Fusion excitation functions for $^{32}S +^{90} Zr$ near sub-barrier energies with E_{cm}-dependent nuclear surface thickness

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Introduction

Many modification has been found in literature, like in reference [1, 2] etc., to reproduce the experimental data near sub barrier energies. An investigation for the same is done here by modifying the nuclear surface thickness of colliding nuclei in the semi-classical extended Thomas-Fermi approach of Skyrme energy density functional (SEDF). As it gives an opportunity to have different potentials (height, position and curvature) for different Skyrme forces and/or for different parameters of two parameter Fermi density distribution (FD) used as nuclear density [3]. Here, the interaction potential is modified by changing the surface thickness parameter a_i to fit the data [1] at a given center of mass energy E_{cm} for the positive Q-value system $^{32}S +^{90} Zr$ in E_{cm} range 73.2 to 95.3 MeV. The comparison is also made with the results of a_i of ref. [3] and a new temperature dependance for a_i.

Methods

The nuclear interaction potential $V_N(R)$ in the slab approximation of SEDF is defined as the interaction between two spherical nuclei of half density radii R_{01} and R_{02}, whose centers are separated by $R = R_{01} + R_{02} + s$, given as

$$\begin{aligned} V_N(R) &= 2\pi\bar{R}\int \{H - [H_1 + H_2]\}\, dz \\ &= 2\pi\bar{R}\int_{s_0}^{\infty} e(s)ds = 4\pi\bar{R}\gamma b\phi(D) \quad (1) \end{aligned}$$

where H the Skyrme Hamiltonian, for detail see [3], and depends upon nuclear density $\rho(= \rho_n + \rho_p)$, kinetic energy density $\tau(= \tau_n + \tau_p)$ and spin-orbit density $\vec{J}(= \vec{J}_n + \vec{J}_p)$, $\bar{R} = R_{01}R_{02}/(R_{01} + R_{02})$ is the mean curvature radius, defining the geometry of the system, 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, $\gamma = 0.9517 \left[1 - 1.7826 \left(\frac{N-Z}{A}\right)^2\right]$ MeV fm^{-2}, the nuclear surface energy constant, and b=0.99 fm, the surface width.

The universal function $\phi(D)$ used here is obtained in exact calculation of SEDF. The temperature-dependent FD distribution [4] for the slab approximation is given by

$$\rho_i(z_i) = \rho_{0i}(T)\left[1 + \exp\left(\frac{z_i - R_{0i}(T)}{a_{0i}(T)}\right)\right]^{-1} \quad (2)$$

with $z_2 = R - z_1$, and central density $\rho_{0i}(T) = \frac{3A_i}{4\pi R_{0i}^3(T)}\left[1 + \frac{\pi^2 a_{0i}^2(T)}{R_{0i}^2(T)}\right]^{-1}$.

Then, following our earlier work [3] for nuclear density ρ_i $(= \rho_{n_i} + \rho_{p_i})$, for the half density radii $R_{0i}(T = 0)$ and surface thickness parameters $a_{0i}(T = 0)$, where $\rho_{n_i} = (N_i/A_i)\rho_i$ and $\rho_{p_i} = (Z_i/A_i)\rho_i$, i=1,2 for two nuclei,

The temperature dependence in the above formulas are then introduced as in Ref. [5], $R_{0i}(T) = R_{0i}(T = 0)[1 + 0.0005T^2]$ and $a_{0i}(T) = a_{0i}(T = 0)[1+0.01T^2]$. Also, the surface width b is made T-dependent [6], $b(T) = 0.99(1 + 0.009T^2)$.

Calculations and results

Using the above information on V_B, R_B and $\hbar\omega_0$ is obtained for an inverted harmonic oscillator fit to the curvature in $V_T(R)$ at the top of the potential barrier in Wong's formula [7] for the cross-sections as a function of the center of mass energy E$_{c.m.}$ as

$$\sigma = \frac{\hbar\omega_0 R_B^2}{2E_{cm}} \ln\left(1 + \exp\left[\frac{2\pi}{\hbar\omega_0}(E_{cm} - V_B)\right]\right) (3)$$

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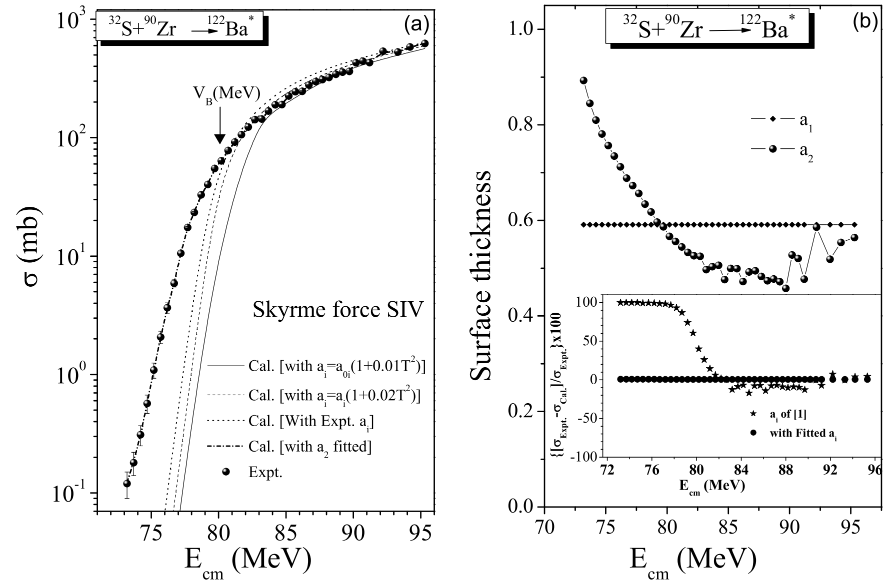

FIG. 1: (a) Comparison of fusion excitation functions for $^{32}S +^{90} Zr$ reaction obtained experimentally [1] (solid spheres) with the calculated in SEDF: the solid line with surface thickness parameter (a_i) of [3], dashed line with new temperature dependence for a_i (given in bracket), dotted line for experimental a_i [8, 9] and the short dash dotted line is with E_{cm} dependent surface thickness a_i. (b) Surface thickness parameter a_i required to fit the data as function of E_{cm}. The inset shows the % age deviation of fusion cross-section, (i) astrict is for a_i [3] with new temperature dependence and (ii) solid circle for fitted a_i.

The fusion excitation functions for $^{32}S +^{90} Zr$ calculated with various surface thickness parameters a_i(i) of [3] (solid line) (ii) with new temperature dependence (dashed line) (iii) experimental [8, 9] (dotted line) (iv) best fitted to the data (short dash dotted line) are compared with the experimental fusion excitation function of [1] (solid spheres) as shown in Fig. 1(a) above. Further, all the surface thickness is found to reproduce data nicely above the barrier potential (V_B =80.1 MeV) but below it the calculated fusion cross- section is very small. So E_{cm} dependent surface thickness is obtained which reproduces the data nicely. Fig. 1(b) shows the surface thickness parameter a_i required as function of E_{cm}. The inset shows the % age deviation of fusion cross-section, (i) astrict is for a_i [3] with new temperature dependence, which is large for below barrier energies and (ii) solid circle for fitted a_i, which is nearly zero. So, to enhance the fusion cross-section surface thickness should decrease with increase of E_{cm} [see Fig. 1(b)]. Still some analytical function is required for which work in in progress. Same results are obtained for $^{32}S +^{96} Zr$ reaction (not shown here).

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