# Sub-barrier fusion of ${}^{32}_{16}S + {}^{94}_{40}Zr$ system and energy dependent Woods-Saxon potential

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Heavy ion fusion reactions have received extensive attention during past few decades as they explore the nuclear structure of participating nuclei besides providing decent description of nuclear interactions. In fusion process, two colliding nuclei come close together to form a compound nucleus either by overcoming or by quantum tunneling through the potential barrier. Theoretically, the simplest way to describe the fusion mechanism is the barrier penetration model (BPM), wherein the collision partners are assumed to penetrate through the fusion barrier and form a composite nucleus [1]. However, an anomalously large enhancement in the fusion cross-section over the predictions of one dimensional barrier penetration model at sub-barrier energies has been observed during last two decades [1]. In general, this fusion enhancement is found to have link with the coupling of relative motion to internal structure of the fusing nuclei such as nuclear shape deformation, inelastic surface vibration of nuclear surface, rotation of nuclei during collision, neck formation, nucleon transfer reactions etc.

Indeed, such couplings produce substantially large enhancement in the fusion cross-section at sub-barrier energies [1]. It is very difficult to include all intrinsic degrees of freedom simultaneously but to identifying those degrees of freedom which have strong influence on the fusion mechanism and consequently to understand the puzzling dynamics of the fusion process has been a matter of considerable interest. The relation between sub-barrier fusion enhancement and intrinsic degrees of freedom such as permanent shape deformation, low lying surface vibration of fusing nuclei have been well described by the various coupled channel formulations [1]. However, the interplay of neutron transfer channels have not been fully understood because the transfering of neutrons are insensitive to the Couomb barrier and such transfer process generally occur at large internuclear separation. As a result fusion reactions have become the most studied processes to explore the importance of structural as well as dynamical effects in the compound nuclear reactions [2].

Very recently, one of us and collaborators has proposed the following parameterization schemes to determine the diffuseness and depth of the potential [2].

$$a(E) = 0.85\left[1+\frac{r_0}{13.75\left(A_P^{-\frac{1}{3}}+A_T^{-\frac{1}{3}}\right)\left(1+\exp\left(\frac{\frac{E}{V_B}-0.96}{0.03}\right)\right)}\right] fm$$

and

$$V_0 = \left[A_P^{\frac{2}{3}}+A_T^{\frac{2}{3}}-\left(A_P+A_T\right)^{\frac{2}{3}}\right]\left[2.38+6.8\left(1+I_P+I_T\right)\frac{A_P^{\frac{1}{3}}A_T^{\frac{1}{3}}}{\left(A_P^{\frac{1}{3}}+A_T^{\frac{1}{3}}\right)}\right] MeV$$

where $I_P = \left(\frac{N_P - Z_P}{A_P}\right)$ and $I_T = \left(\frac{N_T - Z_T}{A_T}\right)$

are the isospin asymmetry of projectile and target nuclei respectively. The energy dependence in the Woods-Saxon potential is entertained via the energy dependent diffuseness parameter. Since the channel coupling effects responsible for enhancing sub-barrier fusion cross-section are the surfacial effects which in turn modify the surface diffuseness as well as the surface energy of the collision partners. Therefore it is necessary to reconcile the depth of the potential which includes the surface energy term that plays a very important role in fusion dynamics.

In order to understand the relative importance of low lying vibrational states and neutron transfer channel, it is useful to consider the fusion of nuclei having rich interplay of inelastic surface excitations and neutron transfer channels. For this, we have considered the fusion of $^{32}_{16}S+^{94}_{40}Zr$ system wherein the relative importance of inelastic surface vibrations of collision partners and role of neutron transfer channels is not yet fully resolved. The $^{32}_{16}S$ nucleus has the nuclear configuration which is non-magic nucleus while the $^{94}_{40}Zr$ nucleus is semi-magic nucleus and both collision partners allow the low lying surface vibrations. For this system the diffuseness parameter '$a$' varies from $a=0.97\,fm$ to $a=0.85\,fm$ in the energy range from $E_{c.m.}$ = 65 $MeV$ to $E_{c.m.}$ = 100$MeV$. The value of depth parameter ($V_0$) comes out to be 95.45$MeV$ while the range parameter '$r_0$' is kept fixed at 1.118 $fm$ and Coulomb barrier height $V_B$ is 80.47$MeV$. Very recently, an energy dependent Woods-Saxon potential model (EDWSP model) has been successfully used to explore the fusion dynamics of various heavy ion systems [2]. Here in the present work, we have analyzed the fusion of $^{32}_{16}S+^{94}_{40}Zr$ system within the framework of EDWSP model and energy independent one dimensional barrier penetration model.

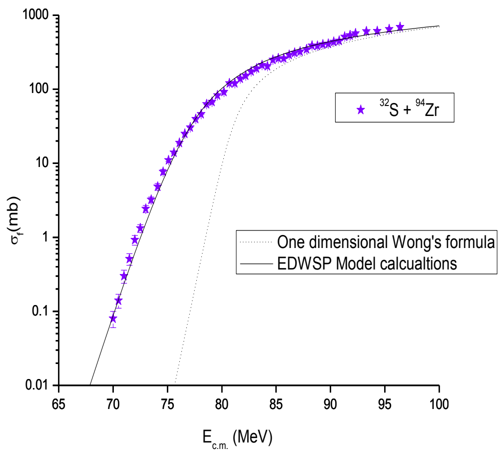


Fig.1. Fusion excitation functions of $^{32}_{16}S+^{94}_{40}Zr$ system using EDWSP model and Wong's formula, compared with the available experimental data.

In Fig.1, we compare the fusion excitation functions of $^{32}_{16}S+^{94}_{40}Zr$ system obtained by using the one dimensional energy independent Wong's formula [3] and the energy dependent Woods-Saxon potential model (EDWSP model) in conjunction with one dimensional Wong's formula [2] along with the corresponding data [4]. Various coupled channel calculations predicted that in addition to coupling to inelastic surface vibrational states of both colliding nuclei, the coupling to neutron transfer channels are necessarily required to reproduce the sub-barrier fusion excitation data. It is so because, the prediction of one dimensional Wong's formula is substantially under predicted by the experimental data. However, the present prescription of EDWSP model accurately describes the fusion dynamics of this system in whole range of energy. This clearly mirrors the fact that the energy dependence in Woods-Saxon potential mocks up the various channel coupling effects as evidently depicted in Fig.1.

In summary, the predictions of the one dimensional barrier penetration model are substantially under-predicted by the experimental data. However, an energy dependent Woods-Saxon potential model (EDWSP model) reasonably addresses the fusion enhancement of $^{32}_{16}S+^{94}_{40}Zr$ system at sub-barrier energies. It is worth noting here that a significantly larger value of diffuseness parameter of Woods-Saxon potential is required to reproduce the sub-barrier fusion data. It will be of future interest to analyze such effects on other isotopes of $Ba$ nucleus.

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