SUB-BARRIER FUSION DYNAMICS OF $^{16,17}O+^{144}Sm$ REACTIONS

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Fusion reactions, which power sun and other stars and play an important role in stellar evolution, are overwhelmingly investigated during past few decades. The interesting aspect of heavy ion fusion reactions is that the experimentally measured fusion data for various projectile-target pairs were found to be strongly enhanced with reference to the outputs of the one dimensional barrier penetration (BPM) model. The various coupled channel approaches explained the fusion data reasonably well by considering the internal structure properties of the fusing pairs [1]. In literature [1-2], the low lying inelastic surface excitations, static deformation of projectile (or target) in its ground state, neck formation, zero point motion, and particle transfer channels were identified as dominant mode of channel couplings. All these relevant channels are generally coupled to the relative motion between the collision partners and the coupled channel predictions obtained by incorporating the important channels fairly reproduced the experimental data of the fusing system under consideration [3].

The aforementioned intrinsic channels are entering in the theoretical calculation via nucleus-nucleus potential and there are considerably large ambiguities in the choice of optimum form of the nuclear potential. Keeping this view, the present work analyzed the fusion dynamics of $^{16,17}O+^{144}Sm$ reactions by opting static Woods-Saxon potential and energy dependent Woods-Saxon potential (EDWSP) model [4-7] in conjunction with Wong formula [8]. The experimental measurements of $^{16,17}O+^{144}Sm$ reactions were done by *Morton et al.* [9] and *Leigh et al.* [10]. The authors reported that the fusion data $^{16,17}O+^{144}Sm$ reactions at sub-barrier energies were found to be significantly larger than that of the one dimensional BPM. The so observed sub-barrier fusion enhancement was explained by incorporating the low lying inelastic surface excitations such as 2^+ and 3^- of the target in the coupled channel description for $^{16}O+^{144}Sm$ system. However, for $^{17}O+^{144}Sm$ system, in addition to inelastic surface excitation of type 2^+ and 3^- of fusing partners, the couplings to neutron transfer channels are urgently required to address the below barrier fusion data. In order to confirm the significance of the inelastic surface excitations and/or neutron transfer channels, the sub-barrier fusion dynamics of $^{16,17}O+^{144}Sm$ reactions are analyzed in the present work. The form of the static Woods-Saxon potential rely on three ingredients: range, depth and diffuseness and is defined as

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

where, V_0 is depth of nuclear potential, r is the range and 'a' is the diffuseness parameter of the nuclear potential. In the EDWSP model, the depth of Woods-Saxon potential is parameterized by the following relation.

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

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 the reacting pairs.

In EDWSP model, the diffuseness parameter $a(E)$ is considered as energy dependent and hence is defined as

$$a(E)=0.85\left[1+\frac{r_0}{13.75\left(A_P^{-\frac{1}{3}}+A_T^{-\frac{1}{3}}\right)\left(1+\exp\left(\frac{\frac{E_{c.m.}}{V_{B0}}-0.96}{0.03}\right)\right)}\right]fm$$

$E_{c.m.}$ is the incident energy in center of mass frame, V_{B0} is height of the Coulomb barrier. The range parameter (r_0) is related with the geometry of the fusing partners via $R_0=r_0\left(A_P^{1/3}+A_T^{1/3}\right)$.

The theoretical estimations of $^{16,17}O+^{144}Sm$ reactions obtained by using static Wood-Saxon potential and the EDWSP model in conjunction with the one dimensional Wong formula are shown in Fig.1. From this figure, it cleared that the calculations based on static Woods-Saxon potential model are substantially under predict the fusion data particularly in below barrier energy regions. This is due to fact that the one dimensional Wong formula does not include the impacts from nuclear structure of the participants and the relative motion between the fusing pairs is the only degree of freedom. As a result, the single interaction barrier formed by combination of attractive nuclear potential and repulsive Coulomb potential is relatively high in comparison to the kinetic energy of the projectiles. Therefore, the projectile has not sufficient energy to overcome this barrier and subsequently the occurrence of fusion is restricted by such interaction barrier. This reveals that the theoretical cross-sections remain significantly smaller in magnitude when compared with experimental fusion data. The same is reflected for $^{16,17}O+{}^{144}Sm$ reactions from Fig.1.

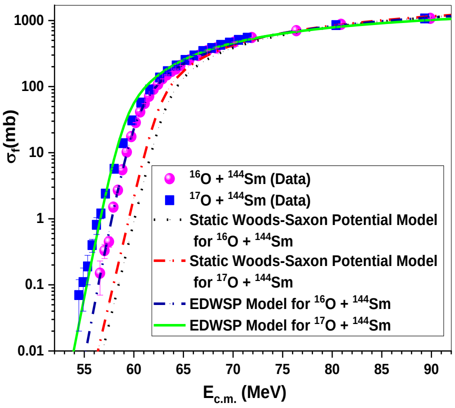

Fig.1. Fusion excitation functions of $^{16,17}O+{}^{144}Sm$ reactions obtained by using the standard Woods-Saxon potential and the EDWSP model. The theoretical calculations are compared with the available experimental data taken from Ref. [9-10].

However in the EDWSP model [4-7], the energy dependent nature of nucleus-nucleus potential generates the spectrum of energy dependent fusion barriers of varying heights and weights. The barriers whose heights are lower than that of the Coulomb barrier allow the incoming flux from elastic channel to fusion channel and consequently the EDWSP model predicts larger fusion cross-sections. The barrier lowering effects are the basic ingredient of the EDWSP model and hence in the essence of barrier lowering effects, the present model adequately addresses the sub-barrier fusion dynamics of the chosen reaction. In Refs.[9-10], authors highlighted that the couplings to low lying inelastic surface excitations such as 2^+ and 3^- of the target are sufficient to reproduce the observed fusion data in whole range of incident energies. Whereas, the considerations of low lying vibrational modes like 2^+ and 3^- of the colliding nuclei are unable to recover the experimental measurement of $^{17}O+{}^{144}Sm$ system. For this reaction, a pair neutron transfer channel exists with positive ground state *Q*-value and it must be included along with vibrational modes of the fusing pairs in coupled channel calculations to reproduce the fusion data in the close vicinity of the Coulomb barrier. From Fig.1, it is unambiguously clarified that the EDWSP model adequately recovers the observed sub-barrier fusion enhancements of the studied reactions and hence intrinsically includes the contributions from the intrinsic degrees of freedom of the collision partners. Furthermore, the significantly larger sub-barrier fusion enhancement of $^{17}O+{}^{144}Sm$ with respect to $^{16}O+{}^{144}Sm$ system can be correlated with the positive *Q*-value neutron transfer channel in former system.

In summary, the theoretical estimations based on static Woods-Saxon potential model fail to explain the observed fusion enhancement of $^{16,17}O+{}^{144}Sm$ reactions. This clearly reflects that the one dimensional Wong formula does not includes the impacts of the channel couplings originated from the nuclear structure of the participants. On the other hand, the EDWSP model intrinsically considers the influences of the low lying inelastic surface excitations of the collision partners and/or pair neutron transfer channel with positive ground state *Q*-value. As consequence of energy dependence in nucleus-nucleus potential, the EDWSP model generates barrier lowering and hence appropriately reproduces the observed fusion dynamics of the present reactions. The EDWSP model and coupled channel model reflect the similar behavior of $^{16,17}O+{}^{144}Sm$ reactions at near and below barrier energies.

REFERNCES

[1] L.F. Canto et al., *Phys. Rep.* **596**, 1 (2015).
[2] G. Montagnoli and A. M. Stefanini, *Eur. Phys. A* **53**, 169 (2017).
[3] K. Hagino et al., *Comput. Phys. Commun.***123**, *143 (1999).*
[4] M. S. Gautam, *Chinese Phys. C* **39**, *114102 (2015), Commun. Theor. Phys.* **64**, *710 (2015), Romanian Rep. Phys.* **68**, *1035 (2016), Chinese J. Phys.* **54**, *86 (2016).*
[5] Manjeet Singh, Sukhvinder and Rajesh Kharab, *Mod. Phys. Lett. A* **26**, 2129 (2011), *Nucl. Phys. A* **897**, 179 (2013), *Nucl. Phys. A* **897**, 198 (2013).
[6] M. S. Gautam, *Phys. Rev. C***90**, *024620 (2014), Nucl. Phys. A* **933**, *272 (2015).*
[7] M. S. Gautam et al., *Phys. Rev. C* **92**, 054605 (2015), *Eur. Phys. A* **53**, 12 (2017), *Eur. Phys. A* **53**, 212 (2017), *Nucl. Phys. A* **984**, *9 (2019), Int. J. Mod. Phys. E* **28**, *1950006 (2019), Int. J. Mod. Phys. E* **29**,*2050029 (2020),Nucl. Phys. A* **998**, 121730 (2020), *Phys. Rev. C* **102**, *014614 (2020).*
[8] C. Y. Wong,*Phys. Rev. Lett.* **31**, *766 (1973).*
[9] C. R. Morton et al., *Phys. Rev. Lett.* **72**, *4074 (1994).*
[10] J. R. Leigh et al., *Phys. Rev. C* **52**, *3151 (1995).*