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Confirmation/Observation of Hindered E2 Strengths in ^{16,18}C *

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Abstract: The lifetime of the first excited 2^+ state in ^{18}C was measured using an upgraded recoil shadow method to determine the electric quadrupole transition. The measured mean lifetime is 18.9±0.9(stat)±4.4(syst) ps, which corresponds to a $B(\mathrm{E2};\ 2_1^+ \to 0_{\mathrm{gs}}^+)$ value of (4.3± 0.2±1.0) $e^2\mathrm{fm}^4$, or about 1.5 Weisskopf units. The mean lifetime of the first 2^+ state in ^{16}C was remeasured to be about 18 ps, about four times shorter than the value reported previously. This discrepancy was explained by incorporating the γ-ray angular distribution measured in this work into the previous measurement. The observed transition strengths in ^{16,18}C are hindered compared to the empirical transition strengths, indicating that the anomalous hindrance observed in ^{16}C persists in ^{18}C.

Key words: neutron-rich nuclei; lifetime measurement; B(E2)

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1 Introduction

The E2 transition strength is a fundamental quantity of a nucleus that reflects the proton contribution to the quadrupole collectivity. For even-even nuclei, the reduced E2 transition probability B(E2) from the first excited 2^+ (2_1^+) state to the ground 0^+ (0_{gs}^+) state as well as the excitation energy $E(2_1^+)$ have long been used as basic observables to extract the magnitude of the quadrupole collectivity. A simple collective model treating a nucleus as a homogeneous quantum liquid drop has been quite successful in describing the systematic tendency of the B(E2), predicting that B(E2) varies in inverse proportion to $E(2_1^+)$[1]. Contrary to this, through a lifetime measurement of the 2_1^+ state, we recently reported a remarkably small

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B(E2) value[2] for the neutron-rich ^{16}C in spite of the small E(2_1^+) value of 1.77 MeV[3]. The result indicates a suppressed proton contribution to the quadrupole collectivity in ^{16}C. Subsequent investigations using the Coulomb-nuclear interference[4] and the proton inelastic scattering[5] have revealed a neutron-dominant excitation to the 2_1^+ state in ^{16}C. To shed light on this exotic phenomenon in which protons and neutrons exhibit very different behaviors, we have measured the B(E2) of the neighboring ^{18}C nucleus using an upgraded recoil shadow method[6].

In this paper, we present a brief report on the experiment results of the lifetime measurement of the 2_1^+ states in ^{18}C as well as the remeasurements for ^{16}C, which have been reported[6] very recently. The paper is organized as follows: In Section 2, we present the details of the experiment. The results of the lifetime measurements as well as a brief discussion on the results are presented in Section 3. Finally, a summary is given in Section 4.

2 Experiment

The lifetime measurements were performed by using the recoil shadow method (RSM)[2], which was developed to complement other methods for lifetime measurement such as the Doppler shift attenuation method and the recoil distance method. Equipped with high-efficiency NaI(Tl) detectors, the RSM was successfully applied for the first time to ps region to measure the mean lifetime of the 2_1^+ state in ^{16}C[2]. The essence of the technique lies in the dependence of lifetime on the emission points of de-excitation γ rays, which is further magnified by placing a γ-ray absorber around the reaction target. However, besides the small number of detectors, the previous setup suffered from uncertainty in terms of the anisotropy of the γ rays which is to arise from nuclear spin alignment. To address these problems, we have upgraded the setup to enhance both the efficiency and the accuracy of the measurement. The upgraded scheme thus employed involved a large array of NaI(Tl) detectors as well as a novel procedure that enables determination of lifetimes independent of the γ-ray anisotropy.

The experiment was performed at the RIKEN accelerator research facility. Secondary beams of ^{16,18}C were produced in two separate measurements through projectile fragmentation of an 110MeV/u ^{22}Ne primary beam, and separated by the RIPS beam line[7]. The ^{16,18}C beams with energies of 72 and 79 MeV/u, respectively, were directed at a 370 mg/cm^2 ^{9}Be target to induce secondary reaction. The lifetime measurement for ^{18}C was performed using the inelastic scattering channel of the ^{18}C beam. For ^{16}C, the lifetime measurements were performed using the inelastic scattering channel of the ^{16}C beam and the breakup channel of the ^{18}C beam. Additional measurement of the angular distribution of the γ rays was performed with a degraded ^{16}C beam at 40 MeV/u to incorporate the distribution into a reanalysis of the data in Ref. [2].

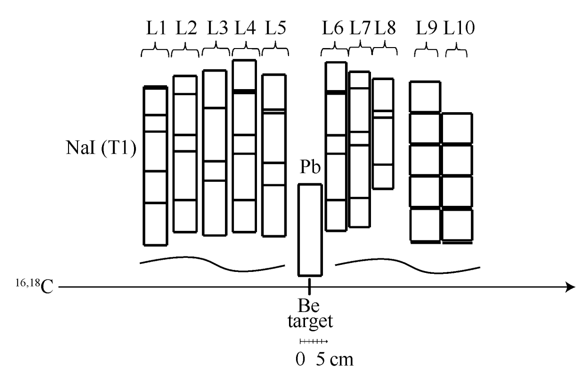

Fig. 1 Schematic view of γ-ray detectors. A beryllium target is surrounded by a 5 cm thick lead shield, and 10 layers of NaI(Tl) scintillators (L1 -L10) placed cylindrically around the beam axis. For clarity, only part of the detectors and lead shield is shown in the inset.

Two sets of parallel plate avalanche counters (PPACs) were placed upstream of the target to measure the position and angle of the projectile incident upon the target. The ^{16,18}C beam on the target had typical intensities of 6.5×10^4 and 2.3×10^4 particles/s, respectively. Outgoing particles from the target were identified by the ΔE-E-TOF method using a plastic scintillator hodoscope[8] located 3.8 m downstream of the target. Scattering angles were determined by combining the hit position information on the hodoscope with the incident angles and hit positions on the target obtained by the PPACs.

In order to implement the RSM concept, a thick γ-ray shield was placed around the target as shown in Fig. 1. The shield was a 5 cm thick lead block with an outer frame of 24 cm×24 cm and an inner hole of 5.4 cm in diameter which housed the ^{9}Be target. The γ rays from the excited nuclei in-flight were detected by an array of 130 NaI(Tl) detectors, which form part of the DALI1[9] and the DALI2[10]. The array was divided into 10 layers, labeled L1-10 as shown in Fig. 1, with each layer consisting of 10－18 detectors arranged coaxially with respect to the beam direction. Several examples of the γ-ray energy spectra are shown in Fig. 2.

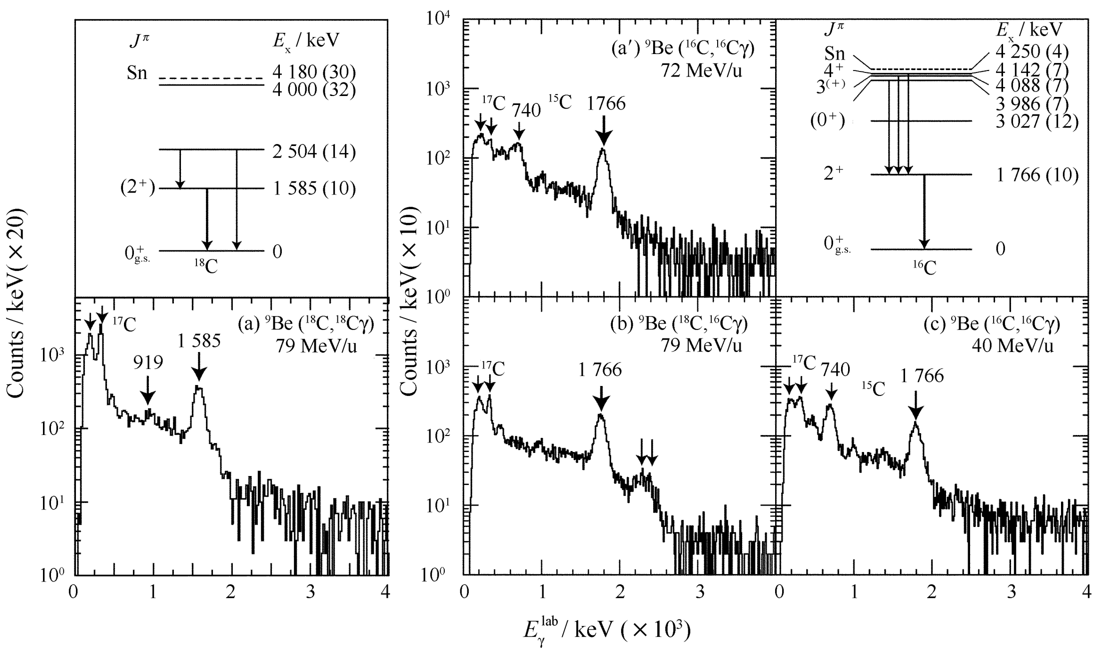

Fig. 2 γ-ray energy spectra obtained during the measurements without the lead shield and the energy level schemes for ^{16,18}C.

In the present work, we counted the number of full-energy-peak events detected by each layer during the measurements with and without the lead shield. For convenience, the numbers obtained with the i-th layer during the former and the latter measurements are denoted by N^i_{wPb} and N^i_{woPb}. The N^i_{wPb} and N^i_{woPb} were obtained by fitting the measured γ-ray energy spectra with response functions obtained with simulations, plus γ-ray spectra for the ^{14}C isotope as backgrounds.

As mentioned earlier, a key point of the present work is the elimination of the dependence of the measured lifetime on the γ-ray angular distribution. For this purpose, we determined the deficiency of the γ-ray yields due to the lead shield. The deficiency (D^i) of the i-th layer detectors is defined as the ratio between the yields detected with and without the shield, i.e.

$$D^i = \frac{f_{\mathrm{b}} N^i_{\mathrm{wpb}}}{N^i_{\mathrm{wopb}}} , \qquad (1)$$

where f_{b} is the normalization factor for different total number of beam particles in the two measurements. The lifetime was determined by comparison of the measured deficiency with the simulated one.

The simulated deficiency of each layer as a function of various lifetimes for the respective de-excitation γ rays was obtained by performing Monte Carlo simulations using the GEANT code[11], taking into account the geometry of the experimental setup, the energy and emittance of the projectile, the angular spread due to reaction and multiple scattering, and the energy loss in the target.

3 Results and Discussion

Table 1 shows the results of lifetime measurements for ^{16,18}C. For comparison, the latest result on ^{16}C from LBL[12] is also shown. As shown in the upper panel of Fig. 3, the B(E2) values for ^{16,18}C are very small and comparable to those of the singly- or doubly-closed shell oxygen and calcium isotopes. In fact, the values are about six and five times smaller than the predictions ($B(\mathrm{E2})_{\mathrm{sys}}$) by

Table 1 Summary of the mean lifetimes of the 2_1^+ states in ^{16}C and ^{18}C, and the corresponding B(E2) values*

	$\tau(2^{\pm})$	B(E2)	
	/ ps	/(e^2fm^4)	/(W. u.)
^{18}C	18.9±0.9±4.4	4.3±0.2±1.0	1.5±0.1±0.4
^{16}C^a	17.7±1.6±4.6	2.7±0.2±0.7	1.1±0.1±0.3
^{16}C^b	19.6±3.0±4.5	2.4±0.4±0.6	1.0±0.2±0.2
^{16}C^c	34±14±9	1.4±0.6±0.4	0.6±0.2±0.2
^{16}C†	11.7±2.0	4.1±0.7	1.7±0.3

* (a) Inelastic channel at 72 MeV/u; (b) Breakup channel at 79 MeV/u; (c) Inelastic channel at 40 MeV/u; (†) LBL data taken from Ref. [12].

the global systematics[13]. The lower panel of Fig. 3 shows the experimental B(E2) values relative to $B(\mathrm{E2})_{\mathrm{sys}}$. As noted in Ref. [13], the $B(\mathrm{E2})/B(\mathrm{E2})_{\mathrm{sys}}$ ratios for most of the open-shell nuclei fall around 1.0, being confined between 0.5 and 2.0. Even for the closed-shell nuclei, the ratio remains larger than 0.20. Thus, the ratios of 0.14 and 0.21 for ^{16,18}C are exceptionally small. In particular, the ratio for ^{14}C with E(2_1^+) = 7 012 keV[3] is as large as 0.68, suggesting different mechanisms for the small B(E2) in ^{14}C and the suppression of the B(E2) values in ^{16,18}C. The small B(E2) value for ^{18}C shows that the hindered E2 strength observed in ^{16}C[2] persists in ^{18}C. As in the case of ^{16}C[4,5], the observation of the small B(E2) value in ^{18}C despite the lowering of the E(2_1^+) may imply a neutron-dominant quadrupole collectivity in ^{18}C.

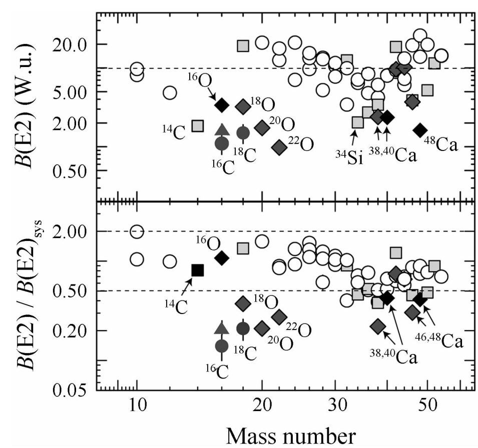

Fig. 3 B(E2) values in W. u. and ratios between the experimental B(E2) values and $B(\mathrm{E2})_{\mathrm{sys}}$ calculated by the empirical formula[13] for even-even nuclei up to $A\approx50$. The filled circles denote the values of ^{16,18}C. The open squares and open diamonds denote the proton- and neutron-closed-shell nuclei, while the filled diamonds represent the double magic nuclei. The latest datum for ^{16}C from LBL taken from Ref. [12] is denoted by the triangle.

4 Summary

The lifetime of the 2_1^+ state in ^{16,18}C were successfully measured using the upgraded RSM with 10-layer NaI(Tl) array, incorporating the inelastic scattering and breakup reaction at around 75 MeV/u. The γ-ray angular distribution for the inelastic scattering of ^{16}C at 40 MeV/u was also measured. Incorporating this angular distribution into the measurement reported previously[2], the $\tau(2_1^+)$ of ^{16}C was found to be in consistent with the present results. The $\tau(2_1^+)$ values for ^{16,18}C thus determined were as long as around 20 ps, indicating that the anomalous suppression of B(E2) observed in ^{16}C persists in ^{18}C. The present results, together with the small $B(E2)$ values for ^{14}C, suggest a possible proton-shell closure in the neutron-rich $^{14,16,18}C$ nuclei.

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