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Study of fusion barriers for proton and helium induced reactions using various parameterized formulae

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ABSTRACT

Our previous study [Kumari R and Kaur S 2014 *Chin. Phys. Lett.* **31** 112501] revealed that out of various proximity potentials, the parameterized forms derived using Proximity 1977 yield fusion barrier heights and positions in good agreement with empirical values for proton as well as helium induced reactions. Also, in an another study [Kumari R and Puri R K 2015 *Nucl. Phys. A* **933** 135], we presented new parameterized forms for fusion barrier heights and positions using empirical data for more than 200 reactions. Our fits using these parameterized forms were found to be better than the others available in the literature. In the present study, all the above mentioned parameterizations are employed to calculate fusion barrier heights and positions for proton and helium induced reactions. Our findings show that our parameterized forms (based on empirical data and the one using Proximity 1977) yield results closer to the empirical values for helium induced reactions as compared to other parameterized forms. However, few deviations are observed in the present study in the case of proton induced reactions.

Nuclear fusion reactions provide an opportunity to the lighter nuclei to achieve stability by enhancing their binding energies. These reactions are very useful in the synthesis of new elements, in particular, super-heavy elements (SHEs) [1–3]. Due to advent of powerful advanced particle accelerators, now it is possible to create conditions similar to those of early universe by fusion reactions between heavy-ions and unfold the mysteries during Big Bang. This development has also encouraged the low energy nuclear physics fraternity to look into the interesting features of nuclei far from stability line i.e. neutron-halo, proton-halo, neutron skin, deformed-halo nuclei etc [4,5]. The study of nuclear dynamics of fusion reaction requires precise knowledge of the total interaction potential between the colliding nuclei, which is sum of repulsive Coulomb potential and attractive nuclear potential.

The outcome of a collision depends upon the available energy, in a way, that if incident energies are higher than the Coulomb barrier, the two colliding nuclei do not find any time to rearrange their densities and the collision results in different products depending on the impact parameter, especially, fusion at low impact parameter. On the other hand, at energies close to the barrier, the fusion is a slow process giving the colliding nuclei sufficient time to rearrange their densities and hence favoring processes like nucleon-transfer [6], neck formations [7], rotations, vibrations etc [8]. But, at energies lower than the Coulomb barrier, the two nuclei cannot fuse classically (sub-barrier fusion) [9]. At these energies, quantum mechanical effects come into play. Therefore, the fusion barrier heights and positions contribute appreciably in deciding the fate of a fusion reaction.

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Table 1
The values of constants a, b and c using Prox. 77 for proton as well as helium induced reactions. The corresponding values of $\chi^2_{reduced}$ (χ^2/ degree of freedom) are also listed. All these values are taken from Ref. [22].

Reaction	a	b	$\chi^2_{reduced}$	c	$\chi^2_{reduced}$
Proton induced	1.03 (0.01)	3.52 (0.06)	5.14E-4	1.313 (0.001)	7.27E-4
Helium induced	1.01 (0.02)	4.40 (0.09)	7.10E-3	1.329 (0.003)	7.90E-3

In order to correctly predict fusion parameters, one always looks forward for accurate parameterizations of barriers. Now, a question arises in our mind about significance of parameterized formulae to the nuclear community. These parameterized expressions for barrier heights and positions guide the experimentalists for designing new experiments and predicting fusion cross-sections. These predictions are helpful in deciding that what combinations of ions and incident energy is favorable for performing experiments for synthesis of SHEs.

A number of methods, both microscopic as well macroscopic, have been used for calculating the total interaction potential. In the microscopic picture, the contribution of internal structure of the nuclei at the nucleon level is considered [10]. On the other hand, the colliding nuclei are assumed to be charged liquid drops in the macroscopic picture [11,12]. Out of various macroscopic models, the proximity potentials are well known for their simplicity [12–16]. The proximity potential and proximity based potentials have been extensively used for studying the isotopic dependence of fusion dynamics [17], role of surface energy coefficients and nuclear surface diffuseness in the fusion process [13], fusion barriers for symmetric as well as asymmetric colliding nuclei [14], fusion dynamics for neutron- and proton-rich nuclei [18], fusion reactions at extreme sub-barrier energies [19,20], half-life of spherical α emitters and intrinsic properties of nuclei [21] etc.

In our previous study [22], we conducted a comparative study using different parameterized expressions for fusion parameters derived from proximity potentials against empirical data on fusion induced by the proton and helium projectiles on various targets. In this study, proximity potential 1977 (Prox. 77) was found to reproduce data better than all other versions of proximity potentials. As already mentioned in Ref. [22], the parameterized forms for barrier positions R_B^{Par} and barrier heights V_B^{Par}, using Prox. 77, were expressed as:

$$R_B^{Par}(\text{Prox. 77}) = a \times A_T^{1/3} + b, \tag{1}$$

and

$$V_B^{Par}(\text{Prox. 77}) = c \times \frac{Z_P Z_T}{R_B^{Par}(\text{Prox. 77})}. \tag{2}$$

Here P and T correspond to projectile and target nuclei, respectively. The values of the constants a, b and c are different for proton and helium induced reactions and are displayed in Table 1.

In a separate study [4], new parameterized forms for fusion barrier heights and positions were presented. In addition, other parameterized formulae based on empirical data were also considered for comparative analysis. The parameterized forms due to Vaz et al. [23] can be written as:

$$V_B^{Par}(Vaz) = \frac{Z_P Z_T e^2}{[2.2951 - 0.2966\ log_{10}(Z_P Z_T)]A'}, \tag{3}$$

and

$$R_B^{Par}(Vaz) = [2.0513 - 0.2455\ log_{10}(Z_P Z_T)]A', \tag{4}$$

where $A' = A_P^{1/3} + A_T^{1/3}$.

Moustabchir and collaborators [24] derived formulae for fusion barrier heights and positions by fitting the values calculated using generalized liquid drop model (GLDM) on 170 fusion reactions. These formulae can be expressed as:

$$V_B^{Par}(Moustabchir) = -19.38 + \Gamma, \tag{5}$$

$$\text{where} \quad \Gamma = \left[\frac{2.1388 Z_P Z_T + 59.427A' - 27.07\ ln(\xi)}{A'(2.97 - 0.12\ ln(Z_P Z_T))}\right], \tag{6}$$

and

$$\xi = \frac{Z_P Z_T}{A_P^{1/3} + A_T^{1/3}}. \tag{7}$$

$$R_B^{Par}(Moustabchir) = \left[1.908 - 0.0857\ ln(Z_P Z_T)\right]A' + \frac{3.94}{Z_P Z_T} \times A'. \tag{8}$$