Multi-body three-stage Classical Molecular Dynamics approach for ^{17}F (One-Proton halo) + ^{208}Pb reaction.

Vipul B. Katariya, Subodh S. Godre*
Department of Physics, Veer Narmad South Gujarat University, Surat - 395007, INDIA
** Email: ssgodre@yahoo.com*

Introduction

Reactions involving weakly bound nuclei are interesting to investigate due to phenomena such as increased probabilities of breakup, neutron transfer, fusion, and incomplete fusion (ICF) [1]. Halo nuclei, with their extended tail-like valence neutron or proton, may give rise to new phenomena. However, in the ^{17}F + ^{208}Pb reaction at energies around the Coulomb barrier, no enhancement of the fusion cross section is observed due to breakup or the large interaction radius [2, 3], contrary to the semiclassical picture, which predicts increased probabilities of neutron transfer and fusion for nuclei with low binding energy. This discrepancy has been investigated through simulations of the reaction near the Coulomb barrier using Improved quantum molecular dynamics model (ImQMD) by X.-Y. He et al. [4].

However, reactions involving halo nuclei can be investigated with the multi-body Three-Stage Classical Molecular Dynamics (Multi-body 3S-CMD) model [5, 6], which includes (1) Rutherford trajectory, (2) Classical Rigid Body Dynamics (CRBD) and (3) Classical Molecular Dynamics (CMD) stages [7]. It has also been applied to study reactions involving neutron halo ^{11}Be + ^{209}Bi [8].

In this model, ^{17}F is constructed as a cluster of tightly bound ^{16}O core and one valance proton where, tightly bound ^{16}O is constructed using variational potential energy minimization STATIC [9] code and "cooled" using DYNAMIC [9] code. For present calculation, ^{17}F is constructed using a "dynamic cooling" method [5, 6] by performing rigid body dynamics like procedure and resetting the cluster velocities and angular momentum to zero at each time step, and thereby determining the equilibrium orientation and position of the center of mass of the constituents (^{16}O + *p*). The distance between the center of mass of ^{16}O and the proton is then adjusted so that the ion-ion potential between them matches the experimental proton separation energy of ^{17}F.

In this work, using the multi-body 3S-CMD model, we calculated the complete fusion cross-sections for ^{17}F + ^{208}Pb and ^{16}O + ^{208}Pb reactions and compared them with experimental results. The model calculations support the experimental observation that the fusion cross-section of a proton-halo nucleus with a heavy target nucleus is not enhanced as expected supporting hypothesis of proton shielding-effect [4]. Additionally, this model can account for direct reactions, such as proton transfer from the projectile. Consequently, it allows for the study of the probabilities of different events as a function of E_{CM} for this reaction.

Model Details

Here, purely phenomenological softcore Gaussian Potential given by,

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

is used. Where, V_0, C, and r_0 are respectively, the depth parameter, repulsive-core radius and range parameter is used with the potential parameter set V_0 = 1155.0 MeV, C = 2.07 fm and r_0 = 1.2 fm to produce ground state properties of ^{208}Pb and ^{17}F mentioned in Table 1,

Table 1: Ground-state properties

Nucleus	Calculated		Experimental	
	B.E. (MeV)	**R (fm)**	**B.E. (MeV)[10]**	**R (fm)**
^{16}O	127.66	2.46	127.62	2.69 [11]
^{17}F (^{16}O + *p*)	128.26	2.73	128.22	2.71 [12]
^{208}Pb	1841.92	6.04	1636.46	5.50 [11]

During the dynamical collision simulation in the multi-body 3S-CMD model, the target and projectile are treated as complete rigid bodies in the second stage. This rigid body constraint can be systematically removed in the third stage for the appropriate projectile-target separation distance.

In the present calculation, dynamical simulations are carried out for the reactions ^{17}F + ^{208}Pb and ^{16}O + ^{208}Pb. In both reactions, ^{208}Pb is treated as non-rigid in the third stage, which begins when the center-of-mass separation between the projectile and target is less than 14 fm. In the ^{17}F + ^{208}Pb reaction, the ^{16}O core in ^{17}F is treated as rigid in the third stage, while the bond between the ^{16}O and the proton is treated as non-rigid. The fusion cross sections for the collision energy E_{cm} are calculated using Wong's formula [13].

$$\sigma_{fus}(E_{CM}) = \left[\frac{{R_B}^2 \hbar\omega_0}{2E_{CM}}\right] \ln\left[1 + \exp\left(2\pi \frac{(E_{CM} - V_B)}{\hbar\omega_0}\right)\right] \quad \ldots\ldots (2)$$

Result and discussions

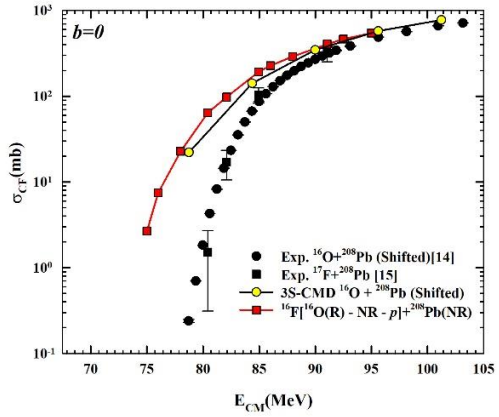

Fig.1 Complete fusion cross sections for the ^{17}F + ^{208}Pb and ^{16}O + ^{208}Pb reactions compared to experimental result.

Fig. 1 shows the complete fusion cross-section calculated using the multi-body 3S-CMD model and is compared to experimental results. The results for the ^{16}O + ^{208}Pb system have been shifted by a factor of 9/8 (ratio of charges of ^{17}F and ^{16}O) in energy for better comparison. It is evident that the fusion cross sections around and above the Coulomb barrier are fairly well reproduced by the model. However, for both the ^{17}F + ^{208}Pb and ^{16}O + ^{208}Pb reactions, the fusion cross sections are overestimated below the Coulomb barrier. This overestimation might be related to the larger RMS radius of ^{208}Pb used in the model, generated using the potential parameter set mentioned in the model details section.

Furthermore, one would expect an enhancement in the fusion cross section for the ^{17}F + ^{208}Pb system compared to the ^{16}O + ^{208}Pb reaction due to the larger RMS radius of ^{17}F. However, no such enhancement is observed, suggesting the presence of a shielding effect, as previously investigated in [4] and corroborated by the current calculations.

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