Anomalously hindered $E2$ strength $B(E2; 2^+_1 \rightarrow 0^+)$ in $^{16}$C

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The electric quadrupole transition from the first $2^+$ state to the ground $0^+$ state in $^{16}$C is studied through measurement of the lifetime by a recoil shadow method applied to inelastically scattered radioactive $^{16}$C nuclei. The measured lifetime is $75 \pm 23$ ps, corresponding to a $B(E2; 2^+_1 \rightarrow 0^+)$ value of $0.63 \pm 0.19 e^2fm^4$, or $0.26 \pm 0.08$ Weisskopf units. The transition strength is found to be anomalously small compared to the empirically predicted value.

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Quadrupole strengths are fundamental quantities in probing the collective character of nuclei. The enhancement of the electric quadrupole ($E2$) transition strength with respect to that of single proton excitation may reflect large fluctuation or deformation of nuclear charge $[^1]$. One of the important $E2$ transitions in an even-even nucleus is that from the first $2^+$ ($2^+_1$) state to the ground state ($0^+_g$), the reduced transition probability $B(E2)$ of which has long been a basic observable in the extraction of the magnitude of nuclear deformation or in probing anomalies in the nuclear structure. With recent advances in techniques for supplying intense beams of unstable nuclei, several exotic properties such as magicity loss $[^2,3]$ have been discovered in neutron-rich nuclei through measurements of $E2$ strengths.

The present Letter reports lifetime measurements of the $2^+_1$ state of the neutron-rich nucleus $^{16}$C. The lifetime is inversely proportional to $B(E2)$. A simple model of a nucleus as a quantum liquid-drop well describes the systematic tendency that $B(E2)$ varies in inverse proportion to the excitation energy $E(2^+_1)$ of the $2^+_1$ state $[^3]$. For carbon isotopes, when $N$ changes from the magic number 8 to 10, $E(2^+_1)$ decreases dramatically from 7.012 to 1.766 MeV $[^4]$. It can then be anticipated that $^{16}$C ($N = 10$) would have a much larger $B(E2)$ than that of $^{14}$C ($N = 8$). Unexpectedly, a remarkably small $B(E2)$ was found for $^{16}$C in the present work. The observed value, in Weisskopf units, turns out to be far smaller than any other $B(E2)$ measured on the nuclear chart.

In the present experiment, a new technique was employed to measure the lifetime of an excited state populated in inverse-kinematics reactions. The technique essentially followed the concept of the recoil shadow method (RSM) $[^5]$, in which the emission point of the de-excitation $\gamma$-ray is located and the $\gamma$-ray intensity is recorded as a function of the flight distance of the de-exciting nucleus. As the flight velocity of the de-exciting nucleus is close to half the velocity of light, the flight distance over 100 ps corresponds to a macroscopic length of about 1.7 cm. Thus, the present shadow method provides a wide range of applicability, extending to lifetimes of as short as a few tens of ps. In particular, the method is useful for determining the $B(E2)$ value of $Z < 10$ nuclei, at which the use of intermediate-energy Coulomb excitation $[^6]$ may suffer from contamination of nuclear excitation.

The experiment was performed at the RIKEN accelerator research facility. A secondary $^{16}$C beam was produced through projectile fragmentation of a 100-MeV/nucleon $^{18}$O primary beam, separated by the RIPS beam line $[^7]$. The $^{16}$C beam was directed at a thick, $370\text{mg/cm}^2$ $^{9}$Be target placed at the exit of the RIPS line for inelastically excited. Particle identification for the secondary beam was performed event-by-event by means of the time-of-flight (TOF)–$\Delta E$ method using a 1.0 mm-thick plastic scintillation counter (PL) located 180 cm upstream of the target. Two sets of parallel plate avalanche coun-
FIG. 1: Schematic of experimental setup. A beryllium target is surrounded by a 5 cm-thick lead wall, and two cylindrically layered NaI(Tl) scintillators (R1 and R2) are placed upstream of the target.

Particles (PPACs) were also placed upstream of the target to record the position and angle of the projectile incident upon the target. The $^{16}$C beam had a typical intensity of $2 \times 10^9$ particles per second and purity of about 97%. The average energy across the target was 34.6 MeV/nucleon.

Particles scattered from the target were identified by the $\Delta E-E$-TOF method using a plastic scintillator hodoscope located 86 cm downstream of the target. The hodoscope, with an active area of $24 \times 24$ cm$^2$, consisted of a 2.0 mm-thick $\Delta E$ plane and a 5.0 mm thick $E$ plane. The scattering angles were measured by another PPAC placed 25 cm downstream of the target.

The experimental setup for $\gamma$-ray detection is shown schematically in Fig. 1. In order to implement the RSM concept, a thick $\gamma$-ray shield was placed around the target. The shield was a 5 cm-thick lead slab with an outer frame of 60×60 cm$^2$ and an inner hole of 6.2 cm φ. The inner hole surrounded the beam tube housing the $^9$Be target. For the sake of later discussion, the $z$-axis is defined as the beam direction, that is close to the flight direction of the de-exciting nucleus. The origin of the $z$-axis, $z = 0.0$ cm, was taken at the upstream surface of the lead slab.

The $\gamma$-rays from the excited $^{16}$C in-flight were detected by two rings of NaI(Tl) detectors labeled R1 and R2, composed respectively of 14 and 18 rectangular NaI(Tl) crystals with volume of $6 \times 6 \times 12$ cm$^3$. These rings circled the beam tube, with crystal centers set at polar angles of 121° and 102°, respectively. The average distance from the target to R1 was 29.2 cm, and 28.7 cm for R2.

The acceptance of the detectors was determined by the geometry of the R1 and R2 detectors with respect to the lead slab and the emission point $z$. Specifically, the $\gamma$-rays emitted between $z = 0.0$ and 2.2 cm can reach the centers of the NaI crystals of R1 without passing through the lead slab ($z = 0.0$ and 0.7 cm for R2). Hence, the relative efficiency of R2 with respect to R1 decreased as the emission point was moved further downstream. This difference of geometrical efficiency results in a dependence of the $\gamma$-ray yield ratio (R1/R2) on the lifetime of the decaying state.

The measurement of R1/R2 was conducted for two target positions, $z = 0.0$ and 1.0 cm. Figure 2 shows a Doppler-uncorrected $\gamma$-ray energy spectrum measured by R1 for the target placed at $z = 0.0$ cm. The spectrum is dominated by a peak at around 1.5 MeV, representing the Doppler-shifted 1766 keV line of the $2^+_1 \rightarrow 0^+_{gs}$ transition in $^{16}$C. A minor peak at around 2.0 MeV is also present, which may correspond to the known $4^+ \rightarrow 2^+_1$ transition in $^{16}$C. As the intensity of the latter transition is only 2% of the former, the contribution of the minor peak is ignored in subsequent analysis.

In deducing the yield ratio, a Gaussian shape for the peak and either an exponential or polynomial shape for the background component were fitted to the $\gamma$-ray energy spectrum. The R1/R2 ratios thus obtained for the 1766-keV $\gamma$-rays were $1.06 \pm 0.03$ and $1.70 \pm 0.06$ for target positions of $z = 0.0$ and 1.0 cm, respectively. The errors are statistical errors only. The influence of the choice of functional for the background is negligible.

In order to relate the R1/R2 ratio to lifetime, Monte Carlo simulation was performed to evaluate the detection efficiencies of R1 and R2 as a function of the position $z$ of $\gamma$ emission. By folding the efficiency over the flight distance, the R1/R2 ratio can be obtained as a function of mean-life $\tau$. The simulation was performed using GEANT code [8], and involved the shape of the detector and the geometry of the experimental setup. The validity of the simulation was tested by first performing a separate measurement in which a $^{22}$Na standard source emitting 1275-keV $\gamma$ rays was placed at twenty-one po-
FIG. 3: Two solid lines represent $\tau$ vs. R1/R2 curves obtained by Monte Carlo simulation for target positions of $z = 0.0$ and 1.0 cm. The hatched zones represent the experimentally deduced R1/R2 ratios for the two target positions. The dashed line denotes the adopted lifetime, and the two dotted lines represent the range of error.

sitions from $z = 0.0$ to 2.0 cm. The R1/R2 ratios thus measured for the different geometries were all reproduced by the simulation within $\pm 3\%$.

The simulation was then applied to the case of $\gamma$-rays emitted from de-exiting fragments in flight. This simulation employed experimentally obtained parameters such as the energy and emittance of the projectile, the angular spread due to inelastic scattering and multiple scattering, and energy loss of the incoming and outgoing particles. The angular distribution of the $\gamma$-ray emission was also incorporated. The distribution was estimated using ECIS79 code [10], employing the optical potential parameters determined for the $^{12}$C + $^{12}$C reaction [11]. The $\tau$ vs. R1/R2 curves thus obtained for the two target positions are shown in Fig. 3 as solid lines.

This figure compares the measured R1/R2 ratios with the simulated curves, allowing the value of $\tau$ to be determined. The vertical widths of the two hatched zones represent the ranges of R1/R2 values obtained experimentally. From the overlap between the simulated curves and the hatched zones, the values of $\tau$ were determined as 92 $\pm$ 22 ps and 63 $\pm$ 17 ps, respectively, for data obtained at target positions of $z = 0.0$ and 1.0 cm. The results obtained for the two different target positions are in reasonable agreement.

It is probable that the choice of optical potential may affect the calculated $\gamma$-ray angular distribution. This possibility was examined by repeating the distorted wave-born approximation calculation using a different set of parameters obtained for the $^{16}$O + $^{12}$C reaction [12]. With the resultant simulation curves, the values of $\tau$ were obtained as 93 $\pm$ 21 ps and 66 $\pm$ 16 ps for the two target positions, $z = 0.0$ and 1.0 cm. These values are close to those obtained using the original parameters of optical potential. The weighted average of these four values is taken as the final value.

The uncertainty of $\tau$ considered above, 19%, is attributable entirely to statistical error. Systematic errors may have arisen primarily from uncertainty of the target position, the accuracy of which was determined to 20%. Another source of systematic error, the 5% difference in lifetimes determined by the two different sets of optical potential parameters, should also be taken into account.

The total systematic error thus estimated is about 25%. By considering all these uncertainties, the lifetime was determined to be $\tau = 75 \pm 23$ ps, which corresponds to the $B(E2)$ value of 0.63 $\pm$ 0.19$e^2$fm$^4$, or 0.26 $\pm$ 0.08 in Weisskopf units (W.u.).

In Fig. 4(a), the $B(E2)$ value obtained for $^{16}$C is compared with all the other $B(E2)$ values known for the nuclei with $A < 50$ [13]. Nuclei with open shells tend to have $B(E2)$ values of greater than 10 W.u., whereas nuclei with shell closure of neutrons or protons or both, tend to have distinctly smaller $B(E2)$ values. Typical examples of the latter category are doubly magic nuclei, $^{16}$O and $^{40}$Ca, for which the $B(E2)$ values are known to be 3.17 and 1.58 W.u., respectively. The value of $B(E2) = 0.26$ W.u. obtained for $^{16}$C is even smaller than these extreme cases by as much as an order of magnitude.

The anomalously strong hindrance of the $^{16}$C transition can be also illustrated through comparison with an empirical formula based on a liquid-drop model [4]. According to the formula, the values of $E(2^+_1)$ and $B(E2)$ are related by

$$B(E2) = 6.47 \times Z^2 A^{-0.69} E(2^+_1)^{-1}.$$

The experimental $B(E2)$ values relative to $B(E2)_{\text{sys}}$ are plotted in Fig. 4(b). As noted in Ref. [5], the $B(E2)/B(E2)_{\text{sys}}$ ratios for open-shell nuclei mostly 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 ratio of 0.03 for $^{16}$C is exceptionally small, far smaller than for any other nuclei, including closed-shell nuclei.

Recently a hindered $B(E2)$ has been reported for $^{136}$Te [14]. This nucleus represents a case similar to $^{16}$C in the viewpoint of neighboring a doubly magic nucleus. The $B(E2)$ value observed for $^{136}$Te is 206 $e^2$fm$^4$, which corresponds to $B(E2)/B(E2)_{\text{sys}} = 0.21$. Thus, the $E2$ strength is indeed hindered. However, the degree of the hindrance is comparable to that of singly closed nuclei, and is far more moderate than for the case of $^{16}$C.

In considering the nature of the $^{16}$C transition, it is instructive to invoke a simple seniority-two empirical model [14] to describe the wave function of the $2^+_1$ state of $^{16}$C. The nucleus $^{16}$C has two missing protons and two extra neutrons with respect to $^{16}$O. Then, the mixing of $\pi^-$ and $\nu^-$ configurations with a residual interaction of $V$ can be considered by taking the observed $2^+_1$ states of $^{14}$C and $^{16}$O as the basis states. The two singly closed
isotopes, \(^{14}\text{C}\) with \(N = 8\) and \(^{18}\text{O}\) with \(Z = 8\), have two missing protons and two extra neutrons with respect to \(^{16}\text{O}\), respectively. Thus, the \(2^+\) state of \(^{14}\text{C}\) may be regarded as primarily due to proton excitations, while that of \(^{18}\text{O}\) can be attributed almost entirely to neutron excitations. The \(E(2^+_1)\) values are 7.01 and 1.98 MeV, and the \(B(E2)\) values are 3.70 and 9.53 \(e^2fm^4\) (or 1.84 and 3.40 W.u.) for \(^{14}\text{C}\) and \(^{18}\text{O}\), respectively. The very large \(E(2^+_1)\) for \(^{14}\text{C}\) indicates a large energy gap between the two proton orbitals, \(1p^3/2\) and \(1p^1/2\), while the moderate energy for \(^{18}\text{O}\) may reflect unoccupied \(sd\)-shell orbitals available for neutron excitation. Correspondingly, \(B(E2)\) for \(^{14}\text{C}\) is close to 1 W.u., whereas that for \(^{18}\text{O}\) is somewhat larger.

By applying the empirical model, \(|V| = 1067\) keV is required to generate the 1766-keV state in \(^{16}\text{C}\). The very high energy of \(|\pi^{-2}\rangle\) results in a configuration dominated by \(|\nu^2\rangle\):

\[
|2^+_1;^{16}\text{C}\rangle = 0.20|\pi^{-2}\rangle - 0.98|\nu^2\rangle.
\]

Here, the interaction \(V\) between proton-holes and neutron-particles is repulsive in the present case, leading to destructive interference between the two \(E2\) components. The calculated \(B(E2)\) for \(^{14}\text{C}\) is 7.0 \(e^2fm^4\), which falls between these components of \(^{14}\text{C}\) and \(^{18}\text{O}\), and overestimates the experimental \(B(E2)\) value of \(^{16}\text{C}\) by almost an order of magnitude. This is in contrast to the case for \(^{130}\text{Te}\), which when treated by seniority-two scheme provides a fairly reasonable estimate of the experimental \(B(E2)\). The unprecedented hindrance for \(^{16}\text{C}\) is suggestive of an anomalous nuclear structure.

In this regard, several unique features of the nuclei in the vicinity of \(^{16}\text{C}\) can be noted. For example, it has been suggested that the energy gaps between single-particle orbitals such as \(1p^3/2\) and \(1p^1/2\), may vary appreciably as the isotope changes from \(^{14}\text{C}\) to \(^{16}\text{C}\). It has also been indicated based on electric quadrupole moment measurement of neighboring nuclei that the \(E2\) effective charges can be markedly reduced for extremely neutron-rich nuclei. Furthermore, delicate interplay between clustering and deformation may prevail in these light nuclei. Elaborate calculations involving such exotic features can be expected to be helpful in accounting for the hindrance of \(B(E2)\) observed for \(^{16}\text{C}\).

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