Skyrme-force dependence of fusion cross-sections using Wong formula in semiclassical formalism

Raj Kumar and Raj K. Gupta
Physics Department, Panjab University, Chandigarh-160014, INDIA.

Introduction

In another contribution to this conference [1] and Ref. [2], we have shown that, for use of the nuclear proximity potential [3], and with multipole deformations up to hexadecapole (β_4), the angular momentum ℓ-summed Wong formula is sufficient to explain the capture cross-sections for ^{48}Ca+^{238}U, ^{244}Pu and ^{248}Cm reactions forming superheavy nuclei, but need (additional) modifications of barriers at sub-barrier energies for the fusion-evaporation cross-sections in ^{58}Ni+^{58}Ni, ^{64}Ni+^{64}Ni, and ^{64}Ni+^{100}Mo reactions known for fusion hindrance phenomenon in coupled-channels calculations. Some barrier modification effects are shown to be already present in ℓ-summed Wong expression though its inbuilt ℓ-dependence [2]. The non-coplanarity degree of freedom (azimuthal angle $\Phi \neq 0$) is also included [1], which does not influence the fits obtained in above noted reactions, expect for one-to-two additional units of ℓ_{max}-value. The barrier modification effects are also supported by the dynamical cluster-decay model (DCM) of preformed clusters by Gupta and collaborators [4], where "barrier lowering" at sub-barrier energies arise in a natural way in its fitting of the only parameter of the model, the neck-length parameter.

In this paper, we use the nuclear proximity potential obtained recently [5] for the Skyrme nucleus-nucleus interaction in the semiclassical extended Thomas Fermi (ETF) approach using Skyrme energy density formalism (SEDF) under frozen-density (sudden-without-exchange) approximation, and $\Phi=0^0$. This method allows the barrier modifications by using different Skyrme forces, since a different Skyrme force would mean different barrier characteristics, and possibly a different force for different reaction cross-section.

Methodolgy

The nucleus-nucleus interaction potential in SEDF, under slab approximation of giving the nuclear proximity potential [6], is

$$\begin{aligned} V_N(R) &= 2\pi\bar{R}\int_{s_0}^{\infty} e(s)ds \\ &= 2\pi\bar{R}\int\{H(\rho)-[H_1(\rho_1)+H_2(\rho_2)]\}dz, \end{aligned} \quad (1)$$

with H as the Skyrme Hamiltonian density in ETF model with both the kinetic energy τ and spin densities $\vec{J}$ as functions of ρ, the nuclear density, included here up to second order, and under the frozen approximation, as

$$\tau(\rho)=\tau_1(\rho_1)+\tau_2(\rho_2), \quad \vec{J}=\vec{J}_1(\rho_1)+\vec{J}_2(\rho_2), \quad (2)$$

with $\rho_i=\rho_{in}+\rho_{ip}$, $\tau_i(\rho_i)=\tau_{in}(\rho_{in})+\tau_{ip}(\rho_{ip})$, and $\vec{J}_i(\rho_i)=\vec{J}_{in}(\rho_{in})+\vec{J}_{ip}(\rho_{ip})$. In Eq.(1), $R=R_1(\alpha_1)+R_2(\alpha_2)+s$, where R_1 and R_2 are the temperature (T) dependent radii of two deformed and oriented nuclei, separated by s with a minimum s_0-value. For ρ_i, we use the T-dependent Fermi density distribution

$$\rho_i(Z_i)=\rho_{0i}(T)\left[1+\exp\frac{z_i-R_i(T)}{a_i(T)}\right]^{-1}, \quad (3)$$

with $-\infty \le z \le \infty$, $z_2=R-z_1$ and $\rho_{0i}(T)=\frac{3A_i}{4\pi R_i^3(T)}\left[1+\frac{\pi^2 a_i^2(T)}{R_i^2(T)}\right]^{-1}$, and nucleon densities ρ_{iq} further defined as

$$\rho_{in}=(N_i/A_i)\rho_i, \quad \rho_{ip}=(Z_i/A_i)\rho_i.$$

Adding Coulomb and centrifugal terms to $V_N(R)$, we get the total interaction potential for deformed and oriented nuclei, as

$$\begin{aligned} V_\ell(R) &= V_N(R,A_i,\beta_{\lambda i},T,\theta_i)+V_C(R,Z_i,\beta_{\lambda i},T,\theta_i) \\ &\quad +V_\ell(R,Z_i,\beta_{\lambda i},T,\theta_i), \end{aligned} \quad (4)$$

with non-sticking moment-of-inertia ($=\mu R^2$, with μ as the reduced mass) for V_ℓ.

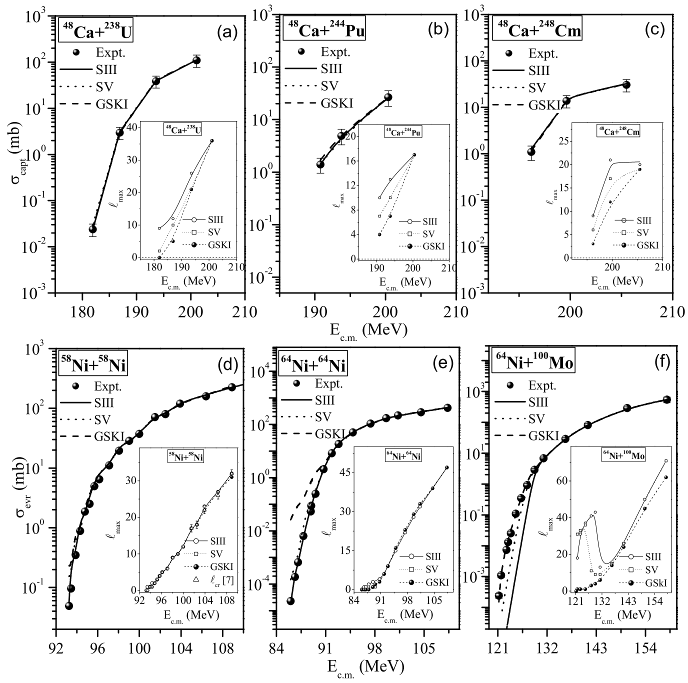

FIG. 1: Comparison of the calculated cross-sections using Skyrme forces SIII, SV and GSkI with experimental data for Ca- and Ni-based reactions. Insets show the variation of deduced $\ell_{max}(E_{c.m.})$.

The ℓ-summed Wong's formula is [2],

$$\sigma(E_{c.m.},\theta_i) = \frac{\pi}{k^2}\sum_{\ell=0}^{\ell_{max}}(2\ell+1)P_\ell(E_{c.m.},\theta_i), \quad (5)$$

where $k=\sqrt{\frac{2\mu E_{c.m.}}{\hbar^2}}$, and penetrability P_ℓ determined in Hill-Wheeler approximation. Integrating over the angles θ_i, we get $\sigma(E_{c.m.})$.

Calculations and Results

Fig. 1 shows our calculations for the Ca- and Ni-based reactions, using the Skyrme forces SIII, SV and GSKI, compared with experimental data. Apparently, the capture cross-section in Fig. 1(a) to (c) are nicely reproduced for all the forces employed, with a small change in ℓ_{max}-values (see insets), whereas the evaporation-residue cross-sections in Figs. 1(d) to (f) require different forces. The σ_{evr} for ^{58,64}Ni+^{58,64}Ni are best fitted for SIII force, and for ^{64}Ni+^{100}Mo by GSkI force, but *not* the vice-versa, i.e., then the barrier modification is to be added empirically. Note that the deduced ℓ_{max} in ^{58}Ni+^{58}Ni reaction for fitted force compare nicely with experimental values [7] at higher $E_{c.m.}$'s.

Thus, for ℓ-summed Wong formula, the Skyrme force dependence in SEDF using ETF method is evident for evaporation residue and not for capture cross-sections.

References

[1] M. Bansal and R. K. Gupta, Contribution to this Symposium.

[2] R. Kumar, M. Bansal, S. K. Arun and R. K. Gupta, Phys. Rev. C **80** (2009) 034618.

[3] J. Blocki, *et al.*, Ann. Phys. (N.Y.) **105** (1977) 427.

[4] R. K. Gupta, Lecture Notes in Physics 818, "Clusters in Nuclei", Vol. I, ed C. Beck, (Springer Verlag) (2010) p. 223.

[5] R. K. Gupta, *et al.*, J. Phys. G: Nucl. Part. Phys. **36** (2009) 075104.

[6] P. Chattopadhyay and R.K. Gupta, Phys. Rev. C **30** (1984) 1191.

[7] M. Beckerman *et al.*, Phys. Rev. C **23**, 1581 (1981).