論文内容の要旨

論文題目　Lifetime Measurement of the First Excited 2+ State in 18C

(訳) 18C の第一 2+ 励起状態の寿命測定

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This thesis reports on an experimental work on ^{18}C, which is one of the experiments undertaken to study the peculiar behavior of the neutron-rich carbon isotopes. The present experiment was aimed at a direct determination of the $B(E2;2_1^+ \rightarrow 0_{g.s.}^+)$ value for ^{18}C, which is crucial for the understanding of the anomalously small *E2* transition strength in ^{16}C.

The *E2* transition strength is a fundamental observable that reflects the static or dynamic deformation of the nuclear charge. For even-even nuclei, the reduced *E2* transition probability (referred to simply as *B(E2)* hereinafter) from the first 2^+ state (2_1^+) to the 0^+ ground state ($0_{g.s.}^+$) has long been used as a basic observable in extracting the nuclear 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 *B(E2)*, predicting that *B(E2)* varies in inverse proportion to the excitation energy $E(2^+)$. Contrary to this, through a lifetime measurement of the 2_1^+ state in ^{16}C, we found that the *B(E2)* value is remarkably small despite the small $E(2^+)$ value of 1.77 MeV. This result indicates an unexpectedly small contribution of protons to the *E2* strength of the $0_{g.s.}^+ \rightarrow 2_1^+$ transition. This finding raises an intriguing question as to whether or not the neutron contribution is similarly small for the relevant quadrupole excitation. To clarify this contradiction, two experiments were performed: one utilizing the Coulomb-nuclear interference in $^{208}Pb+^{16}C$ inelastic scattering, while the other one (performed by our group) using a proton probe. In both experiments, the neutron contribution was found to be "normal". However, when combined with the *B(E2)* value, the results indicate a neutron-dominant quadrupole excitation in ^{16}C. While a hypothesis of emergence of a new proton magic number Z=6 has been suggested based on a shell model calculation, more experimental evidences, especially from the neighboring even-even C isotopes such as ^{18}C, are necessary to scrutinize this hypothesis. As a first step, we have undertaken the task to study the *E2* strength in ^{18}C.

To determine the *B(E2)* value for ^{18}C, we have performed an experiment to measure the mean lifetime of the first excited 2_1^+ state in the neutron-rich ^{18}C using an upgraded recoil shadow method (RSM), incorporating the in-beam gamma-ray spectroscopy. The need for a lifetime measurement arises from the small atomic number of ^{18}C. Although the intermediate-energy Coulomb excitation method has been useful for the determination of the *B(E2)* values for many unstable nuclei, it suffers from nuclear-reaction-model ambiguity when applied to nuclei with $Z < 10$.

The RSM was developed to complement other methods for lifetime measurement, e.g. the Doppler shift attenuation method and the recoil distance method, which require high resolution detectors such as the Ge detectors that tend to have relatively low detection efficiency. 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. The essence of the technique lies in the dependence of lifetime on the emission points of de-excitation gamma rays, which is further magnified by placing a gamma-ray absorber around the reaction target. However, the previous experimental setup suffered from uncertainty in terms of the angular distribution of the gamma rays. Besides, the positioning of the NaI(Tl) detectors covering only two polar angles has resulted in limited statistics and relatively narrow dynamic range of the measurable lifetimes. To address these issues, we have upgraded the setup. First, by improving the flexibility of the setup through introduction of an easily removable gamma-ray absorber, and considering the ratio of the gamma rays detected during measurements with and without the gamma-ray absorber, we have succeeded in eliminating the ambiguity due to the angular distribution. Second, by increasing the number of NaI(Tl) detectors covering a wider range of polar angle, we compensate for the lower beam intensity of ^{18}C as compared to that of ^{16}C and extend the dynamic range of the measurable lifetimes to between about 10 ps and several hundreds of ps.

The present experiment was performed at the RIKEN Accelerator Research Facility using the RI beam line RIPS. A ^{18}C beam was produced in a fragmentation reaction using a 110-MeV/nucleon ^{22}Ne primary beam incident on a ^{9}Be production target. The secondary ^{18}C beam thus produced bombarded a secondary ^{9}Be target, where it was excited to the 2_1^+ state. The secondary beam incident on the secondary target was counted and its timing was measured using two plastic scintillation detectors placed upstream of the target. Tracking of the incident beam was done using two parallel plate avalanche counters placed upstream of the secondary target. The scattered ^{18}C nuclei (the ejectiles) were detected with a plastic scintillation detector hodoscope, placed downstream of the secondary target. The de-excitation gamma rays emitted from the ejectiles were detected by 118 NaI(Tl) detectors placed around secondary target. Placed at ten different polar angles, the NaI(Tl) detectors covered angular range of about 15° ~ 85° and 100° ~ 147°.

From the coincidence measurement of the ^{18}C ejectiles and the de-excitation gamma rays, the number of full-energy peaks detected in each set of the Na(Tl) detectors placed at different angles were determined. From a separate measurement during which a lead shield was placed around the secondary target, the deficiency in the full-energy-peak efficiencies of the each set of NaI(Tl) detectors due to the lead shield (referred to simply as deficiency hereinafter) was determined, by taking the ratio of the number of full-energy peaks obtained in the two separate measurements. The mean lifetime dependence of the deficiencies was calculated by means of a Monte Carlo simulation using the GEANT3 code.

Through comparison between the measured deficiencies and the simulated ones, we have determined the mean lifetime of the 2_1^+ state in ^{18}C to be 17.4±2.6(stat)±4.0(syst) ps. This mean lifetime corresponds to *B(E2)* value of 4.7+0.8/-0.6(stat)+1.4/-0.9(syst) e^2fm^4 or 1.7+0.3/-0.2(stat)+0.5/-0.3(syst) in Weisskopf units. The following figure (a) shows the known *B(E2)* values in Weisskopf units for even-even nuclei from ^{10}Be to ^{54}Cr. The data for ^{18}C is denoted by the red-filled circle. The filled diamonds represent the doubly-closed-shell nuclei, while the open diamonds (squares) represent the proton- (neutron-) closed-shell nuclei (all these nuclei are referred to as magic nuclei hereinafter). The Weisskopf unit represents the *E2* strength for a single particle (proton) transition. As shown in the figure, the value for ^{18}C falls in the same category as those of the singly- or doubly-closed shell O and Ca isotopes. The resemblance of the small *B(E2)* value for ^{18}C, as well as those for ^{14}C and ^{16}C, to those of the singly- or doubly-closed shell O and Ca isotopes indicates a possible development of a proton-closed shell at *Z*=6 in the neutron-rich from ^{16}C and ^{18}C. In figure (b), a plot of the ratios of known experimental *B(E2)* values and the values predicted by a global formula based on a liquid-drop model for even-even nuclei from ^{10}Be to ^{54}Cr (similar to the ones shown in figure (a)) is shown. Although the global formula has predicted the *B(E2)* values to within 50% accuracy for 90% of the even-even nuclei, including some magic nuclei, it somewhat overestimates the *B(E2)* value for ^{18}C by almost a factor of 4. The present result shows that the anomaly observed in ^{16}C persists in ^{18}C, i.e. the lowering of the first excitation energies in both nuclei cannot be explained by the conventional one-fluid quantum liquid-drop model. More experimental and theoretical studies are needed both to understand the mechanism underlying the unusual dynamics shown by and to further explore the dramatic evolution of the nuclear shell structure in the carbon isotopes.