Proximity approach to study fusion probabilities in heavy-ion collisions

Raj Kumari*
Department of Physics, Panjab University, Chandigarh -160 014, INDIA.

Introduction

The pursuit of fusion probabilities at energies near the Coulomb barrier has earned unique attention in the recent past. This renewed interest is also due to the availability of radio-active ion beams that leads to the formation of very neutron rich nuclei. The fusion cross-sections at the sub-barrier energies are found to be enhanced compared to the predictions of the barrier penetration model. For the accurate calculation and reproduction of the fusion cross-sections above the barrier, one should be able to reproduce the barrier height and position accurately. In contrast, the shape of the barrier is most crucial parameter for the sub-barrier studies. A massive hunt by one of our co-worker [1] for the best nucleon-nucleon potential by carefully analyzing many proximity based potentials concluded that the potentials due to Bass 80, Aage Winther (AW) 95 and Denisov DP reproduce barrier heights and positions far better than others in the class. We are interested to test Bass 80, Aage Winther (AW) 95, Denisov DP, Proximity 2010 [2] and Skyrme Energy Density Formalism (SEDF)[3] at energies above as well as below barrier height.

Methodology

All these potentials were parameterized in terms of proximity concept [1–3].

The proximity potential is based on the theorem which states that "the force between two gently curved surfaces in close proximity is proportional to the interaction potential per unit area between two flat surfaces". The interaction potential $V_N(R)$ between two colliding surfaces therefore, is given by

$$V_N = 4\pi\gamma b\overline{C}\Phi(\frac{R - C_1 - C_2}{b})MeV, \qquad (1)$$

where $\overline{C}$ $(= (C_1C_2)/(C_1+C_2))$, b and R are the reduced radius, surface width and central separation, respectively. Here C is the central radius and Φ is the universal function. The surface energy coefficient γ has the form

$$\gamma = \gamma_0[1 - k_s(\frac{N - Z}{A})^2]. \qquad (2)$$

Here γ_0 and k_s are the surface energy coefficient and surface asymmetry constant, respectively.

By adding Coulomb potential to nuclear potential, one can compute total interaction potential $V_T(R)$ and hence barrier positions and heights. The cross-section for a complete fusion $\sigma_{fus}(E_{cm})$ is given by:

$$\sigma_{fus} = 10\frac{R_B^2\hbar\omega_0}{2E_{cm}}ln\Big[1+exp\,\{\frac{2\pi}{\hbar\omega_0}(E_{cm}-V_B)\}\Big]. \qquad (3)$$

Results and Discussions

For the present systematic study, we calculated the fusion probabilities for the reactions of ^{28}Si+^{24,26}Mg ^{30}Si+^{24}Mg and ^{28,30}Si+^{58,62}Ni. In Table 1, calculated fusion barrier heights and barrier positions are displayed for the above mentioned reactions using the potentials due to AW 95, Bass 80, Denisov DP, Proximity 2010 and SEDF (SIII force) along with the experimental data. Some reactions involving various isotopes are not listed in the table, since they yield similar results. From the table, it is evident that all potentials can reproduce experimental barrier quite accurately. This also further justifies that these potentials are better than other available in the literature.

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*Electronic address: `rajkumari80pu@gmail.com`

TABLE I: Fusion barrier heights V_B (MeV) and positions R_B (fm) using AW 95, Bass 80, Denisov DP, Proximity 2010 and SEDF. The corresponding empirical values are also listed.

Reaction	AW 95		Bass 80		Denisov DP		Prox. 2010		SEDF		Empirical		Ref.
	V_B	R_B	V_B	R_B	V_B	R_B	V_B	R_B	V_B	R_B	V_B	R_B	
^{28}Si + ^{24}Mg	25.03	8.98	24.97	8.91	24.56	9.03	25.38	8.75	24.39	9.03	25.10	8.93	[4]
^{28}Si + ^{26}Mg	24.69	9.07	24.63	9.06	24.17	9.17	25.09	8.84	24.05	9.14	25.00	8.95	[4]
^{30}Si + ^{24}Mg	24.73	9.06	24.66	9.05	24.21	9.15	25.12	8.83	24.15	9.13	24.80	9.05	[4]
^{28}Si + ^{58}Ni	53.29	9.86	53.21	9.78	53.07	9.78	53.87	9.69	52.67	9.73	53.80	9.00	
											±0.8	±0.9	[5]
^{30}Si + ^{58}Ni	52.72	9.94	52.61	9.92	52.38	9.96	53.36	9.82	52.10	9.88	52.20	8.30	
											±1.2	±1.1	[5]
^{28}Si + ^{62}Ni	52.62	9.96	52.51	9.94	52.34	9.92	53.28	9.84	52.06	9.89	52.89	9.89	[5]

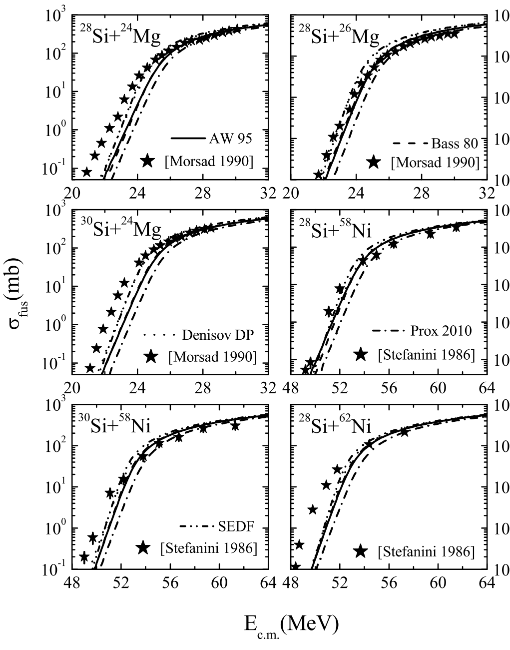

FIG. 1: The fusion cross-sections $\sigma_{\rm fus}$(mb) are displayed as a function of the center of mass energy $E_{\rm c.m.}$(MeV). The experimental data is taken from Morsad 1990 [4] and Stefanini 1986 [5].

In fig. 1, the fusion excitation functions $\sigma_{\rm fus}$(mb) calculated using the Wong formula are plotted as a function of center of mass energy, $E_{\rm c.m.}$(MeV). We found that these proximity based potentials can nicely reproduce the fusion cross-sections at above barrier energies for all the reacting systems. However, small deviations are observed in sub-barrier region and are attributed to many factors like deformed shape of the nuclei, surface vibrations and multi-neutron transfer channels. Further investigations of these deviations of theoretical calculations at sub-barrier energies is needed.

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