Fusion cross sections for ^{16}O+^{40}Ca and ^{32}S+^{40}Ca reactions in three-stage classical dynamical model

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1. Introduction

In classical approximations heavy-ion fusion cross sections have been calculated in Classical **M**olecular **D**ynamics (CMD) approach [1]. Spherical-spherical and mass-symmetrical reactions ^{16}O+^{16}O and ^{40}Ca+^{40}Ca have been studied in this approach with a soft-core Gaussian form of NN-potential [1],

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

Fusion cross sections for ^{40}Ca+^{40}Ca reaction calculated with a potential parameter set P4 (V_0 = 1155 MeV, C = 2.07 fm, r_0 = 1.2 fm) gave reasonable agreement with the expt. data [1].

The CMD calculations in ref [1] were carried out from an initial separation of 20 fm between the target and the projectile after obtaining the initial conditions for the collision from the respective Rutherford trajectories. Only few initial orientations were considered in [1].

It has been shown using a **C**lassical **R**igid-**B**ody **D**ynamics (CRBD) calculation [2] that in the case of deformed nuclei their re-orientation resulting from their long range torque results in modified reaction dynamics and cross sections [2]. On the other hand, at distances close to the barrier, dissipation mechanisms require relaxation of the rigid-body constraint and evolution of the system as in CMD calculation. Therefore, a 3S-CMD model [3] has been developed in which the reaction dynamics proceeds in 3-stages, viz: (1) Rutherford trajectory calculation, followed by (2) CRBD calculation with rigid-body constraint on both the nuclei up to distances close to the barrier, followed by (3) full CMD calculation by finding the trajectories of all the nucleons for further evolution.

Fusion cross sections for ^{16}O+^{16}O and ^{16}O+^{208}Pb reactions calculated with the potential parameter set P4 in 3S-CMD approach gives reasonable agreement with the corresponding expt. data [4]. Therefore, using the same potential parameter set P4 we calculate fusion cross sections for spherical-spherical but mass-asymmetric reactions, viz, ^{16}O+^{40}Ca and ^{32}S+^{40}Ca reactions in 3S-CMD approach in this contribution. Fusion cross sections are calculated using classical and semi-classical approximations and compared with the experiments.

2. Calculation Details

The calculated ground state properties of the nuclei used in the present calculations with potential parameter set P4 and potential energy minimization code *STATIC* [1] are given in the Table below:

Table: Ground state properties of nuclei

	Calculated			Experiment		
	BE(MeV)	R(fm)	β_2	BE(MeV)	R(fm)	β_2
^{16}O	-129.02	2.46	0.37	-127.62	2.73	0.02
^{32}S	-268.64	3.14	-0.04	-271.78	3.23	0.00
^{40}Ca	-324.77	3.52	0.04	-342.05	3.53	0.00

The dynamical collision simulation is carried out in the 3S-CMD model which is described in detail in [2]. In the present calculations the CMD stage is carried out for $R_{cm} \leq$ 13 fm for ^{16}O+^{40}Ca and ^{32}S+^{40}Ca reactions.

In the classical approximation, fusion cross section is calculated from the following classical formula [1],

$$\pm_{fusion} = ® b_{cr}^2 \qquad (2)$$

where b_{cr} is the maximum (critical) impact parameter for which the two nuclei fuse.

The barrier parameters V_B, R_B, ω calculated from the dynamically evolved ion-ion potential for a trajectory near the critical impact parameter (b_{cr}) are used in the Wong's formula [5] to calculate fusion cross-section in the semi-classical approximation for a given orientation of a collision energy E_{cm}, as in ref [2],

$$\pm_{fus} = \left[\frac{\hbar \mu_B}{2E_{cm}}\right] R_B^2 \ln\left[1+\exp\left(2® \frac{E_{cm}-V_B}{\hbar \mu_B}\right)\right] \qquad (3)$$

For a given E_{cm} a large number of random initial orientations (about 500 at lower energies and 200 at higher energies) are considered in the present calculation and the orientation-averaged fusion cross section is calculated.

3. Result and Discussions

$^{16}O+^{40}Ca$ Reaction :

Fusion cross sections for $^{16}O+^{40}Ca$ reaction calculated in 3S-CMD simulation with potential P4 and eq.(2) are shown in Fig.1, which are in good agreement with the expt. data [6-8]. Although, the rms radius of ^{40}Ca produced with the potential parameter set P4 matches well with the expt. value, but the rms radius of ^{16}O produced with this potential P4 (see Table) is smaller by about 10%. The smaller size of ^{16}O results in slight underestimation of the expt. cross sections.

Semi-classical fusion cross sections calculated using eq.(3) with potential P4 are also shown in Fig.1. Inclusion of penetrability factor in eq.(3) results in cross sections which are slightly higher than those with eq.(2) at lower energies. However, cross sections with eq.(3) are highly overestimated at higher energies.

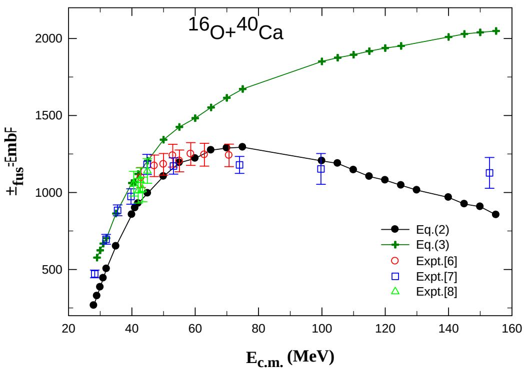

Fig. 1: Fusion cross section for $^{16}O+^{40}Ca$ reaction.

$^{32}S+^{40}Ca$ Reaction :

Using the potential P4 we also calculate fusion cross sections of ^{40}Ca with a spherical but a nucleus heavier than ^{16}O, viz ^{32}S.

Fusion cross sections for $^{32}S+^{40}Ca$ reaction calculated in 3S-CMD simulation with potential parameters P4 and eq.(2) are shown in Fig.2 and compared with the expt. data [9]. The calculated cross sections are in over all good agreement with the expt. data except at energies below the barrier where they are underestimated. The rms radius of ^{40}Ca matches well with the expt. value, but the rms radius of ^{32}S produced with this potential P4 (see Table) is smaller by about 3%. Further, the lack of barrier penetrability in a classical calculation results in a small underestimation of the fusion cross sections in the classical calculation.

Semi-classical calculation of fusion cross sections with eq.(3) are only slightly over estimated as compared to the expt. data with enhancement at lower energies as compared to the classical calculation with eq.(2)

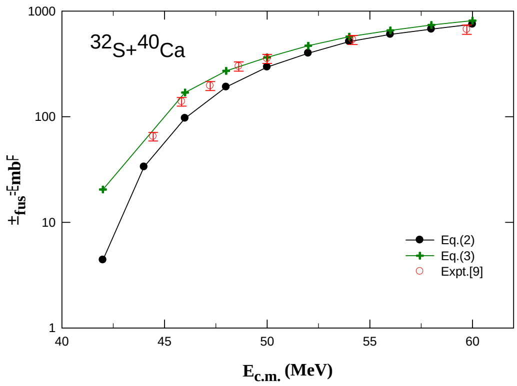

Fig 2: Fusion cross section for $^{32}S+^{40}Ca$ reaction.

References

[1] S. S. Godre, Y. R. Waghmare, Phys. Rev. C **36**, 1632 (1987)

[2] P. R. Desai, S. S. Godre, Eur. Phys. J. A **47,** 146 (2011)

[3] S. S. Godre, EPJ Web of Conferences **86**, 00012 (2015)

[4] J. H. Patel, M. R. Morker, and S. S. Godre, *this proceedings* (2016)

[5] C. Y. Wong, Phys. Rev. Lett. **31**, 766 (1973)

[6] Y. Nagashima et al, Phys. Rev. C 33, 176 (1986)

[7] S. E. Vigdor, *et al.*, Phys. Rev. C 20, 2147(1979)

[8] D. F. Geesaman, *et al.*, Phys Rev. C 18, 284(1978)

[9] H. H .Gutbrod *et al*, Nucl. Phys A **213,** 267(1973)