# Barrier distribution for $^{16}O+^{92}Zr$ reaction in three-stage classical molecular dynamics model

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## Introduction

The nuclear structure of the interacting nuclei has a significant impact on nuclear fusion close to the barrier, in addition to Coulomb repulsion and collision dynamics. The latter, generally, results in large enhancements in cross section near to and below the barrier energy, and to variations in the energy dependence of the fusion excitation function compared with that due to penetration of a single Coulomb-plus nuclear potential barrier. It is formally demonstrated that couplings between reaction channels produce an energy distribution of effective potential barriers [1]. Such couplings give rise to a distribution of the Coulomb barrier [2,3]. For heavy- ion fusion cross section calculations, coupled channel formalisms have been extensively utilized. CCFULL is the calculation code for standard coupled channels which utilizes the Woods-Saxon potential.

Within the classical approximation, 3S-CMD [4] model is developed comprising of (1) Rutherford trajectory stage, (2) Classical rigid-body dynamics stage (CRBD) and, (3) CMD stage [4]. This model explicitly takes into account not only the long-range reorientation effect at large separations but internal excitations at close separations as well, seamlessly in the same simulation code.

In the present work we use the calculated result of fusion cross sections for $^{16}O+^{92}Zr$ system of ref. [5]. In ref. [5] fusion cross sections have been calculated using a soft-core Gaussian form of NN-potential (eq.(1)), with the parameter set P4 [4] and NP [5] in 3S-CMD model. Using these fusion cross sections, we find barrier distribution for spherical + spherical system $^{16}O+^{92}Zr$ in 3S-CMD model.

## Calculation Details

The soft-core Gaussian form of NN-potential is given by,

$$V_{ij}(r_{ij}) = -V_0\left(1-\frac{C}{r_{ij}}\right)\exp\left(-\frac{r_{ij}^2}{r_0^2}\right) \qquad (1)$$

where $V_0$, $C$ and $r_0$ are the depth parameter, repulsive core-radius and range parameter respectively. The nuclei are generated using the parameter set P4 ($V_0$ = 1155 MeV, C = 2.07 fm, $r_0$ = 1.2 fm) [4] and NP ($V_0$ = 900 MeV, C = 1.95fm, $r_0$ = 1.2 fm) [5] which reproduces the ground state properties of the colliding nuclei close to the experimental values (see Table 1).

**Table 1:** Ground state properties of **$^{16}O$** and **$^{92}Zr$** nuclei used in present calculation [5].

| | | | BE(MeV) | R(fm) | $\beta_2$ |
|---|---|---|---|---|---|
| **$^{16}O$** | Cal. | P4 | -122.28 | 2.43 | -0.05 |
| | | NP | -140.40 | 2.43 | 0.16 |
| | **Exp.** | | **-127.62** | **2.73** | **0.00** |
| **$^{92}Zr$** | Cal. | P4 | -827.33 | 4.59 | -0.14 |
| | | NP | -1067.33 | 4.32 | -0.10 |
| | **Exp.** | | **-799.73** | **4.30** | **0.00** |

Fusion cross sections in 3S-CMD model are calculated using the classical formula [6],

$$\sigma_{fusion} = \pi b_{cr}^2 \qquad (2)$$

where, $b_{cr}$ is the maximum (critical) impact parameter for which the two nuclei fuse. The barrier distribution is calculated by taking the second derivative of eq. (2),

$$D(E) = \frac{d^2}{dE^2}[E\sigma] \qquad (3)$$

## Result and Discussions

### $^{16}O+^{92}Zr$Reaction:

Fusion cross-sections calculated using potentials P4 and NP and eq.(2) in 3S-CMD model from ref. [5] are shown in fig. 1. Fusion cross sections calculated using potential P4 are highly overestimated compared to the experimental data [7], while Fusion cross sections calculated using potential parameter set NP and eq.(2) in 3S-CMD model from ref. [5] matches well with the experimental data above the barrier

energies. Below the barrier energies it is only slightly overestimated. This figure also shows the fusion cross section calculated using SBPM [4] model with potential parameter P4 and NP. The fusion cross sections calculated using P4 potential and SBPM model shows overall good agreement with experimental data at high energies while at lower energies it slightly overestimated. The fusion cross sections calculated using NP potential and SBPM model are underestimated at all energies with the experimental data.

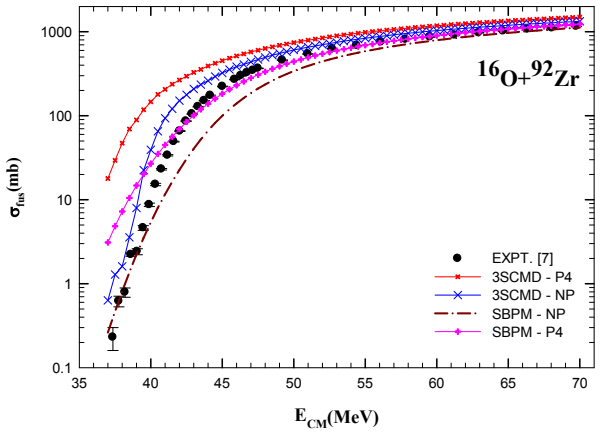


**Fig. 1:** Fusion cross section for $^{16}$O+$^{92}$Zr reaction

Fig. 2 shows barrier distribution for $^{16}$O+$^{92}$Zr system calculated using 3S-CMD model and SBPM and compared with the experimental data taken from Ref. [7]. Here the barrier distribution calculated with SBPM model are evaluated with $\Delta E_{CM}$ = 2.0 MeV. For the barrier distribution calculated using 3S-CMD model with P4 and NP potential parameters, we take $\Delta E_{CM}$ = 2.5 MeV to make the distribution smoother. Barrier distribution calculated using SBPM model with potentials P4 and NP gives a single peaked structure at $E_{CM}$ = 41.5 MeV. At higher energies it shows good agreement with the experimental data. At lower energies the barrier distribution underestimated with the experimental data.

In fig. 2 Solid blue and red line shows the barrier distribution calculated using 3S-CMD model with potential parameters NP and P4 respectively. It shows that the single peak seems to splits into multiple peaks. This may be due to the vibrational degrees of freedom of participating nuclei in the sub-barrier region.

As shown in fig. 2, the barrier distribution calculated using P4 potential parameter set and with 3S-CMD model shows better agreement at higher energies. The highest peak also matches well with the experimental data. At higher energies it also matches well with the barrier distribution calculated using P4 potential parameter set and SBPM model.

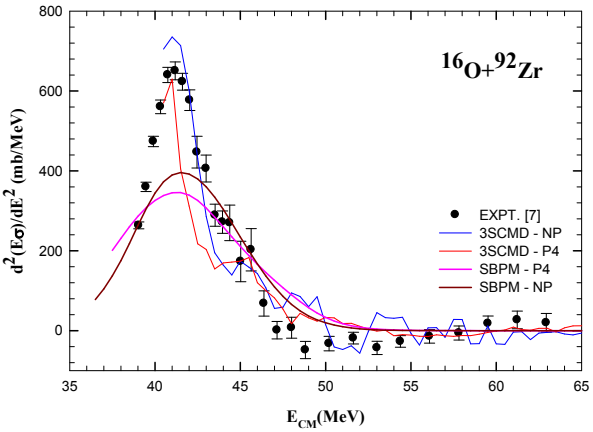


**Fig. 2:** Calculated barrier distribution for $^{16}$O+$^{92}$Zr reaction

The barrier distribution calculated using NP potential parameter set and with 3S-CMD model shows some agreement at higher energies with experimental data and also with the barrier distribution calculated using P4 potential and 3S-CMD model. In this case we get the highest peak at the same energy as in the experiment but it slightly overestimated with the experimental data as well as P4 potential (red line).

## References


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