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Inelastic proton scattering on ^{16}C

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Abstract. We have studied the 2_1^+ state in neutron-rich ^{16}C via inelastic proton scattering in inverse kinematics, using a 33 MeV/nucleon beam. From the angle-integrated cross-section, the deformation parameter $\beta_{pp'} = 0.50(8)$ is obtained. This value is greater than the deformation parameter deduced from the lifetime measurement. With these two result combined, the ratio of the neutron and proton quadrupole matrix elements is deduced to be approximately 7, indicating a neutron-dominant quadrupole collectivity in ^{16}C.

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1 Introduction

The $E2$ transition strength is a fundamental quantity of a nucleus and the reduced transition probability $B(E2)$ from the first 2^+ (2_1^+) state to the ground (0_{gs}^+) state for an even-even nucleus reflects the proton contribution to the quadrupole collectivity. Recently, an anomalously small $B(E2)$ for the 2_1^+ state in ^{16}C was highlighted via a lifetime measurement of this state [1]. The result indicates an unexpectedly weak proton contribution to the transition. On the other hand, as shown in table 1, the relatively small energy gap between the ground state and the 2_1^+ state $E(2_1^+)$, only 1766 keV, compared to the neighboring even-even C isotopes indicates a possible deformation in the ^{16}C nucleus. It is then of great interest to study the neutron contribution in order to disentangle this contradiction. A large difference in neutron and proton contributions has been reported by a recent study on $^{16}\text{C} + {}^{208}\text{Pb}$ inelastic scattering [2]. Extended studies using simpler hadronic probes should be helpful in exploring the nature of this phenomenon.

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Table 1. $B(E2; 2_1^+ \to 0_{gs}^+)$ and excitation energies of the first excited 2_1^+ state of several even-even C isotopes.

	^{10}C	^{12}C	^{14}C	^{16}C
$B(E2)$ (e^{2}fm^4)	12 [3]	8.2 [3]	3.8 [3]	0.63(19) [1]
$E(2_1^+)$ (keV)	3353	4439	7012	1766

We report inelastic proton scattering (p, p') on ^{16}C in reversed kinematics incorporating the technique of in-beam γ-ray spectroscopy. To determine the neutron contribution to the quadrupole collectivity, we have combined the (p, p') data with the lifetime measurement. At an intermediate energy of several tens of MeV, the inelastic proton scattering is about three times more sensitive to neutrons than to protons [4]. Thus, a combination of this (p, p') data with the lifetime measurement [1] allows us to disentangle the proton and neutron quadrupole collectivities.

2 Experiment

The experiment was performed at the RIKEN Accelerator Research Facility. A secondary ^{16}C beam was produced through fragmentation reaction by bombarding a 740 mg/cm^2 ^{9}Be target with a 94 MeV/nucleon ^{40}Ar primary beam. The ^{16}C was separated by the RIKEN Projectile Fragment Separator (RIPS) [5]. The flight times of the secondary beams between the second focal plane F2 and the final focal plane F3 were measured using two 1 mm thick plastic scintillators (F2PL and F3PL) placed at F2 and F3. Particle identification was performed by combining the time-of-flight (TOF) and the ΔE information, measured with F3PL. The ^{16}C beam, the energy of which was measured to be 33 MeV/nucleon at the center of the target using the TOF information, bombarded a liquid hydrogen target placed 1.3 m downstream of the F3PL.

The scattered particles were detected by a set of detector telescopes placed downstream of the secondary target. The telescope consisted of a parallel plate avalanche counter PPAC and a stack of Si detectors. The stack of Si detectors comprised four layers, each with four Si detectors of the same thickness arranged in a 2×2 matrix. The thicknesses of the four layers were 0.5 mm, 0.5 mm, 1.0 mm and 0.5 mm. Most of the ^{16}C nuclei were stopped in the third layer of the Si-telescope. The Si detectors provided information on ΔE and E. The PPAC provided the timing signals and was also used together with two upstream PPACs to measure the scattering angles of the ^{16}C particles. Particle identification was performed by means of the TOF-ΔE and ΔE-E methods. The acceptance of the Si-telescope was found to effectively cover 53(3)% of the angle-integrated cross-section of the inelastic scattering using a Monte Carlo simulation.

The de-excitation γ-rays were detected by an NaI(Tl) array consisting of 105 scintillators, which form part of the DALI2 [6]. The total full-energy peak efficiency was calculated with the GEANT simulation code [7] to be 6.3(4)% for 1.77 MeV γ-rays emitted from the ^{16}C nuclei in flight.

3 Result and discussion

To determine the angle-integrated cross-section, we evaluated the γ-ray yield associated with the $2^+ \to 0^+$ transition (see fig. 1), and obtained a value of 24.1(36) mb. To extract the deformation parameter $\beta_{pp'}$ and the deformation length $\delta_{pp'}$ ($= \beta_{pp'} r_0 A^{1/3}$), distorted-wave Born approximation calculations were performed. In the calculations, three sets of optical potential parameters, namely the global optical potential parameter set CH89 [8], and potential parameters obtained from elastic scattering on ^{12}C at 31 MeV and on ^{16}O at 34 MeV [9] were used. The $\beta_{pp'}$ and the $\delta_{pp'}$ obtained are shown in table 2. Since no significant preference between the three was found, we adopted the average values over the three sets of optical potential parameters. Hence, the deformation parameter and deformation length were determined to be 0.50(8) and 1.4(2) fm. This deformation length is larger than that of the lifetime measurement where only a small value of 0.41(6) fm was observed.

To obtain the magnitude of neutron contribution, we have combined the $\delta_{pp'}$ and the deformation length deduced from the lifetime measurement. Using the neutron and proton quadrupole matrix elements, M_n and M_p, defined in ref. [4], and applying the equation for the M_n/M_p ratio suggested therein, the M_n/M_p ratio was determined to be 6.6(15), assuming the same sign for the deformation lengths. This result is consistent with the recent measurement of $^{16}\mathrm{C} + {}^{208}\mathrm{Pb}$ inelastic scattering where a value of 7.6(17) was reported [2]. The $(M_n/M_p)/(N/Z) = 4.0(9)$ obtained for ^{16}C is by far the greatest value ever observed in any nucleus; it is about two times greater than the values for ^{20}O [10] and ^{48}Ca [11].

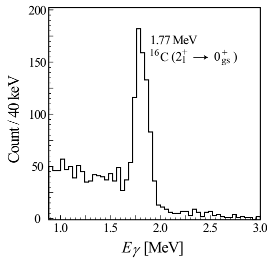

Fig. 1. Doppler-shift corrected γ-ray energy spectrum measured by 105 NaI(Tl) scintillators in coincidence with the scattered ^{16}C particles. The full-energy peak corresponding to the $2_1^+ \to 0_{gs}^+$ is clearly seen around 1.77 MeV.

Table 2. Nuclear deformation parameter $\beta_{pp'}$ and deformation length $\delta_{pp'}$ deduced from DWBA calculations.

Optical potential	$\beta_{pp'}$	r_0 (fm)	$\delta_{pp'}$ (fm)
CH89 [8]	0.493(41)	1.16	1.44(12)
$p + {}^{12}$C [9]	0.550(47)	1.10	1.52(13)
$p + {}^{16}$O [9]	0.456(38)	1.14	1.31(11)

4 Conclusion

We have performed an inelastic proton scattering on ^{16}C to study the 2_1^+ state in ^{16}C. From the angle-integrated cross-section, determined to be 24.1(36) mb, the deformation parameter $\beta_{pp'} = 0.50(8)$ is extracted. This result contrasts the result of the lifetime measurement where a small deformation parameter is observed. Combining these two results, a large value of 4.0(9) is obtained for the ratio of the neutron and proton quadrupole matrix elements $(M_n/M_p)/(N/Z)$. This result, together with the similar result reported in ref. [2], suggests that the 2_1^+ state in ^{16}C is dominated by neutron excitations.

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