/2 assignment to the 198-keV state. In addition, the excited $5/2^+_1$ and $5/2^+_2$ states at 0.653(95) MeV and 1.46(10) MeV were proven unbound via neutron removal reactions [19] and proton inelastic scattering [18].

In the shell model picture the low lying states of the heavy carbon nuclei can be considered as neutron excitations above the ^{14}C core. The configuration of the two low lying states in ^{19}C relative to ^{14}C is $\nu[d^3_{5/2}s^2_{1/2}]_{5/2}$ and $\nu[d^4_{5/2}s^1_{1/2}]_{1/2}$. In addition, because of the $j-1$ rule for the j^3 configurations [26] the $\nu[d^3_{5/2}s^2_{1/2}]_{3/2}$ state is expected to be close to the 5/2 state. Indeed the $\nu[d^3_{5/2}s^0_{1/2}]_{3/2}$ state is the ground state of ^{17}C. Considering that the ground state of ^{20}C is made of $d_{5/2}$ and $s_{1/2}$ pairs, one can easily understand that the main intensity in a neutron knock-out goes to the 1/2 or 5/2 states, while the 3/2 state based on the broken $d_{5/2}$ pair state can be excited via a two step process or by mixing broken pair states into the ground state of ^{20}C leading to a somewhat small cross section. Glauber model calculations with the H and Be targets [3,20] show that indeed this is the case.

All the shell model calculations and even the recent *ab initio* coupled cluster calculations [27] give a triplet of low lying states. The order of the states is determined by the $d_{5/2}$ and $s_{1/2}$ single-neutron energy difference and the neutron interaction matrix elements. The WBP and WBT interactions [28] give a 1/2–5/2–3/2 order, while the MK2 Millener-Kurath [29] and the newer SFO [30] interaction give the right order of the states for the price of mixing up the order of the states in ^{17}C. The recent theoretical interaction deduced from the QCD chiral interaction with a low momentum cutoff [31] can reproduce the right order of the states in ^{19}C and the ground state of ^{17}C. The right order of the states could also be reproduced by a neutron + ^{18}C AMD core coupling model [32]. When comparing the experimental and theoretical energies one has to remember that the uncertainty of the shell model predictions is of the order of 200 keV using empirical interactions [28].

IV. SUMMARY

The one-neutron knock-out reaction ^{1}H(^{20}C,^{19}Cγ) was studied at RIKEN using the DALI2 array. A weak γ-ray transition was observed at 198(10) keV. Based on the comparison between the experimental production cross section and a theoretical prediction, the transition was assigned to the de-excitation of the $3/2^+_1$ state to the ground state. If we had a bound $5/2^+$ state above the $3/2^+$ one, two transitions should have been observed with 20 times larger intensity than the intensity of the present 198-keV transition. Combining this observation with the conclusion made by Kanungo [13], i.e, nonobservation of isomeric states in ^{19}C, the existence of a bound $d_{5/2}$ state in ^{19}C can be excluded.

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