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EVIDENCE OF ENTRANCE CHANNEL MASS ASYMMETRY EFFECTS IN FORMATION OF $^{240}_{98}\mathrm{Cf}$ -NUCLEUS AND ENERGY DEPENDENT WOODS-SAXON POTENTIAL

MANJEET SINGH GAUTAM

Thapar University, School of Physics and Material Science, Patiala (Punjab) – 147004, India
E-mail: gautammanjeet@gmail.com

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Abstract. The entrance channel mass asymmetry effects in the formation of $^{240}_{98}\mathrm{Cf}$-nucleus have been analyzed within the context of energy dependent Woods-Saxon potential model (EDWSP model). The theoretical calculations of fusion dynamics of $^{32}_{16}\mathrm{S}+^{208}_{82}\mathrm{Pb}$, $^{34}_{16}\mathrm{S}+^{206}_{82}\mathrm{Pb}$ and $^{36}_{16}\mathrm{S}+^{204}_{82}\mathrm{Pb}$ systems are performed by using static Woods-Saxon potential and EDWSP model in conjunction with one dimensional Wong formula. The larger mass asymmetric fusing system leads to least fusion enhancement at sub-barrier energies while less mass asymmetric fusing system produces larger sub-barrier fusion enhancement. The static nucleus-nucleus potential systematically fails to recover the experimental data of $^{32}_{16}\mathrm{S}+^{208}_{82}\mathrm{Pb}$, $^{34}_{16}\mathrm{S}+^{206}_{82}\mathrm{Pb}$ and $^{36}_{16}\mathrm{S}+^{204}_{82}\mathrm{Pb}$ systems. However, the EDWSP model calculations accurately address the sub-barrier fusion enhancement of these systems. It is worth noting here that energy dependence in nucleus-nucleus potential require a much smaller value of diffuseness parameter ranging from a = 0.85 fm to a = 1.0 fm for reproduction of the fusion dynamics while in literature, the diffuseness parameter a = 1.47 fm was predicted for adequate description of these systems.

Key words: heavy-ion near-barrier fusion reactions, depth and diffuseness, Woods-Saxon potential, diffuseness anomaly.

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1. INTRODUCTION

The availability of radioactive beams of neutron-rich nuclei makes the possibility of production of nuclei away from the valley of stability and superheavy elements. Heavy ion fusion reactions can be used to probe the role of nuclear structure and nuclear interaction between fusing nuclei. In neutron rich nuclei, due to larger number of neutrons and larger nuclear size, the magnitude of fusion cross-section is quite large as compared to that of stable isotopes. In the past few decades, the keen interest for exploration of fusion reactions increases on theoretical as well as experimental front because of the occurrence of substantially large fusion enhancement at sub-barrier energies over the theoretical predictions of one dimensional barrier penetration model. This fusion enhancement can be correlated with the coupling of relative motion of fusing nuclei to inelastic surface excitations of projectile (target) or permanent deformations and/or nucleon (multi-nucleon) transfer channels [1–4]. Indeed, the coupling between elastic channel and intrinsic degrees of freedom leads to splitting of single barrier into a distribution of barrier and thus results in an anomalously large sub-barrier fusion enhancement. The role of permanent deformation and inelastic surface vibrations of colliding nuclei in the fusion process are accurately described by the various theoretical approaches [1–8].

The nucleus-nucleus potential play a central role in the exploration of reaction dynamics and the basic knowledge about this potential greatly simplifies the problem of complete understanding of fusion dynamics. In addition, the success of any theoretical approach critically depends upon the choice of optimum form of nucleus-nucleus potential. But due to presence of large ambiguities in optimum form of nucleus-nucleus potential, it puts limits on the better understanding of the different nuclear interactions. To resolve such issues, large set of parameterizations of nuclear potential are available in literature which are regularly used to explain the different aspects of heavy ion fusion reactions [9–15]. Generally, the static Woods-Saxon potential is most widely used for description of the dynamics of sub-barrier fusion reactions [1–6]. The diffuseness parameter of static Woods-Saxon potential is related to the slope of nuclear potential in the tail region of Coulomb barrier and a wide range of diffuseness parameter ranging from a = 0.75 fm to a = 1.5 fm was used for complete description of the sub-barrier fusion data. Surprisingly, such values are much larger than a value a = 0.65 fm which is best suited for the systematics of elastic scattering data [16–17]. This diffuseness anomaly, which might be an artifact of various static and dynamical physical effects, reflects the systematic failure of static Woods-Saxon potential for simultaneous exploration of the elastic scattering data and the fusion data [18–22]. The various channel coupling effects occurring in the surface region of nuclear potential or in the tail region of Coulomb barrier are responsible for modification in the value of the parameters of nuclear potential. Furthermore, to understand diffuseness anomaly and puzzling behavior of sub-barrier fusion dynamics, in the previous work, several attempts were made by studying the fusion of large set of projectile-target combinations within the framework of energy dependent Woods-Saxon potential model (EDWSP model) [23–34]. In heavy ion reactions, the closely similar physical effects that arise due to internal structure of colliding pairs can be induced by entertaining the energy dependence in real part of nucleus-

nucleus potential in such a way that it becomes more attractive at sub-barrier energies. This energy dependent nucleus-nucleus potential will effectively decrease the interaction barrier between fusing nuclei and hence predicts substantially larger sub-barrier fusion cross-section data with reference to energy independent one dimensional barrier penetration model as evident from the earlier work (EDWSP model) [23–34].

In general, the magnitude of sub-barrier fusion enhancement increases with increase of mass asymmetry in the entrance chancel. The larger mass asymmetric projectile-target combination leads to larger fusion enhancement at sub-barrier energies in comparison to less mass asymmetric fusing system [35–40]. The fusion dynamics of ${}^{32}_{16}\mathrm{S}+{}^{208}_{82}\mathrm{Pb}$, ${}^{34}_{16}\mathrm{S}+{}^{206}_{82}\mathrm{Pb}$ and ${}^{36}_{16}\mathrm{S}+{}^{204}_{82}\mathrm{Pb}$ systems are quite interesting due to presence of entrance channel mass asymmetric effects [41]. The fusion of ${}^{32}_{16}\mathrm{S}+{}^{208}_{82}\mathrm{Pb}$, ${}^{34}_{16}\mathrm{S}+{}^{206}_{82}\mathrm{Pb}$ and ${}^{36}_{16}\mathrm{S}+{}^{204}_{82}\mathrm{Pb}$ systems, which leads to formation of ${}^{240}_{98}\mathrm{Cf}$-nucleus, offers opposite entrance channel mass asymmetry effects on sub-barrier fusion enhancement. The entrance channel mass asymmetry is largest for ${}^{32}_{16}\mathrm{S}+{}^{208}_{82}\mathrm{Pb}$ system while it is smallest for ${}^{36}_{16}\mathrm{S}+{}^{204}_{82}\mathrm{Pb}$ system and the larger sub-barrier fusion enhancement is expected for ${}^{32}_{16}\mathrm{S}+{}^{208}_{82}\mathrm{Pb}$ system and the smaller sub-barrier fusion enhancement is expected for ${}^{36}_{16}\mathrm{S}+{}^{204}_{82}\mathrm{Pb}$ system. But it is quite interesting that the experimental measurement of these systems as reported in Ref. [41], indicates the opposite dependence of entrance channel mass asymmetry factor which produces larger sub-barrier fusion enhancement for lesser mass asymmetric fusing systems (${}^{36}_{16}\mathrm{S}+{}^{204}_{82}\mathrm{Pb}$ system) while the smaller sub-barrier fusion enhancement has been observed for more asymmetric fusing system (${}^{32}_{16}\mathrm{S}+{}^{208}_{82}\mathrm{Pb}$ system). The present work adequately addresses dynamics of these systems within the context of static Woods-Saxon potential and energy dependent Woods-Saxon potential model (EDWSP model) [23–34]. Theoretical calculations are performed by using energy independent Woods-Saxon potential as well as energy dependent Woods-Saxon potential model in conjunction with one dimensional Wong formula [42]. The failure of static Woods-Saxon potential in conjunction with one dimensional Wong formula to explain the complete description of fusion of ${}^{32}_{16}\mathrm{S}+{}^{208}_{82}\mathrm{Pb}$, ${}^{34}_{16}\mathrm{S}+{}^{206}_{82}\mathrm{Pb}$ and ${}^{36}_{16}\mathrm{S}+{}^{204}_{82}\mathrm{Pb}$ systems reflects the inconsistency of static Woods-Saxon potential for explanation of fusion dynamics of various projectile-target combinations. However, the EDWSP model adequately describe the fusion enhancement of these systems wherein the energy dependence in the Woods-Saxon potential simulates various channels coupling effects that arise due to internal structure of colliding nuclei.

2. THEORETICAL FORMALISM

2.1. ONE DIMENSIONAL WONG FORMULA

The fusion cross-section within partial wave analysis is given by the following expression

$$\sigma_F = \frac{\pi}{k^2}\sum_{\ell=0}^{\infty}(2\ell+1)T_\ell^F . \quad (1)$$

Hill and Wheeler proposed an expression for tunneling probability (T_ℓ^F) which is based upon the parabolic approximation wherein the effective interaction between the collision partners has been replaced by an inverted parabola [1–6, 23–34, 43].

$$T_\ell^{HW} = \frac{1}{1+\exp\left[\frac{2\pi}{\hbar\omega_\ell}(V_\ell - E)\right]} . \quad (2)$$

This approximation was further simplified by Wong using the following assumptions for barrier position, barrier curvature and barrier height [1–6, 23–34, 42].

$$R_\ell = R_{\ell=0} = R_B$$

$$\omega_\ell = \omega_{\ell=0} = \omega$$

$$V_\ell = V_B + \frac{\hbar^2}{2\mu R_B^2}\left[\ell + \frac{1}{2}\right]^2 . \quad (3)$$

By using these assumptions and Eq. (2) into Eq. (1), the fusion cross-section can be written as

$$\sigma_F = \frac{\pi}{k^2}\sum_{\ell=0}^{\infty}(2\ell+1)\frac{1}{\left[1+\exp\frac{2\pi}{\hbar\omega}(V_\ell - E)\right]} . \quad (4)$$

Wong assumes that infinite number of partial waves contribute to the fusion process so changing the summation over ℓ into integral with respect to ℓ in Eq. (4) and by solving the integral one can obtain following expression of Wong formula [1–6, 23–34, 42].

$$\sigma_F = \frac{\hbar\omega\ R_B^2}{2E}\ell n\left[1 + \exp\left(\frac{2\pi}{\hbar\omega}(E - V_B)\right)\right] . \quad (5)$$

2.2. ENERGY DEPENDENT WOODS-SAXON POTENTIAL MODEL (EDWSP MODEL)

The nucleus-nucleus potential is the fundamental characteristic of heavy ion fusion reactions. In the present study, the theoretical calculations are performed by using static Woods-Saxon potential and energy dependent Woods-Saxon potential in conjunction with one dimensional Wong formula [23–34]. The form of static Woods-Saxon potential is defined as

$$V_N(r) = \frac{-V_0}{\left[1 + \exp\left(\frac{r - R_0}{a}\right)\right]}, \tag{6}$$

with $R_0 = r_0 (A_P^{\frac{1}{3}} + A_T^{\frac{1}{3}})$. The quantity V_0 is depth and a is the diffuseness parameter of nuclear potential. In EDWSP model, the depth of real part of the Woods-Saxon potential is defined as [23–34]

$$V_0 = \left[A_P^{\frac{2}{3}} + A_T^{\frac{2}{3}} - \left(A_P + A_T\right)^{\frac{2}{3}}\right]\left[2.38 + 6.8\left(1 + I_P + I_T\right)\frac{A_P^{\frac{1}{3}} A_T^{\frac{1}{3}}}{\left(A_P^{\frac{1}{3}} + A_T^{\frac{1}{3}}\right)}\right], \tag{7}$$

in 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 collision partners. The present parameterization of depth is based upon the reproduction of fusion excitation function data of wide range of projectile-target combinations ranging from $Z_P Z_T = 84$ to $Z_P Z_T = 1640$ [23–34]. The first term in the square bracket of Eq. (7) is directly proportional to the surface energy of nucleus and hence strongly depends on the collective motion of all the nucleons inside the nucleus. For instance, the colliding nuclei overlap in the neck region wherein the densities of collision partners get fluctuated. These kinds of fluctuation in densities are dynamical physical effects which are responsible for modification of diffuseness parameter and hence bring the necessity of larger value of diffuseness parameter ranging from a = 0.75 fm to a = 1.5 fm for reproduction of fusion excitation function data. The first term inside the square bracket of Eq. (7) accommodates all such physical effects. The second term inside the square bracket of Eq. (7) is directly related to the isospin asymmetry effects of colliding nuclei. The isospin asymmetry is different for different isotopes of a particular element and hence isotopic effects are also included in the nucleus-nucleus potential *via* this term. In literature, an abnormally large value of diffuseness parameter ranging from a = 0.75 fm to a = 1.5 fm has been used to account the fusion dynamics of wide range of projectile-target combinations. This abnormally large diffuseness might be an artifact of various kinds of static and dynamical physical effects such as fluctuation of densities and surface energy of colliding pairs. In this connection, the energy dependence in the Woods-Saxon potential is introduced *via* its diffuseness parameter and hence given by the following expression [23–34].

$$a(E) = 0.85\left[1+\frac{r_0}{13.75\left(A_P^{-\frac{1}{3}}+A_T^{-\frac{1}{3}}\right)\left(1+\exp\left(\frac{\frac{E}{V_B}-0.96}{0.03}\right)\right)}\right], \text{ in fm.} \quad (8)$$

The range parameter (r_0) is considered as free parameter and varied to reproduce the sub-barrier fusion data. The value of range parameter is quite sensitive to the nature of colliding systems under consideration. In EDWSP model calculations, this expression provides a wide range of diffuseness depending upon the value of r_0 and the bombarding energy of collision partners.

3. RESULTS AND DISCUSSION

Recently, the EDWSP model was successfully used to describe the dynamics of heavy ion fusion reactions. The present work is motivated to address the unexpected entrance channel mass asymmetry effect by analyzing the fusion dynamics of ${}^{32}_{16}\mathrm{S}+{}^{208}_{82}\mathrm{Pb}$, ${}^{34}_{16}\mathrm{S}+{}^{206}_{82}\mathrm{Pb}$ and ${}^{36}_{16}\mathrm{S}+{}^{204}_{82}\mathrm{Pb}$ systems wherein unexpected entrance channel mass asymmetry effects are present. Furthermore, these projectile-target combinations lead to the formation of same compound nucleus ${}^{240}_{98}Cf$. In Table 1, the values of potential parameters as required in the EDWSP model calculations for ${}^{32}_{16}\mathrm{S}+{}^{208}_{82}\mathrm{Pb}$, ${}^{34}_{16}\mathrm{S}+{}^{206}_{82}\mathrm{Pb}$ and ${}^{36}_{16}\mathrm{S}+{}^{204}_{82}\mathrm{Pb}$ systems are listed.

Table 1

Range, depth and diffuseness of Woods-Saxon potential used in the EDWSP model calculations for various heavy ion fusion reactions [23–34]

System	r_0 [fm]	V_0 [MeV]	$\frac{a^{Present}}{Energy\ Range}\left[\frac{\mathrm{fm}}{\mathrm{MeV}}\right]$
${}^{32}_{16}\mathrm{S}+{}^{208}_{82}\mathrm{Pb}$	1.152	127.43	$\frac{0.996\ \text{to}\ 0.85}{110\ \text{to}\ 165}$
${}^{34}_{16}\mathrm{S}+{}^{206}_{82}\mathrm{Pb}$	1.154	137.43	$\frac{0.999\ \text{to}\ 0.85}{110\ \text{to}\ 165}$
${}^{36}_{16}\mathrm{S}+{}^{204}_{82}\mathrm{Pb}$	1.158	146.95	$\frac{1.00\ \text{to}\ 0.85}{110\ \text{to}\ 165}$

The fusion dynamics of ${}^{32}_{16}\mathrm{S}+{}^{208}_{82}\mathrm{Pb}$, ${}^{34}_{16}\mathrm{S}+{}^{206}_{82}\mathrm{Pb}$ and ${}^{36}_{16}\mathrm{S}+{}^{204}_{82}\mathrm{Pb}$ systems are analyzed by using static Woods-Saxon potential and energy dependent Woods-Saxon potential model in conjunction with one dimensional Wong formula. The authors in Ref. [41], mainly focused on the diffuseness anomaly *i.e.* the requirement of larger value of diffuseness parameter (a = 1.47 fm) to reproduce the fusion excitation function data. However, the present work is focused on diffuseness anomaly as well as on the entrance channel mass asymmetry effects. In the fusion of ${}^{32}_{16}\mathrm{S}+{}^{208}_{82}\mathrm{Pb}$, ${}^{34}_{16}\mathrm{S}+{}^{206}_{82}\mathrm{Pb}$ and ${}^{36}_{16}\mathrm{S}+{}^{204}_{82}\mathrm{Pb}$ systems, the theoretical calculations based upon static Woods-Saxon potential are significantly smaller than that of experimental data. This indicates that static Woods-Saxon potential is not suitable for analysis of sub-barrier fusion dynamics. However, when the fusion dynamics of these fusing systems are analyzed within the framework of energy dependent Woods-Saxon potential model (EDWSP model), it adequately explain the sub-barrier fusion excitation function data as evident from Fig. 1.

In EDWSP model, the energy dependent diffuseness parameter leads to a distribution of barrier of varying heights. Some of barriers have their heights smaller than that of uncoupled Coulomb barrier and these are responsible for the maximum flux lost from elastic channel to fusion channel. This ultimately predicts larger sub-barrier fusion cross-section data over the expectation of energy independent one dimensional Wong formula as evident from Fig. 1. In EDWSP model, the fluctuation of diffuseness parameter is effectively equivalent to increase of capture radii of colliding nuclei which in turn suggest that the fusion process starts at much larger inter-nuclear separation between the collision partners [24]. For these projectile-target combinations, in the EDWSP model calculations, a = = 1.00 fm is the largest value of diffuseness parameter resulting in the lowest fusion barrier. This lowest fusion barrier can cause the maximum flux lost from the elastic channel to fusion channel. As the incident energy increases, the value of diffuseness parameter decreases resulting in an increase of the height of the corresponding fusion barrier. In above barrier energy regions, wherein the fusion cross-section is almost independent of different channel coupling effects (internal structure of colliding nuclei), the value of diffuseness parameter gets saturated to its minimum value ($a = 0.85$ fm). At this diffuseness parameter, the corresponding fusion barrier is highest as evident from Fig. 2. The similar results are found for other two fusing systems. Furthermore, such kinds of static and dynamical physical effects are also evident from the coupled channel analysis of wide range of projectile-target combinations [1–6].

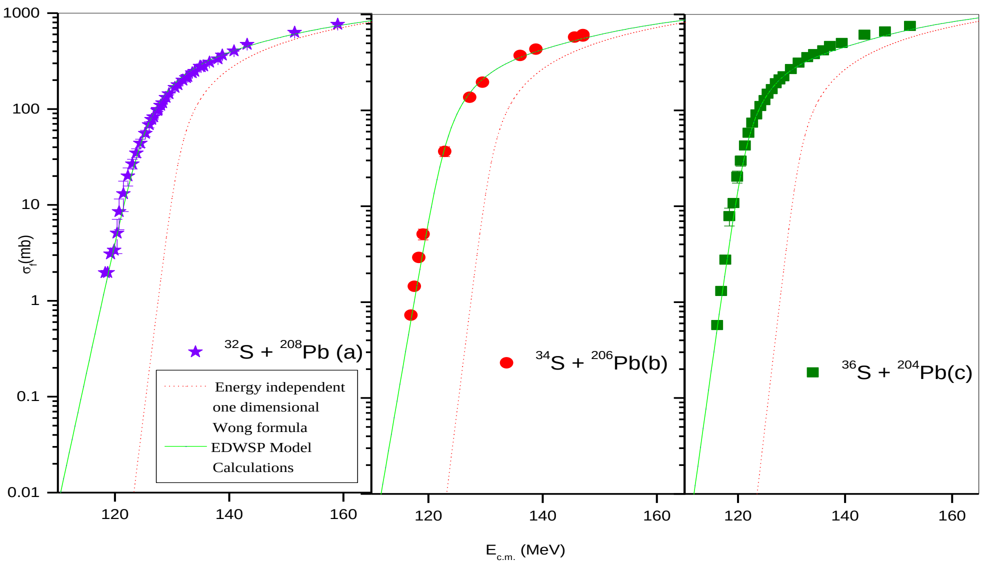
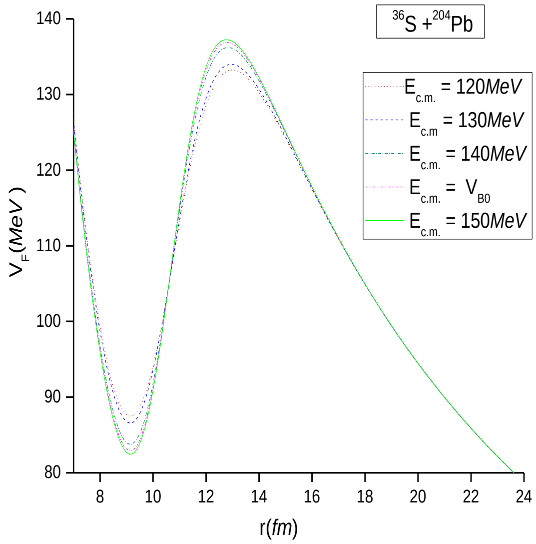
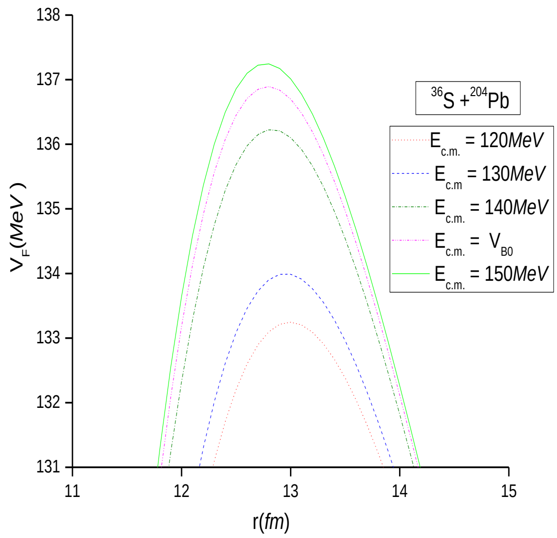


Fig. 1 – The fusion excitation functions of ${}^{32}_{16}\mathrm{S} + {}^{208}_{82}\mathrm{Pb}$ (a), ${}^{34}_{16}\mathrm{S} + {}^{206}_{82}\mathrm{Pb}$ (b) and ${}^{36}_{16}\mathrm{S} + {}^{204}_{82}\mathrm{Pb}$ (c) systems obtained by using static Woods-Saxon potential model and energy dependent Woods-Saxon potential model (EDWSP model) [23–34]. The results are compared with available experimental data (*) taken from Ref. [41].

The fusion cross-section data show a strong dependence on the entrance channel mass asymmetry effects. The size of the neck formed between the colliding nuclei leading to the formations of same compound nucleus strongly depends upon the entrance channel mass asymmetry effect. In the Ref. [35], authors clearly showed that the fusion inhibition factor decreases with increase of entrance channel mass asymmetry. This unambiguously suggested that larger the entrance channel mass asymmetry leads to substantially enhanced sub-barrier fusion cross-section and hence favors the fusion process.



a



b

Fig. 2 – The potential barrier (fusion barrier) for $^{36}_{16}S + ^{204}_{82}Pb$ system obtained by using the present energy dependent Woods-Saxon potential model [23–34]. The similar results are found for $^{32}_{16}S + ^{208}_{82}Pb$ and $^{34}_{16}S + ^{206}_{82}Pb$ systems.

For instance the fusion of $^{46}_{22}Ti+^{64}_{28}Ni$ system and $^{50}_{22}Ti+^{60}_{28}Ni$ system leads to the formation of same compound nucleus $^{110}_{50}Sn$ and the larger sub-barrier fusion enhancement of $^{46}_{22}Ti+^{64}_{28}Ni$ system in comparison to $^{50}_{22}Ti+^{60}_{28}Ni$ system can be correlated with the larger entrance channel mass asymmetry of former fusing system [24]. Therefore, the magnitude of sub-barrier fusion enhancement should be increases with increase of entrance channel mass asymmetry (η). However, the situation is quite opposite in the fusion of $^{32}_{16}S+^{208}_{82}Pb$, $^{34}_{16}S+^{206}_{82}Pb$ and $^{36}_{16}S+^{204}_{82}Pb$ systems.

For instance, for $^{32}_{16}S+^{208}_{82}Pb$ system is $\eta=\left|\frac{A_P-A_T}{A_P+A_T}\right|=0.733$, $^{34}_{16}S+^{206}_{82}Pb$ system is $\eta=\left|\frac{A_P-A_T}{A_P+A_T}\right|=0.716$ and $^{36}_{16}S+^{204}_{82}Pb$ system is $\eta=\left|\frac{A_P-A_T}{A_P+A_T}\right|=0.70$. It is expected that larger mass asymmetric fusing system produces larger sub-barrier fusion enhancement with respect to less mass asymmetric fusing system. However, in actual practice the less mass asymmetric fusing system leads the larger fusion enhancement at sub-barrier energies over the expectation of one dimensional barrier penetration model as evident from Fig. 3.

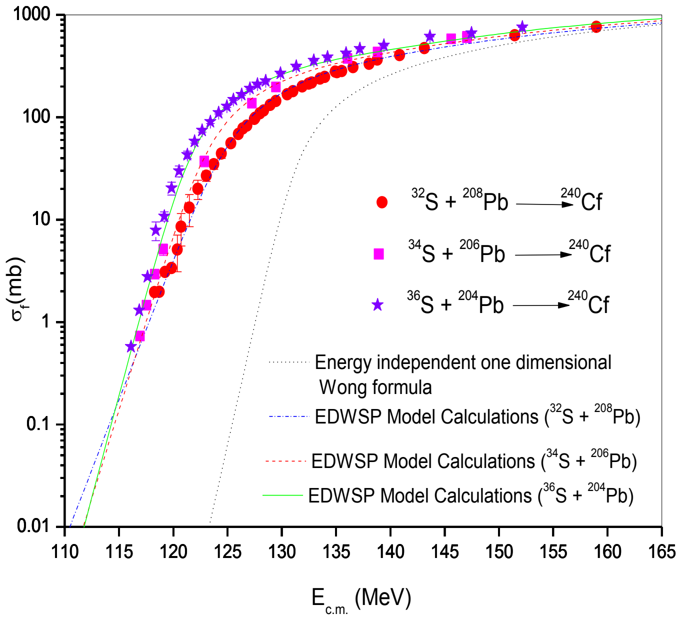


Fig. 3 – Same as Fig. 1.

In addition, the authors [41] reported that a significantly larger value of diffuseness parameter ($a = 1.47$ fm) is required to account the fusion excitation function data of $^{32}_{16}S + ^{208}_{82}Pb$, $^{34}_{16}S + ^{206}_{82}Pb$ and $^{36}_{16}S + ^{204}_{82}Pb$ systems. Although, in the present work, larger value of diffuseness parameter ranging from $a = 0.85$ fm to $a = 1.00$ fm, which is much larger than a value extracted from the elastic scattering data, are needed for reproduction of sub-barrier fusion excitation function data. But these values are much smaller than a value of diffuseness parameter ($a = 1.47$ fm) reported in literature. The maximum value of diffuseness parameter ($a = 1.00$ fm) in the present work is consistent with our previous analysis wherein $a = 0.85$ fm to $a = 0.98$ fm were used for successful exploration of fusion dynamics of wide range of projectile-target combinations. This clearly indicates that the energy dependent Woods-Saxon potential has an effect closely similar to that of static Woods-Saxon potential with abnormally large diffuseness. In literature, it is well recognized that in the eigenchannel approximation, the effects of coupling between relative motion of colliding nuclei and internal structure degrees of freedom is to split the uncoupled fusion barrier into a distribution of barrier and the passage through the barriers whose heights are smaller than that of uncoupled fusion barrier is more probable. This spectrum of barriers of different heights can be directly manifested as fusion enhancement at sub-barrier energies. In similar way, the EDWSP model produces a spectrum of barriers of varying heights and reasonably addresses the fusion enhancement at sub-barrier energies as already discussed in Fig. 2. Furthermore, energy dependence in Woods-Saxon potential simulates the effects of internal structure degrees of freedom such as inelastic surface vibrations of colliding pairs and hence adequately explains the sub-barrier fusion dynamics. This raises number of questions on the validity of static Woods-Saxon potential for description of fusion process and thus the various channel coupling effects with regard the sub-barrier fusion enhancement whether mirrors the true picture of fusion process or simply mocks up the inconsistency of static Woods-Saxon potential is still not clear and requires more intensive investigations theoretical as well as experimental front.

4. CONCLUSIONS

The present work analyzed the limitations of static Woods-Saxon potential model and the applicability of the EDWSP model by studying the fusion dynamics of $^{32}_{16}S + ^{208}_{82}Pb$, $^{34}_{16}S + ^{206}_{82}Pb$ and $^{36}_{16}S + ^{204}_{82}Pb$ systems. The entrance channel mass asymmetry effect is found to be one of the most important parameter which significantly influences the fusion of these systems. The less mass asymmetric fusing system ($^{36}_{16}S + ^{204}_{82}Pb$) leads to the larger sub-barrier fusion enhancement while the more mass asymmetric fusing system ($^{32}_{16}S + ^{208}_{82}Pb$) produces smaller sub-barrier fusion enhancement. Theoretical calculations based upon static Woods-Saxon potential systematically fail to reproduce the fusion dynamics of these systems. However, the energy dependent Woods-Saxon potential model (EDWSP model) in conjunction with one dimensional Wong formula accurately addresses the fusion dynamics of $^{32}_{16}S + ^{208}_{82}Pb$, $^{34}_{16}S + ^{206}_{82}Pb$ and $^{36}_{16}S + ^{204}_{82}Pb$ systems. In EDWSP model calculations, a wide range of diffuseness parameter ranging from $a = 0.85$ fm to $a = 1.00$ fm is required for reproduction of the fusion enhancement of various heavy ion fusion reactions which is much smaller than a value of diffuseness parameter ($a = 1.47$ fm) used in the literature for explaining the systematics of these fusing systems.

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REFERENCES

1. M. Beckerman, Rep. Prog. Phys. **51**, 1047 (1988).
2. M. Dasgupta *et al*., Annu. Rev. Nucl. Part. Sci. **48**, 401 (1998).
3. A. B. Balantekin and N. Takigawa, Rev. Mod. Phys. **70**, 77 (1988).
4. L. F. Canto *et al*., Phys. Rep. **424**, 1 (2006).
5. K. Hagino and N. Takigawa, Prog. Theor. Phys. **128**, 1061 (2012).
6. B. B. Back *et al*., Rev. Mod. Phys. **86**, 317 (2014).
7. V. I. Zagrebaev, Phys. Rev. C **67**, 061601 (2003).
8. G. Montagnoli *et al*., Eur. Phys. J A **15**, 351 (2005).
9. R. N. Sagaidak *et al*., Phys. Rev. C **76**, 034605 (2007).
10. N. Wang and W. Scheid, Phys. Rev. C **78**, 014607 (2008).
11. O. N. Ghodsi and R. Gharaei, Eur. Phys. J. A **48**, 21 (2012).
12. Sukhvinder, M. Singh and R. Kharab, Mod. Phys. Lett. A **26**, 1017 (2011).
13. Sukhvinder, M. Singh and R. Kharab, Int. J. Mod. Phys. E **21**, 1250054 (2012).
14. Sukhvinder, M. Singh and R. Kharab, Commun. Theor. Phys. **55**, 649 (2011).
15. Sukhvinder, M. Singh and R. Kharab, Phys. At. Nucl. **74**, 49 (2011).
16. C. H. Dasso and G. Pollarolo, Phys. Rev. C **68**, 054604 (2003).
17. K. Hagino *et al*., Phys. Rev. C **67**, 054603 (2003).
18. J. O. Newton *et al*., Phys. Rev. C **70**, 024605 (2004).
19. K. Hagino and N. Rowley, Phys. Rev. C **69**, 054610 (2004).
20. A. Mukherjee *et al*., Phys. Rev. C **75**, 044608 (2007).
21. M. V. Chushnyakova, R. Bhattacharya and I. I. Gontchar, Phys. Rev. C **90**, 017603 (2014).
22. I. I. Gontchar, R. Bhattacharya and M. V. Chushnyakova, Phys. Rev. C **89**, 034601 (2014).
23. M. Singh, Sukhvinder and R. Kharab, Mod. Phys. Lett. A **26**, 2129 (2011).
24. M. Singh, Sukhvinder and R. Kharab, Nucl. Phys. A **897**, 179 (2013).
25. M. Singh, Sukhvinder and R. Kharab, Nucl. Phys. A **897**, 198 (2013).
26. M. Singh, Sukhvinder and R. Kharab, AIP Conf. Proc. **1524**, 163 (2013).
27. M. Singh, Sukhvinder and R. Kharab, Atti Della "Fondazione Giorgio Ronchi" Anno LXV, **6**, 751 (2010).

28. M. Singh, M. Phil., Dissertation (unpublished), 2009, Kurukshetra University Kurukshetra, Haryana, India.
29. M. Singh, Ph.D, Thesis (unpublished), 2013, Kurukshetra University, Haryana, India.
30. M. Singh and R. Kharab, EPJ Web of Conferences **66**, 03043 (2014).
31. M. S. Gautam, Phys. Rev. C **90**, 024620 (2014).
32. M. S. Gautam, Nucl. Phys. A **933**, 272 (2015).
33. M. S. Gautam, Mod. Phys. Lett. A **30**, 1550013 (2015).
34. M. S. Gautam, Phys. Scr. **90**, 025301 (2015).
35. R. M. Anjos *et al*., Phys. Rev. C **42**, 354 (1990).
36. N. V.S.V. Prasad et al, Nucl. Phys. A **603**, 176 (1996).
37. M. Dasgupta *et al*., Nucl. Phys. A **539**, 351 (1984).
38. J. F. Mateja *et al*., Phys. Rev. C **30**, (1984) 134.
39. L. C. Dennis *et al*., Phys. Rev. C **26**, 981 (1982).
40. R. M. Anjos *et al.*, Phys. Rev. C **49**, (1994) 2018.
41. D. J. Hinde *et al*., Phys. Rev. C **75**, 054603 (2007).
42. C. Y. Wong, Phys. Rev. Lett. **31**, 766 (1973).
43. D. L. Hill and J. A. Wheeler, Phys. Rev. **89**, 1102 (1953).