Investigation of nuclear shapes through Coulomb-excitation reorientation-effect measurements

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The low-energy Coulomb excitation is a most direct method which selectively excite the collective states with cross sections that are a direct measure of nuclear matrix elements. This technique is precise and safe as the Coulomb electromagnetic interaction is well known and is free from nuclear contributions. Reorientation effect (RE) in such Coulomb-excitation measurements plays a vital role in nuclear structure physics as it facilitates information about the shape of even-even nuclei by determining the diagonal matrix elements $\langle 2_1^+ \mid\mid \hat{E}2 \mid\mid 2_1^+\rangle$, which are, in turn, proportional to the spectroscopic quadrupole moment, $Q_s(2_1^+)$ [1],

$$\begin{aligned} Q_S(2_1^+) &= \sqrt{\frac{16\pi}{5}} \frac{1}{\sqrt{2J+1}} \langle JJ20 \mid JJ\rangle \langle 2_1^+ \mid\mid E2 \mid\mid 2_1^+\rangle \\ &= 0.75793 \langle 2_1^+ \mid\mid E2 \mid\mid 2_1^+\rangle. \end{aligned} \quad (1)$$

The RE is a time-dependent second-order perturbation effect in Coulomb-excitation theory which causes the hyperfine splitting of magnetic substates and influence their population according to the sign and magnitude of $Q_s(2_1^+)$,

$$\sigma_{E2} = \sigma_R\ k_1 B(E2)\left(1 + k_2 Q_S(2_1^+)\right), \quad (2)$$

where $k_1(\vartheta_{c.m.}, \xi)$ and $k_2(\vartheta_{c.m.}, \xi)$ contain the dependence of σ_{E2} on the trajectory of the projectile. A positive sign of $Q_s(2_1^+)$ indicates an oblate shape in the intrinsic frame whereas a negative sign of it represents a prolate shape.

According to Morinaga and Ikeda, A=4n self-conjugate light nuclei can exhibit α cluster structures gradually emerging with increasing internal energy which are fully realized at the α threshold [2, 3]. The original experimental evidence for α clusters came from the identification of the 0_2^+ excited state at 7.654 MeV as the *Hoyle state* [4] in ^{12}C, composed of three α particles, and which resonance accounts for the observed carbon abundance in nature. These α cluster states may mix with the shell-model or mean-field states at lower excitation energies. Considerable mixing of $\approx$ 15% with the ground state is predicted in fermionic molecular dynamics (FMD) calculations [5]. Experimentally this mixing is also supported with the reported large electric monopole transition strength, $10^3 \times \rho^2(E0) = 500(81)$, from electron scattering experiments [6]. The mixing of α cluster states with the mean-field has pronounced effect on the ground state shape in ^{12}C which was reported to have a oblate shape. Various scattering measurements have been performed to estimate the quadrupole deformation (β_2) such as (e, e'), (p, p'), (α, α'), although most of these experiments are insensitive to the sign of deformation. These studies reported the β_2 values spanning from $\approx +0.3$ to -1.37 which does not show conclusive evidence for the oblate ground state deformation in ^{12}C predicted in α cluster models [7].

Previously, only one Coulomb-excitation RE measurement (CERE) was performed in 1983 by Vermeer et al.,[8] who determined the $Q_s(2_1^+)$ value in ^{12}C through inelastic scattering data of ^{12}C on ^{208}Pb at 53 MeV. This study estimated the $Q_s(2_1^+) = +0.06(3)$ eb through normalization procedure (considering B(E2) = 38.8(22) e^2fm^4 and global nuclear polarizability parameter, $\kappa(2_1^+) = 1$) which supporting the oblate shape for the 2_1^+ in ^{12}C.

A CERE measurement of ^{12}C was carried at TRIUMF/ISAC facility using TIGRESS clover detector array comprised of 8 TIGRESS HPGe clover detector each having 32-fold segmentation. A beam of ^{12}C ions with 4.97 MeV/u was used to Coulomb excite the first 2^+ state at 4.439 MeV in ^{12}C by impinging on a 3 mg/cm^2 thick ^{194}Pt target. The scattered beam and recoiling particles were detected in a double sided, 500-μm thick, CD-type silicon annular detector which was mounted at 19.4 mm downstream from the target position. Fig. 1 is a representative sum γ−ray spectrum obtained from the TIGRESS array in coincidence with the particles detected in CD de-

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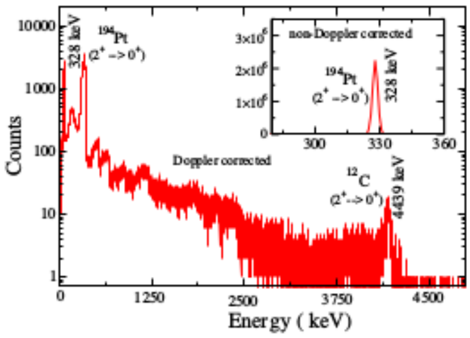

FIG. 1: A representative Doppler corrected sum γ-ray spectrum generated employing the coincidence and particle energy sharing conditions which illustrate the 328 keV and 4439 keV γ transitions from 2_1^+ state in ^{194}Pt and ^{12}C, respectively. The inset shows the non-Doppler corrected spectrum.

tector including the energy sharing condition and inelastic particle gates. This spectrum shows the evidence for the 328 keV and 4439 keV γ-ray transitions from the first 2^+ states in both the target (^{194}Pt) and projectile (^{12}C) excitations, respectively.

A semi classical coupled-channel Coulomb-excitation least-squares code GOSIA [10] was used for analyzing the experimental results. In Coulomb excitation theory, the second order effect such as nuclear polarizability [11] due to virtual electric dipole excitations of states near Giant dipole resonance (GDR) region also influence the sign and magnitude of $Q_s(2_1^+)$. The GOSIA code take this effect into account by considering the nuclear polarizability parameter $[\kappa(2_1^+)] = 1$. However, the value of $\kappa(2_1^+)$ was shown to be significantly different from a value of 1 for the light nuclei in recent studies based on shell model (SM) calculations [12] which have been successful in reproducing the κ parameters for p shell nuclei. In this work, the no-core shell model (NCSM) calculations were performed using *CD-Bonn 2000 2N* potential and estimated the value of nuclear polarizability $(\kappa) = 2.2(2)$ for 2_1^+ state in ^{12}C which was implemented in GOSIA analysis. $Q_s(2_1^+) = +0.053(44)$ eb and $Q_s(2_1^+) = +0.08(3)$ eb are determined for the present work and from the reanalysis of the previous work, respectively, whose waited average yields a final value of $Q_s(2_1^+) = +0.071(25)$ eb is in agreement with the recent *ab initio* calculations [13]. The present work confirms the oblate deformation for the 2^+ state in ^{12}C, and further emphasis the effect of nuclear polarizability in Coulomb-excitation studies of light nuclei.

Nuclei close to N = Z line in mass 40 region shows dramatic shape changes from a prolate to an oblate shape or vice-versa. For example, the systematic observation of measured spectroscopic quadrupole moment, $Q_s(2_1^+)$ values of ^{20}Ne, ^{24}Mg, ^{28}Si, ^{32}S, ^{36}Ar and predicted values in ^{40}Ca show Zig-Zag of shape changes starting from a prolate to an oblate and vice versa, which are interpreted to be caused due to multiparticle-multihole excitations across N = Z= 20 shell gap. However there are huge discrepancies between predicted and determined values and also due to lack of experimental accuracy. Thus a series of reorientation measurements have been performed at iThemba Labs to determine the $Q_s(2_1^+)$ values in mass 40 region. Results of these experiments and planned experiments with CAGRA clover array at RCNP, Japan will be presented.

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