Fusion cross section measurements induced by heavy ions

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Introduction

With the advent of heavy-ion reactions, nuclear physics has acquired a new frontier. Many studies have been performed to understand the nuclear properties and the nucleus internal structure. Heavy ion-induced fusion reactions around the Coulomb barrier have been pursued quite intensely for the past few decades [1, 2]. Fusion cross sections are found to be enhanced, in some cases by several orders of magnitude, over the prediction from the one-dimensional barrier penetration model near and below the Coulomb barrier. The coupling of internal degrees of freedom such as transfer of valence neutrons, neck formation, zero point motion, and static deformation have been considered in order to explain observed enhancements of the fusion cross sections. The coupling with intrinsic degrees of freedom has an effect of changing the height of the barrier. Barriers lower than the one-dimensional Coulomb barrier are then responsible for the enhancement of fusion cross sections. Deformation of one or both the reaction partners is known to enhance sub-barrier fusion cross sections. The barrier distributions are known to be highly sensitive to higher order nuclear deformations. The experimental barrier distributions can be obtained from the fusion cross sections as well as from quasi elastic scattering data.

In this thesis we aimed to study the heavy ion induced fusion reactions around the Coulomb barrier energies. An attempt has been made to measure the influence of higher order static deformations on sub-barrier fusion cross sections. Also our purpose to obtain information on the structure of nuclei participating in a reaction from fusion cross sections. Isotopically enriched targets of ^{174}Yb and ^{176}Yb used in the study were prepared at target laboratory of IUAC using vacuum evaporation technique. We also studied the effect of higher order deformation on fusion cross section in orientation degrees of freedom using realistic calculations for both Coulomb and nuclear potentials. In addition, we studied the deformation effects, theoretically on fusion cross section using various global nuclear potentials and obtained some remarkable insights.

Experimental aspect

The experiments have been performed in the HIRA facility using Pelletron beams of IUAC. Pulsed beam of ^{16}O with a pulse separation of 4μs was bombarded on isotopically enriched ^{174}Yb (99.99%) and ^{176}Yb (96.63%) targets of thicknesses 125 μg/cm^2 and 170 μg/cm^2 respectively on 25 μg/cm^2 $^{\mathrm{nat}}$C backing. Evaporation residue (ER) excitation functions were measured at laboratory beam energies (E_{lab}) of 64.6 –79.6 MeV, in steps of 1 MeV near the barrier and 81.6 –103.6 MeV, in steps of 2 MeV at well above the barrier (at the centre of the targets). Two silicon detectors were placed inside the target chamber at ± 15.5^o with respect to the beam direction in the horizontal plane to record Rutherford-scattered beam particles for absolute normalization of ER cross sections. To reset charge states of the ERs, a 30 μg/cm^2 thick $^{\mathrm{nat}}$C foil was placed 10 cm downstream from the target. A multi-wire proportional counter (MWPC), with an active area of 150 mm × 50 mm, was placed at the focal plane of the HIRA to detect the ERs.

We performed the measurement of ER excitation function and BD for ^{16}O + ^{174,176}Yb systems using the recoil mass spectrometer HIRA. Utmost caution was exercised in identifying ERs, particularly at the lowest energies,

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so that those are not contaminated with more abundant background events. Since the presence of the compound nucleus fission (CNF) and non-compound nucleus fission (NCNF) in these reactions are expected to be insignificant, measured ER excitation functions were taken as the fusion excitation functions. We investigated the role of negative hexadecapole deformation (β_4) in reproducing the fusion data with the help of coupled-channel calculations and observed supplementary results. Our experimental results suggested a new β_4 value of -0.020 for the systems studied [3]. Fusion BDs were also extracted from the cross sections. But, it was not possible to draw proper conclusions from BDs independently. Also, the derived BD was not useful to determine the value of β_4 which demands more precise data. We must note here that experimental determination of β_4 is difficult. Experimentally determined β_4 are susceptible to systematic uncertainties and also heavily dependent on the model used in a particular work. Thus, more precise measurements in this mass region using different experimental techniques are called for to achieve convergence of the results and to overcome dependence on models.

Theoretical aspect

We present a theoretical study on the impact of fusion barrier parameters and fusion cross section for the reactions ^{16}O + ^{176}Yb, ^{16}O +^{166}Er, and ^{16}O +^{154}Sm. The influence of static quadrupole and hexadecapole deformation of nuclei in the lanthanide region are studied using various global nuclear potentials. For evaluation of the fusion barriers parameters ($V_{\rm B}$, $R_{\rm B}$, $\hbar\omega$), up to eleven versions of proximity-based potentials are employed. These parameters are used for calculation of the fusion cross section of the present reactions through the Wong's formula within parabolic approximation. The comparison between the total interaction potential on fusion barriers for ^{154}Sm ($\beta_4 > 0$) and ^{176}Yb ($\beta_4 < 0$) suggests that the effect of positive and negative hexadecapole deformations have played a crucial role predicted by theoretical estimates. From the studies of nucleus-nucleus potential it is found that the deformation and orientation effects are more pronounced on the Bass 77, Bass 80, AW 95, and BW 91 potentials than the rest. Since the barrier parameters $V_{\rm B}$, $R_{\rm B}$ and $\hbar\omega$ are orientation (θ) dependent, the fusion cross section from the θ dependent potential were estimated ; thereby a variation of the cross sections was seen. Based on the deformed and energy dependent barrier penetration models, calculations have improved for the majority of nuclear interaction potentials at below as well as at above barrier energies in comparison to experimental results. For instance, the fusion cross sections by Prox 77 and Prox 00 potentials showed good agreement with the experimental data at both subbarrier and above barrier energies. Overall, the fusion cross sections by Prox 77, Prox 88, Prox 00, Prox 00DP, Denisov DP, Bass 80, CW 76, and AW 95 potentials appear to exhibit stronger agreement with the experimental data, than the rest. Hence, it is concluded that the total interaction potential is extracted by taking into account the Coulomb corrections for the majority of the potentials, except BW 91 where both the Coulomb and nuclear corrections is considered. The deviation of fusion cross sections from the experimental data may be attributed to the fact that both Coulomb and nuclear corrections are needed for all the proximity potentials [4].

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