The fusion excitation function for a positive Q-value system at near and deep sub-barrier energies using Skyrme energy density formalism

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Introduction

During the last decade, the measurement of fusion cross-sections has been extended to deep sub-barrier energies and an enigmatic behaviour has been observed [1, 2] that is the measured fusion cross-section falls more rapidly with respect to the Wong's formula [1], the standard coupled channel (CC) calculations [2] and optical model calculations [3, 4]. However, the observed fusion cross-sections has been reproduced using many theoretical calculations, but with certain adjustments made in parameters of the theory to obtain the required potentials, like large surface diffusion is used in Woods-Saxon potential with in the CC calculation [5].

Recently, fusion cross-sections has been measured by C. L. Jiang et al. [6] for a positive Q-value system: $^{24}Mg +^{30} Si$ (Q = 17.89 MeV) and the calculations has been performed by reconstructing nuclear potential (M3Y+repulsive) using parametrisation of nuclear densities with optimisation of the radii of interacting nuclei.

In this paper, *without any adjustment*, the nuclear interaction potential is obtained in semiclassical extended Thomas-Fermi approach of the Skyrme energy density formalism, where the potential is expressed as the sum of (i) spin-orbit density independent part (attractive) and (ii) the spin-orbit density dependent potential part (repulsive), following our earlier work [7] for arbitrarily chosen Skyrme force SIV over the center of mass energy range 20 to 30 MeV. The total interaction potential is obtained by adding Coulomb potential directly to the nuclear potential. The characteristics of the said interaction potential are used in Wong's formula to calculate the fusion cross-section as a function of center of mass energies.

Methodology

The interaction potential between two nuclei of radii R_{01}, R_{02} at separation $R_{01}+R_{02}+s$, in slab approximation, (for detail see [7] and references there in) is,

$$V_N(R) = 2\pi\bar{R}\int_{s_0}^{\infty} e(s)ds, \qquad (1)$$

where $\bar{R} = R_{01}R_{02}/(R_{01} + R_{02})$ is the mean curvature radius and $e(s)$ is the interaction energy per unit area between two flat slabs of semi-infinite nuclear matter with surfaces parallel to the $x-y$ plane and moving in the z-direction and separated by distance s, having a minimum value s_0 and is given by,

$$\int_{s_0}^{\infty} e(s)ds = \int\left[H(\rho,\tau,\vec{J}) - \sum_{i=1}^{2} H_i(\rho_i,\tau_i,\vec{J}_i)\right]dz, \qquad (2)$$

where H is the Skyrme Hamiltonian density, $\rho(=\sum_i \rho_i)$, $\tau(=\sum_i \tau_i)$ and $\vec{J}(=\sum_i \vec{J}_i)$, are nuclear density, kinetic energy density and spin-orbit density, respectively, for composite system and $i = 1, 2$ for the two interacting nuclei. Here the two parameters Thomas-Fermi density is used as nuclear density, which in slab approximation is given as,

$$\rho_i(z_i,T) = \rho_{0i}(T)\left[1 + e^{\left(\frac{z_i - R_{0i}(T)}{a_{0i}(T)}\right)}\right]^{-1} \qquad (3)$$

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with $z_2 = R - z_1$ and central density is, $\rho_{0i}(T) = \frac{3A_i}{4\pi R_{0i}^3(T)}\left[1 + \frac{\pi^2 a_{0i}^2(T)}{R_{0i}^2(T)}\right]^{-1}$ where central radii $R_{0i}(T)$, surface thicknesses $a_{i0}(T)$ are taken from [7]. The nuclear potential $V_N(R)$ is expressed as the sum of two part one proximity part $V_P(R)$ (attractive) and $V_J(R)$ (repulsive) and is given as

$$V_N(R) = V_P(R) + V_J(R) \tag{4}$$

The total interaction potential $V_T(R)$ is obtained by adding Coulomb potential, kZ_1Z_2/R to $V_N(R)$. The characteristics of $V_T(R)$: barrier height $V_B(E_{cm})$, barrier position $R_B(E_{cm})$ and curvature $\hbar\omega_0(E_{cm})$, for s partial wave ($l = 0$) are used in Wong's formula [8], given below,

$$\sigma(E_{cm}) = \frac{\hbar\omega_0 R_B^2}{2E_{cm}} \ln\left[1 + e^{\left\{\frac{2\pi}{\hbar\omega_0}(E_{cm}-V_B)\right\}}\right] \tag{5}$$

to calculate fusion cross-section as a function of center of mass energy.

Calculations and results

The fusion cross-sections as a function of center of mass energies i.e. the fusion excitation functions are calculated with and without spin-orbit interaction potential in the total potential. In Fig.(1), the dotted line shows the fusion excitation function with spin-orbit interaction potential, the solid line represent the same but without spin-orbit interaction potential and the solid spheres shows the experimental data [6]. On the comparison of the calculated fusion excitation functions with the experiment [6], as shown in Fig.(1), it is clear that the fusion excitation functions calculated with the total interaction potential excluding spin-orbit interaction is reproducing the observed data very nicely at deep sub-barrier energies and even near barrier energies, where as the fusion cross-section calculated including spin-orbit interaction in the total potential is under-estimating the experimental data over this energy range.

In conclusion, we found that the total interaction potential, for the fusion of ^{24}Mg and ^{30}Si, in semiclassical extended Thomas-Fermi approach of Skyrme energy density formalism, excluding spin-orbit interaction and with nuclear density parameters of [7] for Skyrme force SIV, has the ability to reproduce the observed data [6] very nicely with Wong's formula.

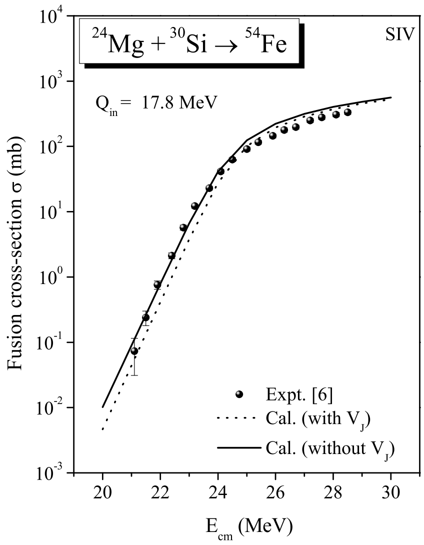

FIG. 1: A comparison of calculated and experimental fusion excitation functions.

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