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Effect of nuclear density distributions on the fusion dynamics of ^{48}Ca-induced reactions

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Introduction

In the study of low-energy heavy-ion reactions, it is imperative to have a complete picture of all the factors affecting nucleus-nucleus interaction. The repulsive Coulomb and centrifugal interaction potentials have well-defined formulae, whereas the picture of attractive nuclear interaction potential is not clear. There are different microscopic, semi-microscopic and phenomenological models developed to calculate nuclear interaction potential between two colliding nuclei. One such model is the well-known double folding approach which estimates the real part of nuclear interaction potential by integrating an effective nucleon-nucleon (NN) potential over the nuclear densities [1, 2].

There are different radial nuclear density models are available which allow us to calculate nucleus-nucleus interaction potential. The microscopic Relativistic Mean Field (RMF) theory [2] and the non-relativistic Skyrme Hartree-Fock (SHF) formalism [3] are employed in the present work to find out theoretical radial mass densities. These densities are folded to calculate the nuclear interaction potential which ultimately in the addition of Coulomb potential gives the nuclear fusion barrier of the heavy ion reactions. The extracted characteristics of this fusion barrier are then used in the calculation of fusion cross-section. In the present study, we have investigated the shift in the fusion and/or capture cross-section around the Coulomb barrier, when it is being calculated using radial mass densities from RMF and SHF formalism. The fusion reaction is strongly affected by the surface density of the interacting nuclei, which further depends on the different theoretical approaches and assumptions taken into the consideration. The M3Y model is used to calculate NN interaction potential with RMF and SHF densities within the double folding approach [1]. The fusion cross section is calculated with the simple, $\ell = 0$ barrier-based Wong formula [2]. The systems considered in this study are ^{48}Ca+^{90}Zr,^{208}Pb,^{238}U.

Theoretical Formalism

The Skyrme-Hartree-Fock-Bogoliubov approach is a well-defined non-relativistic model for the ground state properties of nuclei. The SHF radial densities used here are provided in nuclear reaction code TALYS [3]. The radial densities are also obtained from the microscopic self-consistent Relativistic Mean Field (RMF) theory, in which the nucleus is considered a composite system of nucleons interacting through the exchange of mesons and photons [2]. The nuclear potential V_n is obtained using these RMF and SHF densities within the double folding approach [1, 2].

$$V_n(\vec{R}) = \int \rho_p(\vec{r}_p)\rho_t(\vec{r}_t)V_{eff} \\ (|\vec{r}_p - \vec{r}_t + \vec{R}| \equiv r)d^3r_p d^3r_t \qquad (1)$$

Here V_{eff} is the M3Y effective NN interaction potential, and ρ_p, ρ_t are the radial densities of the projectile and target nuclei calculated using both SHF and RMF models. The nuclear interaction potential along with the Coulomb and centrifugal potentials provide us with the total fusion potential. The fusion characteristics i.e. barrier height (V_B), position (R_B) and oscillator frequency ($\hbar\omega$) of this interaction potential are further used in calculating the fusion cross section using simple Wong formula [2].

TABLE I: The barrier position R_B (in fm) and barrier height V_B (in MeV) for the reaction systems under study obtained using RMF and SHF densities.

Reaction	RMF		SHF	
	R_B	V_B	R_B	V_B
^{48}Ca+^{90}Zr	10.8	99.31	10.7	100.66
^{48}Ca+^{208}Pb	12.4	177.93	12.2	181.47
^{48}Ca+^{238}U	12.8	194.18	12.6	196.92

Result and Discussions

Fig.1(a) shows the RMF (solid lines) and SHF (dashed lines) radial density distributions for all the interacting nuclei under consideration i.e., ^{48}Ca, ^{90}Zr, ^{208}Pb and ^{238}U. It is observed from Fig.1(a) that there is a slight difference in the RMF and SHF densities at the surface or tail region of all the above-said nuclei. To explore the effect of this change in density on the fusion dynamics, next, the barrier height (V_B) and position (R_B) are listed in Table I for the respective systems. The relative change in the density is reflected in the subsequent calculation of the fusion barrier height and position of the systems. A lower barrier height is observed for RMF densities in comparison to the SHF densities. Moreover, the change in V_B is increasing as we move towards the heavier target. With the values listed in Table I, the fusion and/or capture cross-section is calculated using the simple Wong formula. Fig.1(b) shows the percentage shift $\{(\sigma^{RMF} - \sigma^{SHF})/\sigma^{RMF}\} \times 100$. We can observe a drastic change in the shift of fusion and/or capture cross-section when we move from lower Z_1Z_2 to higher Z_1Z_2 systems, Z_1 and Z_2 being the atomic numbers of the projectile and target nuclei, respectively. The sub-barrier region of the heaviest system $^{48}Ca +^{238} U$ shows a high percentage of the shift in the cross-section as compared to the lightest ^{48}Ca+^{90}Zr one under consideration. The slope observed in the near-barrier region of the systems is observed to decrease with Z_1Z_2 value inversely. These observations suggest that a small change in the density of interacting nuclei at the surface region directly influences the barrier characteristics and inherently the fusion and/or capture cross-section. Thus a non-relativistic or phenomenological density cannot mimic the relativistic ones in the study of heavy ion reactions. More systematic analysis including reactions from the different mass regions is being carried out.

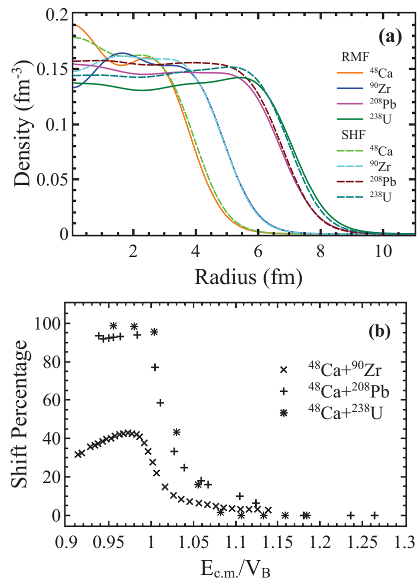

FIG. 1: (a) The RMF (solid lines) and SHF (dashed lines) total radial density distribution for all nucleus involved in considered reactions. (b) Percentage shift vs $E_{c.m.}/V_B$ for ^{48}Ca+^{90}Zr,^{208}Pb, and ^{238}U reactions.

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