Mass asymmetry dependence of fusion time-scales in $^{11}$B + $^{237}$Np and $^{12}$C, $^{16}$O, $^{19}$F + $^{232}$Th reactions in a dynamical trajectory model

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Abstract. Dynamical trajectory calculations were carried out for the reactions of $^{11}$B + $^{237}$Np and $^{12}$C, $^{16}$O and $^{19}$F + $^{232}$Th, having mass asymmetries on either side of the Businaro-Gallone critical mass asymmetry $\alpha_{BG}$, in order to examine the mass asymmetry dependence of fusion reactions in these systems. The compound nucleus formation times were calculated as a function of the partial wave of the reaction for all the systems. This study brings out that for systems with $\alpha < \alpha_{BG}$, the formation times are significantly larger than for $\alpha > \alpha_{BG}$, which is caused by the dynamical effects involved in the large scale shape changes taking place in the fusion process as well as due to the interplay between the thermal and the collective motion during the collision process. The calculated time scales are comparable to the experimental values derived from the pre-fission neutron multiplicity measurements.

Keywords. Heavy ion fusion reactions; time scales; dynamical trajectory model; dependence on mass asymmetry.

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1. Introduction

There have been a number of experimental and theoretical investigations in the past [1–9] to determine the role of the entrance channel mass asymmetry in the fusion dynamics of heavy ion induced reactions. Recently, in the work of Ramamurthy et al [4] on the fission fragment angular distributions, it was pointed out that the value of $\alpha$ relative to the liquid drop Businaro-Gallone critical mass asymmetry [10] ($\alpha_{BG}$) may be important in deciding the fusion path in heavy ion reactions. There have been also some experimental studies to determine the fusion-fission time delay from the studies of pre-scission neutron multiplicities in heavy ion induced reactions which seem to suggest the above behaviour. In the work of Saxena et al [6], the fusion-fission time scales were determined for $^{11}$B + $^{237}$Np and $^{11}$B, $^{12}$C, $^{16}$O + $^{232}$Th systems by measuring the pre-scission neutron multiplicities and it was found that for $^{16}$O + $^{232}$Th system ($\alpha < \alpha_{BG}$) the fusion-fission time is larger than that for $^{11}$B + $^{237}$Np, $^{11}$B + $^{232}$Th and $^{12}$C + $^{232}$Th systems ($\alpha > \alpha_{BG}$).

The dynamical threshold for the onset of fusion depends critically on the total charge, orbital angular momentum and mass asymmetry of the system. For mass asymmetric reactions, there are two different saddle points in the potential energy surface [7–9]. The first is the Bohr-Wheeler mass-symmetric saddle point and the second is the conditional saddle point which is obtained with the constraint that mass asymmetry is fixed at the initial value of the reaction. During the fusion reaction,
the target-projectile system is trapped in the valley of the fusion potential, and the dinuclear system drifts along the mass asymmetry co-ordinate by exchange of mass to form a fused nucleus. During this time the inter-nuclear distance $R$ changes because the distance $R_p$ corresponding to the bottom of the pocket in the potential depends on both the mass asymmetry $\alpha$ and angular momentum. The drift along mass asymmetry $\alpha$ will be governed by the potential energy of the quasi-molecular system which has been formed. The total energy calculated with the potential energy $V(R_p)$ taken for several values of initial mass asymmetry $\alpha$ shows that there are two regions of interest: the one corresponds to the system which will drift towards symmetry for $\alpha < \alpha_{BG}$ and the second region corresponds to the system which will drift towards more asymmetric configuration for $\alpha > \alpha_{BG}$. In other words the initial mass asymmetry of the system may have a great influence on the latter development along the mass asymmetry coordinate. There has not been, however, so far detailed dynamical study of the fusion time scales for systems lying on either side of the critical BG point, to bring out clearly the influence of mass asymmetry in such reactions.

The dynamical evolution of the two colliding nuclei can be described by a sequence of shapes which basically consist of two spheres connected by a conical neck. The three macroscopic variables used are: the distance separating the two centres of mass, the neck co-ordinate and the mass asymmetry co-ordinate. The system is then described by the classical equations of motion for obtaining the mean values of the macroscopic variables and their second moments, with the frictional forces taken to be proportional to the velocities in the collective degree of freedom. We have used the formalism of Feldmeier et al [11, 12] to study the fusion dynamics of various target projectile systems with mass asymmetries lying on either side of the liquid drop Businaro-Galline critical mass asymmetry. The systems studied are $^{11}\text{B} + ^{237}\text{Np}$ and $^{12}\text{C}, ^{16}\text{O}, ^{19}\text{F} + ^{232}\text{Th}$ reactions for which the fusion-fission time scales have been experimentally deduced from pre-scission neutron multiplicity measurements [6, 13]. It may be noticed that $^{11}\text{B} + ^{237}\text{Np}$ and $^{16}\text{O} + ^{232}\text{Th}$ lead to the same compound nucleus, but have mass asymmetries lying on either side of $\alpha_{BG}$. The calculated values of the fusion time scales are found to compare well with the experimental values. The details of the calculation procedure are given in the section below. Section 3 gives the results and discussion of the calculations and § 4 contains the summary on the present work.

2. Classical dynamical calculations

We use the model of Feldmeier et al [11, 12] where the colliding nuclei are treated as two Fermi gases which exchange particles, momentum and entropy through a window in the mean single particle potential. The time development of the collision trajectories are calculated by solving a Langevin equation with a fluctuating dissipative force. The properties of the fluctuating force are determined from a microscopic picture of particle exchange between two nuclei. The macroscopic shapes of the nuclear system are represented by axially symmetric configurations with sharp surfaces. These shapes are uniquely determined by three macroscopic degrees of freedom: the distance between the nuclei $s$, the neck coordinate $\sigma$, and the mass asymmetry $\Delta$ defined as:

\begin{align*}
    s &= \text{distance between two sphere centres} \\
    \sigma &= \left[ V_0 - \frac{4\pi}{3}R_1^3 - \frac{4\pi}{3}R_2^3 \right] / V_0 \\
    \Delta &= \left[ R_1 - R_2 \right] / \left[ R_1 + R_2 \right]
\end{align*}

(1)