Investigation of the determination of nuclear deformation using high-energy heavy-ion scattering†

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Deformation of atomic nuclei is a fundamental characteristic that influences nuclear structure and reaction dynamics. Accurate determination of the quadrupole deformation length (δ_2) is essential for understanding nuclear behavior, as it reflects collective properties of nucleus. Conventionally, δ_2 has been determined using the deformed potential (DP) model,[1)] which assumes the relation:

$$\delta_2 = \delta_2^{(\mathrm{pot})}, \tag{1}$$

where $\delta_2^{(\mathrm{pot})}$ denotes the deformation length of the nuclear potential. However, this assumption has no basis and is questionable because $\delta_2^{(\mathrm{pot})}$ includes the information on the projectile and target nuclei, and also the nuclear force. Based on this unestablished assumption (1), δ_2 has been experimentally determined via the DP model.

This study aimed to investigate the validity of the DP model by systematically comparing $\delta_2^{(\mathrm{pot})}$ with δ_2 directly derived from the deformed density (DD) model. The DD model is based on the double-folding model, and the diagonal and coupling potentials are constructed by folding the effective nucleon-nucleon interaction with the projectile and target densities. The coupling potentials are calculated using the transition densities, which reflect the deformation effect (δ_2). Thus, the DD model enables us to extract δ_2 directly as opposed to via $\delta_2^{(\mathrm{pot})}$.

In this study, we calculated the inelastic scattering cross sections for the 2_1^+ state of ^{12}C, denoted as $\sigma(2_1^+)$, using the DD and DP models. We analyzed $\sigma(2_1^+)$ for ^{12}C projectiles on ^{12}C, ^{16}O, ^{40}Ca, and ^{208}Pb targets in a wide range of the incident energies (E/A = 50–400 MeV). We first assume the deformed density characterized by $\delta_2 = -1.564$ fm. Then, we can construct the diagonal and coupling potentials microscopically via the folding procedure. Once these potentials are determined, $\sigma(2_1^+)$ can be calculated in the standard Coupled-Channel framework. The result of the DD model was used as a reference calculation in this study. By contrast, in the DP model, we derived the coupling potential by assuming a deformed potential characterized by $\delta_2^{(\mathrm{pot})}$. The value of $\delta_2^{(\mathrm{pot})}$ was determined to reproduce the $\sigma(2_1^+)$ calculated with the DD model. Finally, we systematically compared $\delta_2^{(\mathrm{pot})}$ with δ_2 in high-energy heavy-ion scattering and elucidated the relationship between them.

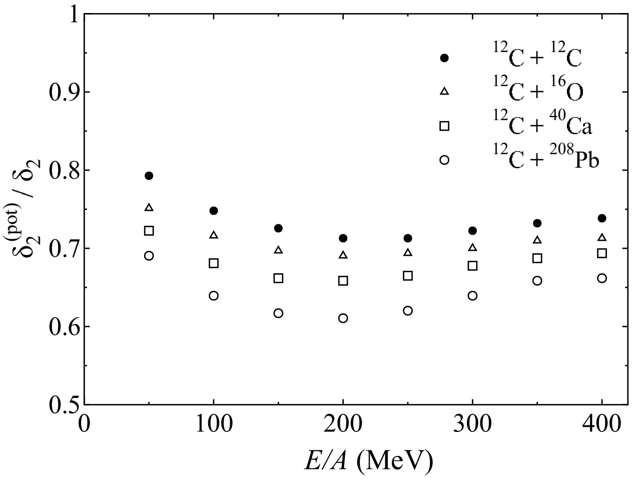

Fig. 1. Deformation length of the nuclear potential $\delta_2^{(\mathrm{pot})}$ derived from ^{12}C inelastic scattering cross sections at E/A = 50–400 MeV, divided by $\delta_2 = -1.564$ fm. The filled circles, open triangles, open squares, and open circles represent the results for the scattering by ^{12}C, ^{16}O, ^{40}Ca, and ^{208}Pb targets, respectively.

Figure 1 shows the energy dependence of $\delta_2^{(\mathrm{pot})}$, derived from $\sigma(2_1^+)$ calculated using the DD model. It should be noted that the values of $\delta_2^{(\mathrm{pot})}$ were divided by δ_2. The filled circles, open triangles, open squares, and open circles represent the results for the scattering of ^{12}C by ^{12}C, ^{16}O, ^{40}Ca, and ^{208}Pb targets, respectively. The results indicate that $\delta_2^{(\mathrm{pot})}$ was systematically underestimated by approximately 20–40%, and exhibits strong dependencies on incident energy and target mass. Notably, $\delta_2^{(\mathrm{pot})}$ became smaller as the target mass increased. This significant discrepancy raises questions about the reliability of determining δ_2 from $\delta_2^{(\mathrm{pot})}$ in high-energy heavy-ion scattering. A systematic underestimation of the quadrupole deformation length is thus expected in studies relying on the DP model's assumption of $\delta_2 = \delta_2^{(\mathrm{pot})}$.

Reference
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† Condensed from the article in Phys. Rev. C **110**, 024604 (2024)
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DOI:10.34448/RIKEN.APR.58-013