# Role of surface diffuseness and the coupling of relative motion with intrinsic motion in fusion of negative & positive Q-value systems

Ankita Jamwal, Shailja Mohini Sharma, Kushmakshi, and Dalip Singh Verma*
*Department of Physics and Astronomical Science,*
*Central University of Himachal Pradesh, Dharamshala,*
*District Kangra,(H.P)-176215, INDIA*

## Introduction

It is well established that fusion cross-sections at sub-barrier energies may be enhanced by several orders of magnitude as compared to the prediction of one dimensional model due to the coupling of relative motion to the nuclear intrinsic degree of freedom. The coupling leads to the modification of the potential energy term and hence the enhancement in the fusion cross-section at below barrier energies ([1] and references there in). The potential modification can also be done by changing the parameters of the potential used. In this paper, we have calculated the fusion cross-section for four quadrupole-deformed systems $^{36}S + ^{64}Ni$, $^{36}S + ^{48}Ca$, $^{16}O + ^{182}W$ and $^{16}O + ^{144}Nd$ by considering the coupling of low-lying $2^+$ vibrational states, due to the addition of single quadrupole surface vibrations to all systems i.e. the target as well as the projectile, using CCFULL code [1]. Also, the surface diffuseness parameter 'a' of Woods-Saxon potential has been adjusted to fit the observed data for the cases where coupling is not reproducing the data.

## Formalism

The fusion cross-section as a function of center of mass energy ($E_{cm}$) is given as,

$$\sigma_{fusion}(E_{cm}) = \frac{\pi}{k_o^2}\sum_J (2J+1)P_J(E_{cm}) \quad (1)$$

where, $P_J(E_{cm})$ is penetration probability, J is total angular momentum, $k_o$ is wave vector of projectile. For the penetration probability, the coupled channel equation has been solved using Numerov method [2] where incoming wave boundary condition is employed [3]. The coupled channel equation is,

$$[-\frac{\hbar^2}{2\mu}\frac{d^2}{dr^2} + \frac{J(J+1)\hbar^2}{2\mu r^2} + V_N^{(O)}(r) + \frac{Z_P Z_T e^2}{r} + \epsilon_n - E_{cm}]\psi_n(r) + \sum_m V_{nm}(r)\psi_m(r) = 0 \quad (2)$$

where, $E_{cm}$ is bombarding energy in the center of the mass frame, $\epsilon_n$ is excitation energy of the $n^{th}$ channel, $V_{nm}$ is matrix elements of the coupling hamiltonian, $V_N^{(O)}$ is Woods-Saxon potential used as nuclear potential. The nuclear coupling matrix for both rotational and vibrational coupling is given as

$$\begin{aligned} V_{nm}^{(N)} &= \langle n|V_N(r,\hat{O})|m\rangle - V_N(r)\delta_{n,m} \\ &= \sum_\alpha \langle n|\alpha\rangle\langle\alpha|m\rangle V_N(r,\lambda_\alpha) \\ &\quad -V_N(r)\delta_{n,m} \end{aligned} \quad (3)$$

The last term in this equation is included to avoid the double counting of the diagonal component. The detail of formalism can be seen in ref. [1].

## Calculations and results

Fusion cross-sections are calculated, with and without coupling effects and by adjusting parameter 'a', as a function of center of mass energy. The coupling include the $2^+$ low lying energy states of the target and projectile, the excitation energy for these low lying energy states $\Omega_i$ (i=1, 2) for different systems are (i) $^{36}S + ^{64}Ni$: $\Omega_1$=3.2909 MeV & $\Omega_2$= 1.3458 MeV (ii) $^{36}S + ^{48}Ca$: $\Omega_1$= 3.2909 MeV & $\Omega_2$= 3.8317 MeV (iii) $^{16}O + ^{182}W$: $\Omega_1$= 6.9171 MeV & $\Omega_2$= 0.1001 MeV and (iv) $^{16}O + ^{144}Nd$: $\Omega_1$= 6.9171 MeV & $\Omega_2$= 0.6965

*Electronic address: dsverma@cuhimachal.ac.in

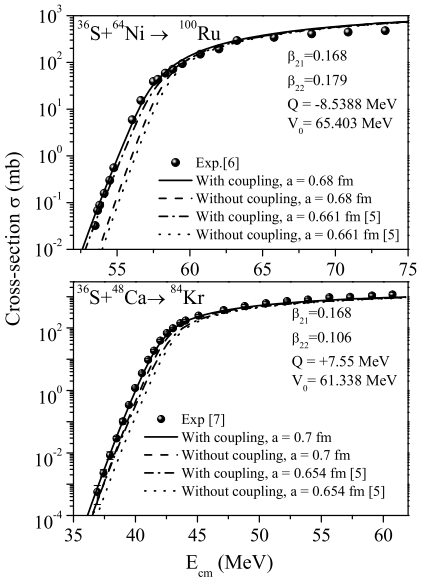


FIG. 1: The calculated fusion cross-sections for quadrupole deformed systems $^{36}S + ^{64}Ni$ and $^{36}S + ^{48}Ca$ with and without coupling of low lying $2^+$ vibrational states of target and projectile, due to the single quadrupole surface vibrations, for two different diffuseness parameters in energy range of $E_{cm}$= 35-61 MeV and 52-74 MeV, is compared with the experimental data [6] and [7], respectively.

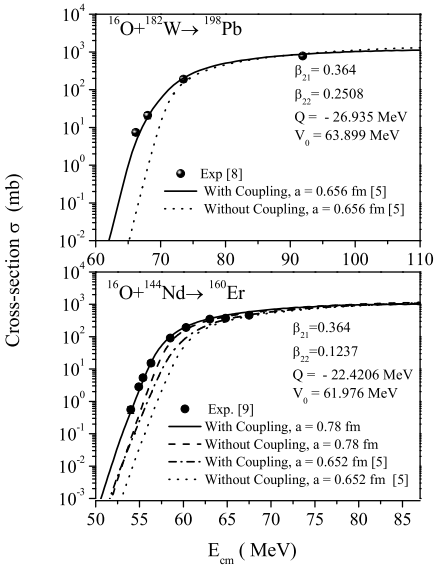


FIG. 2: Same as Fig.1, but for the systems $^{16}O+^{182}W$ and $^{16}O+^{144}Nd$ in energy range $E_{cm}$= 62-110 MeV and 52-87 MeV compared with the experimental data [8] and [9], respectively.

MeV [4]. The quadrupole deformation parameters $\beta_{2i}$ along with other input information is given in the respective figure. Fig. 1 shows the comparison of the calculated fusion cross-sections as a function of center of mass energies, first with and without coupling for 'a' of ref. [5] and then for that value of 'a' which reproduces the observed data for: (i) a negative Q-value system $^{36}S + ^{64}Ni$ [6] (upper panel), and $^{36}S + ^{48}Ca$ [7], a positive Q-value system (lower panel). Similarly, Fig. 2 shows a comparison of the calculated fusion cross-sections for $^{16}O + ^{182}W$, a negative Q-value system, with data [8] and the calculations are without any adjustment to parameter 'a' (upper panel) while for negative Q-value system $^{16}O + ^{144}Nd$ [9] the data is reproduced by adjusting the parameter 'a' (lower panel). So, we conclude that coupling alone is not sufficient to reproduced the observed data for the chosen systems, except $^{16}O + ^{182}W$, but suitable interaction potential is also needed, which here is obtained by adjusting the surface diffuseness parameter of the nuclear potential.

## References

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