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Extraction of ground state deformation parameters of ^{154}Sm via fusion barrier distribution

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The intrinsic deformation of atomic nuclei has been explored employing a host of experimental techniques and theoretical approaches over the last several decades. Some of the experimental probes are high-energy heavy ion collisions, electron-scattering, muonic X-rays, isotopes shift, Coulomb excitation, neutron-scattering, α-scattering, proton scattering, deuteron-scattering, ^{3}He-scattering and low-energy heavy ion collisions. It has been found that extraction of unambiguous and accurate value of hexadecapole (β_4) deformation is rather challenging, compared to the lower-order multipoles *i.e.*, quadrupole (β_2) and octopole (β_3).

It is well known from studies of low-energy heavy ion-induced reactions that the measured fusion cross sections (σ_{fus}) below the barrier are significantly larger in comparison with the prediction of no-coupling model calculations. The observed enhancement can be understood in most cases by considering the couplings between the relative motion and the low-lying collective states of the collision partners and nucleon transfer channels. The couplings lead to a distribution of fusion barrier heights ($\mathcal{D}$) and, thus the shape of the $\mathcal{D}$ contains information about the inherent structure of the participating nuclei. $\mathcal{D}$ for a specific reaction can be derived from precisely measured fusion and differential quasielastic scattering excitation functions, as the two phenomena are complementary to each other due to conservation of incident flux.

In recent years, determination of ground state deformation parameters of sd-shell [1, 2], as well as rare earth [3, 4, 5] nuclei, based on either fusion or quasielastic scattering measurements in conjunction with coupled-channels (CC) calculations, has been reported. In this context, a combined analysis of both the fusion and the quasielastic scattering data [6] to extract the deformation parameters of a specific nucleus would be interesting and useful for verifying the robustness of the adopted methodology.

We present here CC analysis, using a modified version of the code ccfull [7], of both fusion and quasielastic scattering excitation functions and $\mathcal{D}$s for the system ^{16}O+^{154}Sm. We note that the $\mathcal{D}$ is more sensitive to minor variations in the reaction parameters compared to the excitation function. The $\mathcal{D}$, which is defined as the double derivative of the σ_{fus} times E (energy available in the centre of mass frame of reference) with respect to E, is usually derived from measured fusion excitation function using the point difference formula [8]. This method suffers from an ambiguity, related to the energy step size (ΔE), and also results in larger uncertainty in the higher energy end. We have derived the $\mathcal{D}$ from fusion data using a multi-Gaussian analytic recipe proposed by Jiang *et al.* [9], which circumvents these limitations to a large extent. In the CC calculations, ^{16}O has been treated as inert, while rotational coupling has been considered for ^{154}Sm including the states 0^+, 2^+, 4^+ and 6^+, for both fusion and quasi-elastic scattering. In both cases, a broad parameter space for β_2 and β_4, ranging from -0.6 to $+0.6$, has been scanned in fine steps of 0.01 to obtain the best fit of the $\mathcal{D}$ through χ^2-minimization.

Further, a Bayesian analysis has been performed using a Markov-Chain Monte Carlo (MCMC) framework to quantify the deformation parameters β_2 and β_4 along with their uncertainties. Uniform priors have been applied to β_2 and β_4 and a Gaussian likelihood function has been used based on the χ^2 statistic. The `emcee` Python package, which implements the Affine-Invariant MCMC Algorithm [10, 11], has been used to sample the posterior distributions. The fusion data has yielded the values of $\beta_2 = 0.32^{+0.02}_{-0.02}$ and $\beta_4 = 0.06^{+0.02}_{-0.02}$, based on $\mathcal{D}$ with a step size of 1.5 MeV.

For the quasi-elastic cases the optimum values have been found to be $\beta_2 = 0.34^{+11}_{-12}$ and $\beta_4 = 0.31^{+04}_{-04}$. Thus, the values of β_2 obtained from both fusion and quasielastic data agree quite well. However, determination of β_4 by this approach appears to be questionable. Similar studies on other nuclei are necessary to verify effectiveness of the method.

The present study demonstrates that the Gaussian analytic method can be useful in deriving the $\mathcal{D}$, which can be corroborated by CC calculations to obtain structural information of the collision partners. It might be rewarding to revisit the wealth of experimental data on heavy ion-induced fusion, that are available in the literature, for similar studies.

It is also important to note here that influence of the $2n$-pickup channel on fusion in the present system has been reported in earlier studies (see *e.g.*, in Ref. [12]). However, the current fusion models are inadequate to account for multi-nucleon transfer (MNT) channels that might affect fusion. Recent studies [13, 14], highlight the limitations of the conventional CC approach in describing low-energy heavy-ion collisions. These limitations suggest that the deformation parameters extracted from fusion and quasielastic scattering data, based on the current theoretical models, may change as deeper understanding of the interplay between MNT channels and fusion is achieved.

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Consent

Primary author: KUMAR, Chandra (Inter-University Accelerator Centre)

Presenter: Dr NATH, Subir (Inter University Accelerator Centre)

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