Analysis of fusion excitation function of ${}^{32}_{16}S+{}^{90}_{40}Zr$ system using an energy dependent Woods-Saxon potential

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The process in which two colliding nuclei come close together to form a compound nucleus either by overcoming or by quantum tunneling through the potential barrier is known as nuclear fusion reaction. The simplest theoretical way to understand the fusion of the two nuclei is the barrier penetration model (BPM), wherein the projectile is assumed to penetrate through potential barrier between two interacting nuclei and form a composite nucleus. However, at energies below the Coulomb barrier, the extensive experimental as well as theoretical studies have revealed that there is an anomalously large enhancement in the fusion cross-section over the predictions of one dimensional barrier penetration model [1]. It indicates that the fusion of two nuclei is a complex rearrangement process which involves a large number of the degrees of freedom and a strong coupling between the projectile-target relative motion and the internal degrees of freedoms. 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.

The channel coupling effects are taken into account by employing the well known coupled channel technique wherein the second order coupled differential equations are solved numerically. Although this method is highly involved, nonetheless K. Hagino *et al.*[2] have developed a very handy code CCFULL to study the heavy ion fusion. In the present work we have also used the code CCFULL. In this code Woods-Saxon parameterization is used for nuclear potential and hence the range, depth and diffuseness of the Woods-Saxon potential are the essential inputs needed for using the code CCFULL. Very recently, we have proposed the following parameterization schemes to determine the diffuseness and depth of the potential l[3,4].

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

and

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

respectively. The energy dependence in the potential is incorporated through the energy dependent diffuseness parameter. In the expression for depth the term in the round bracket is directly proportional to the surface energy of the nucleus and hence strongly depends on the collective motion of all the nucleons inside the nucleus. The need for this term is necessitated by the fact that the channel coupling effects responsible for enhancing sub-barrier fusion cross-section are the surfacial effects. Obviously these surfacial effects 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 terms and play very important role in fusion dynamics.

In order to understand the behavior of sub-barrier fusion excitation function with respect to the coupling to low lying vibrational states, it is useful to consider the fusion of nuclei having closed shell and near closed shell configurations. Here we have considered the fusion of ${}^{32}_{16}S+{}^{90}_{40}Zr$ system in near barrier energy regions. The ${}^{32}_{16}S$ nucleus has the nuclear configuration which is close to magic nucleus while the ${}^{90}_{40}Zr$ nucleus is doubly magic nucleus and has low lying surface vibrations only. The deformation parameters and the corresponding excitation energies of the collision partners are given in the Table which are taken from the Ref.[5].

Table:The deformation parameter and corresponding excitation energies of colliding nuclei.

Nucleus	β_2	E_2 (MeV)	β_3	E_3 (MeV)
${}^{32}_{16}S$	0.32	2.230	0.40	5.006
${}^{90}_{40}Zr$	0.09	2.186	0.22	2.748

For this system the diffuseness parameter ‘a’ varies from $a = 0.97\,fm$ to $a = 0.85\,fm$ in the energy range from E = 70 *MeV* to E= 100*MeV*. The value of depth parameter (V_0) comes out to be 91.23*MeV* while the range parameter ‘r_0’ is kept fixed at 1.2 *fm* and Coulomb barrier height ‘V_B’ is 79 *MeV*. In Fig.1, we compare the fusion excitation functions of ${}^{32}_{16}S + {}^{90}_{40}Zr$ system obtained by using the CCFULL code in conjunction with new prescription for energy dependent potential with the corresponding data [5]. Since there is no possibility of neutron transfer channels with large positive ground state Q-values, the contribution of the nucleon transfer channel are completely ruled out. Here, we have considered three phonon quadrupole and octupole vibration in target and one phonon quadrupole and octupole vibration in projectile. The results are also compared with those obtained by using Ning Wang *et al.* parameterization [6] for potential model as well as with those obtained by neglecting all couplings. It may be clearly observed from the figure that the experimental data is substantially underestimated by the calculation performed by using the Ning Wang *et al.* parameterization as well as by considering no coupling case while the agreement between the data and the present calculations is reasonably good. Thus, our results favors the fact that larger diffuseness is needed to explain the sub-barrier fusion data.

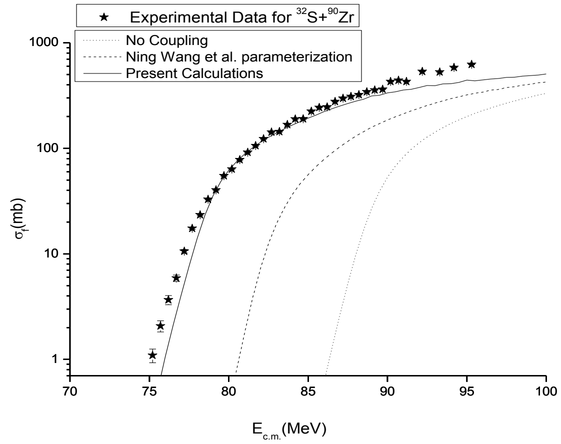

Fig.1 Fusion excitation functions of ${}^{32}_{16}S + {}^{90}_{40}Zr$ system corresponding to the calculations performed by using present energy dependent potential, Ning Wang *et al.* parameterization and no coupling are compared with the experimental data taken from Ref.[5]

To summarize we have proposed a new parameterization schemes for determining the depth and diffuseness of the Woods-Saxon potential which when used in conjunction with the coupled channel code CCFULL explain the fusion excitation function data around the barrier over wide range of projectile target combination reasonably well.

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