Relative relevance of Skyrme forces in reference to barrier characteristics of deformed nuclei

Shivani Jain,* Vishal Parmar, Raj Kumar, and Manoj K. Sharma
School of Physics and Materials Science,
Thapar Institute of Engineering and Technology, Patiala - 147004, INDIA

Introduction

It is well known that the collision between two nuclei is governed mainly by two forces, the long-range repulsive Coulomb force and the attractive short-range nuclear force. When these two forces get balanced, there is formation of a nuclear fusion barrier. The fusion barrier height of the interaction potential is one of the important tool to understand the nuclear fusion mechanism. In some of the previous studies [1, 2] it has been examined that, the fusion barrier height gets influenced by various parameters, such as deformations, orientations, angular momentum etc., which are used to describe the nuclear properties.
In the work of [1], the combination of spherical and elongated quadruple deformed nuclei within optimum cold fusion configuration, exhibit highest interaction radius, which in turn gives the smallest barrier height. On the other hand, the most compact state of the spherical+deformed pair, having optimum hot fusion configuration, shows the highest barrier height with the smallest interaction radius. Here, in the present work, the hot optimum configuration is considered to study the fusion barrier characteristics within the framework of Skyrme energy density formalism (SEDF), for two different Skyrme forces, i.e. SLy4 and SSk, and compared with the available empirical data for spherical (sph.)+oblate ($\beta_2 < 0$), sph.+sph. and sph.+prolate ($\beta_2 > 0$) combinations. The related optimum orientation angles for above given combinations are decided by the signs of quadruple deformations alone.

*Electronic address: `jain.shivani04@gmail.com`

Methodology

In the nuclear fusion reaction, the fusion barrier height is defined as the combination of the Coulomb potential V_C and attractive nuclear proximity potential V_N, at the barrier position $R = R_B$, and reads as

$$V_B = V_C(R_B, Z_i, \beta_{2i}, \theta_i) + V_N(R_B, A_i, \beta_{2i}, \theta_i), \quad (1)$$

where β_{2i} is the static quadruple deformation and i=1, 2 for projectile and target, respectively. In the above expression, the well-defined V_C for the deformed and oriented nuclei is referred from [1]. Further, in the calculation of nucleus-nucleus potential, the Energy density formalism (EDF) [2] is considered, which provides one of the pertinent way to express the potential, as given below

$$V_N(R) = E(R) - E(\infty) = 2\pi\bar{R}\int_{s_0}^{\infty}\{H(\rho,\tau,\vec{J}) - H_1(\rho_1,\tau_1,\vec{J_1}) - H_2(\rho_2,\tau_2,\vec{J_2})\}ds. \quad (2)$$

In the above expression, the Skyrme Hamiltonian density ($H(\rho, \tau, \vec{J})$) as a function of nucleon density $\rho(r)$, kinetic energy density $\tau(\rho)$ and spin-orbit density $\vec{J}(\rho)$ is developed on the basis of Skyrme force parameters and gets modified with the choice of different sets of Skyrme forces, like SLy4 (old) and SSk (new). Further, to analyze the difference in the theoretically calculated barrier heights $\triangle V_B^{cal}$ (positions $\triangle R_B^{cal}$) with the empirical ones, the following formalism has been adopted:

$$\triangle V_B\% = \frac{|V_B^{emp} - V_B^{cal}|}{V_B^{emp}} \times 100\%,$$
$$\triangle R_B\% = \frac{|R_B^{emp} - R_B^{cal}|}{R_B^{emp}} \times 100\%. \quad (3)$$

TABLE I: The percentage of difference in the calculated V_B and R_B, at hot optimum orientation, with the available empirical data [3].

Reactions	β_{22}	Opt. θ_2	$\triangle V_B\%$		$\triangle R_B\%$	
			SLy4	SSk	SLy4	SSk
$^{16}O+^{28}Si$	-0.363	0^o	3.25	1.86	4.01	10.28
$^{16}O+^{29}Si$	-0.349	0^o	8.09	2.82	7.89	2.41
$^{16}O+^{30}Si$	-0.236	0^o	6.95	1.86	6.32	0.87
$^{40}Ca+^{40}Ca$	0.0	0^o	3.34	1.82	7.37	14.74
$^{40}Ca+^{46}Ti$	0.021	90^o	2.71	7.55	13.04	29.35
$^{40}Ca+^{62}Ni$	0.107	90^o	3.51	8.31	3.58	10.14
$^{16}O+^{24}Mg$	0.393	90^o	4.15	9.94	1.19	5.95

Results and discussions

In the work of [3], the fusion barrier heights calculated using various versions of proximity potentials address the empirical data using spherical configuration. Further, in [2], it has been analyzed that two different Skyrme forces, SLy4 and SSk, show a remarkable difference in the barrier height for the prolate-prolate projectile-target combination. On the basis of above results, it would be interesting to analyze the behavior of calculated V_B and R_B, using above mentioned Skyrme forces under the SEDF approach, for the sph.+sph. and sph.+quadrupole deformed ($\beta < 0$ and $\beta > 0$) combinations with the corresponding choice of optimum orientation of nuclear reactions (mentioned in the table I), in comparison with the empirical data shown in [3].

In Fig.1, the calculated V_B and R_B using SLy4 and SSk Skyrme forces compared with the empirical data are depicted with the change in deformations of the target (β_{22}) nuclei. It can be seen from panel (a) of Fig.1 that, for spherical case ($\beta_{22} = 0$), the two forces show good agreement with V_B^{emp} [3]. On the left of $\beta_{22} = 0$, the SSk force gives better response than SLy4. However, on the right side, the SLy4 force approaches more closer to the data. The similar observations are noticed in the calculation of barrier position (R_B), except at two points, i.e. at $\beta_{22} = 0$ and -0.363. Moreover, for better description, the percentage of difference in the calculated barrier height (position) and the empirical ones is shown in table I. Also, on the basis of the standard deviation

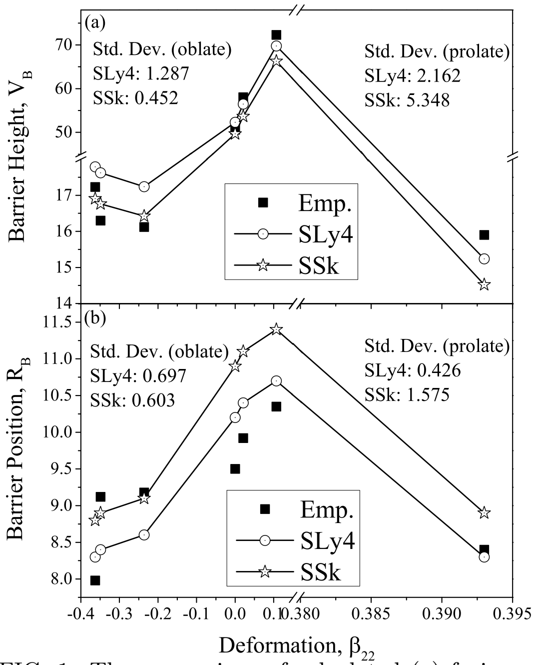

FIG. 1: The comparison of calculated (a) fusion barrier height V_B and (b) barrier position R_B using SLy4 and SSk Skyrme forces with the available empirical data [3].

values given in the figure, it is evident that for oblate cases, the SSk force gives relatively close agreement with the data, whereas, SLy4 seems to perform better for the prolate targets.

References

[1] R. K. Gupta *et.al.*, J. Phys. G: Nuc. Part. Phys. **31**, 631-644 (2005).

[2] D. Jain *et.al.*, Eur. Phys. J. A **50**, 155 (2014).

[3] I. Dutt and R. K. Puri, Phys. Rev. C **81**, 064609 (2010).