

## Sensitivity of the transition energy towards mass asymmetry of the colliding nuclei

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**Abstract.** We investigate the role of the mass asymmetry on the transition energy by studying asymmetric reactions using the isospin dependent quantum molecular dynamics (IQMD) model. Substantial and the uniform effect of the asymmetry of the reaction has been observed on the transition energy. Moreover, isospin effects shows a small influence on the mass asymmetry ( $\eta$ ) dependence of transition energy.

### 1 Introduction

Collective flow is the measure of transverse motion imparted to the particles and fragments during the collision of two nuclei. Collective flow has been found to be of immense importance in search of nuclear equation of state (NEOS). Elliptical flow has been used as an important parameter to study the hot and dense nuclear matter. A detailed study of elliptical flow can provide useful information about the nucleon-nucleon interactions and origin of isospin effects in heavy-ion collisions. The interesting phenomena of elliptical flow is the transition from in-plane to out-of-plane in the mid-rapidity region. This energy is dubbed as transition energy. The variation of  $E_{Trans}$  with the combined mass of the system has been reported by Kumar *et al.* [1] for the symmetric reactions. Moreover, Zhang *et al.* [2] reported the system mass dependence of  $E_{Trans}$  at a fixed colliding geometry for the reactions of  $^{58}Ni + ^{58}Ni$ ,  $^{90}Zr + ^{90}Zr$ ,  $^{124}Sn + ^{124}Sn$ ,  $^{160}Gd + ^{160}Gd$ ,  $^{197}Au + ^{197}Au$  and  $^{112}Sn + ^{112}Sn$ . All these studies take only symmetric reactions into account. Efforts have been made theoretically to study the effect of mass asymmetry of a reaction on multifragmentation [3], transverse in-plane flow and its disappearance [4] and the transverse momentum dependence of elliptical flow [5]. V. Kaur *et al.* [5] reported that for mass asymmetric systems, the transition energy increases with mass asymmetry. Experimentally, FOPI group studied the flow for the asymmetric reactions of  $^{40}Ca + ^{197}Au$  and later on for the reactions of  $^{58}Ni$  and  $^{208}Pb$  [6]. They reported that asymmetric collisions is a key observable for investigating the reaction dynamics. Asymmetry parameter ( $\eta$ ) is defined as,  $\eta = |(A_T - A_P)/(A_T + A_P)|$ , where  $A_P$  and  $A_T$  are the masses of projectile and target respectively. Clearly,  $\eta = 0$  corresponds to the symmetric reactions and  $\eta \neq 0$  corresponds to asymmetric reactions. Moreover, asymmetry of the reaction play a key role in heavy-ion collisions. This happens because excitation energy in symmetric colliding nuclei leads to larger compression while asymmetric reactions lack the compression since large part of the excitation energy is in the form of thermal energy. The second point is the isospin degree of freedom. Isospin degree of freedom

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enters via quantities such as symmetry potential, isospin dependent nucleon-nucleon cross-section and Coulomb potential. A comparative study that will show a shift in transition energy due to symmetry potential, isospin dependence of nucleon-nucleon cross-section and Coulomb potential for the mass asymmetric reactions in a controlled fashion is still missing in the literature. In the present manuscript, we shall study the shift in the transition energy due to the comparative effect of above mentioned observables. The asymmetry is varied by adding neutron/protons, while the total mass of the colliding nuclei remain fixed.

The present study is performed within the framework of isospin-dependent quantum molecular dynamics (IQMD) model [7]. Section 2 explains the results and discussion and Section 3 summarizes the results.

## 2 Results and discussion

For the present study, we simulated various reactions for 10,000 events in the incident energy range between 100 and 400 MeV/nucleon. In particular, we simulated the reactions of  ${}^{56}_{26}\text{Fe}_{30} + {}^{96}_{44}\text{Ru}_{52}(\eta = 0.2)$ ,  ${}^{50}_{24}\text{Cr}_{26} + {}^{120}_{44}\text{Ru}_{56}(\eta = 0.3)$ ,  ${}^{40}_{20}\text{Ca}_{20} + {}^{112}_{50}\text{Sn}_{62}(\eta = 0.4)$  and  ${}^{32}_{16}\text{S}_{16} + {}^{120}_{50}\text{Sn}_{70}(\eta = 0.5)$ . Here we fixed the total system mass  $A_{tot} = 152$  and varied the mass asymmetry of the reaction. The transition energy is calculated from the excitation function of elliptical flow, which is defined as the second order Fourier coefficient from azimuthal distribution of detected particles at mid-rapidity as [8]:

$$\frac{dN}{d\phi} = p_0(1 + 2c_1\text{Cos}\phi + 2c_2\text{Cos}2\phi + \dots). \quad (1)$$

Here  $\phi$  stands for the azimuthal angle of the emitted particles. Here,  $c_1$  &  $c_2$  are constants which determine the strength of flow. Note that the positive values of  $\langle \text{Cos}2\phi \rangle$  reflects a preferential in-plane emission of nucleons. On the other hand, a negative value of  $\langle \text{Cos}2\phi \rangle$  denotes preferential out-of-plane emission of the nucleon.

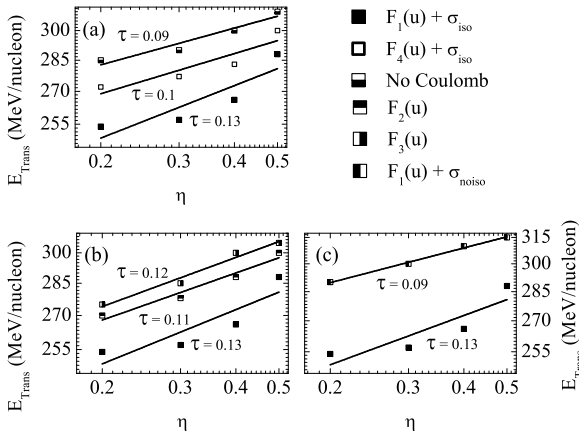
Mathematically, it can be written as [9]:

$$\langle v_2 \rangle = \langle \text{Cos}2\phi \rangle = \left\langle \frac{p_x^2 - p_y^2}{p_x^2 + p_y^2} \right\rangle \quad (2)$$

where  $p_x$  and  $p_y$  are the  $x$  and  $y$  components of the momentum. The parameter  $\langle \text{Cos}2\phi \rangle$  depends on the complex interplay between the expansion, rotation and shadowing of the spectator, apart from the incident energy.

Further to explore the influence of isospin effects more clearly, we study the  $E_{Trans}$  as a function of mass asymmetry of the colliding nuclei. As we are taking the mass asymmetric systems, therefore the shift in  $E_{Trans}$  is due to the interplay of Coulomb potential, symmetry energy and mass asymmetry of colliding nuclei. In our calculations we use the well constrained value of symmetry energy which is of the form  $c(\frac{\rho}{\rho_0})^\gamma$ , where  $c$  is the strength of symmetry potential, taking value of 0 and 32 MeV. We have taken  $\gamma = 0, 0.66$  and 2 represented by  $F_1(u)(\propto (\frac{\rho}{\rho_0})^0)$ ,  $F_2(u)(\propto (\frac{\rho}{\rho_0})^{0.66})$ ,  $F_3(u)(\propto (\frac{\rho}{\rho_0})^2)$  and  $F_4(u)$  represents the calculations without symmetry potential. As mentioned earlier isospin dependence of nucleon-nucleon cross-section also plays a significant role in reaction dynamics. In addition to these two, the Coulomb potential is expected to play dominant role due to its repulsive nature.

First to study the comparative effect of Coulomb potential and symmetry energy on the transition energy for mass asymmetric nuclei, we display in Fig.1(a), the transition energy as a function of  $\eta$ .



**Figure 1.** (Color Online) The transition energy as a function of asymmetry parameter  $\eta$ . Panel (a) shows the comparative effect of Coulomb potential and symmetry energy, panel (b) shows the influence of various forms of density dependence of symmetry energy and panel (c) shows the influence of isospin dependence of nucleon-nucleon cross-section on the mass asymmetry dependence of transition energy.

Lines are the power law fit to the theoretical results of kind ( $\propto \eta^a$ ). First we calculate the  $E_{Trans}$  by excluding the symmetry potential (open squares) and then by excluding the Coulomb potential (lower filled squares). One can see that, transition energy increases on excluding the symmetry potential. This is due to the repulsive nature of symmetry energy, that push the participant zone in out-of-plane direction. Therefore,  $E_{Trans}$  decreases in the presence of symmetry and Coulomb potential. On excluding the Coulomb potential the transition energy further increases due to the enhancement of the chemical and mechanical instability domains in the absence of Coulomb potential [10]. One can see that, effect of mass asymmetry is not at all negligible. Further the effect of asymmetry is 12% for ( $F_1(u) + \sigma_{iso}$ ), 9% for ( $F_4(u) + \sigma_{iso}$ ) and 8% for no Coulomb. This percentage change is calculated by using the formula:

$$\Delta E_{Trans}(\%) = \frac{(E_{Trans})^{\eta=0.5} - (E_{Trans})^{\eta=0.2}}{(E_{Trans})^{\eta=0.5}} \times 100 \quad (3)$$

As a next step, in Fig.1(b) we display the,  $\eta$  dependence of  $E_{Trans}$  for the different density dependence of symmetry energy. We find that, transition energy increases for stiff form of density dependence. Moreover, the slope of the  $\eta$  dependence of the transition energy is sensitive to the density of symmetry energy first decreases in case of stiff density dependence ( $F_2(u)$ ) compared to ( $F_1(u)$ ) whereas with super stiff ( $F_3(u)$ ) density dependence, the slope further increases. In this case also we observe a uniform change in the transition energy for the mass asymmetry of the colliding nuclei 10% for ( $F_2(u)$ ) and 9% ( $F_3(u)$ ).

Since isospin degree of freedom also comes into picture through the isospin dependence of nucleon-nucleon cross-section ( $\sigma_{iso}$ ) ( $\sigma_{np} = 3\sigma_m = 3\sigma_{pp}$ ). So as a next step, we also wish to check the sensitivity of nucleon-nucleon cross-section to the  $\eta$  dependence of  $E_{Trans}$ . For this we further make the binary nucleon-nucleon cross-section isospin independent ( $\sigma_{noiso}$ ) ( $\sigma_{np} = \sigma_m = \sigma_{pp}$ ) and calculate the  $E_{Trans}$  for all the colliding nuclei as shown in Fig.1(c). One can see that, increase in  $E_{Trans}$  increases for the isospin independent cross-section. This is because the magnitude of the nucleon-nucleon cross-section decreases in case of ( $\sigma_{noiso}$ ). Moreover, the percentage change in the  $E_{Trans}$  with asymmetry is 8% for the isospin independent cross-section which is less compared to isospin dependent cross-section.

### 3 Summary

We studied the role of the mass asymmetry on the transition energy by studying asymmetric reactions using the isospin dependent quantum molecular dynamics (IQMD) model. Substantial and the uniform effect of the mass asymmetry of the reaction has been observed on the transition energy. The mass asymmetry parameter dependence of transition energy follow a power law behavior. Moreover, isospin effects shows a small influence on the  $\eta$  dependence of transition energy. At lower asymmetry ( $\eta = 0.2$ ) the percentage of isospin effects is 7% for  $(F_4(u) + \sigma_{iso})$ , 11% for no Coulomb, 6% for  $(F_2(u))$ , 8% for  $(F_3(u))$  and 12% for  $(F_1(u) + \sigma_{noiso})$  w.r.t  $(F_1(u) + \sigma_{iso})$  and for higher asymmetry ( $\eta = 0.5$ ) the percentage of isospin effects is 4% for  $(F_4(u) + \sigma_{iso})$ , 7% for no Coulomb, 4% for  $(F_2(u))$ , 6% for  $(F_3(u))$  and 9% for  $(F_1(u) + \sigma_{noiso})$  w.r.t  $(F_1(u) + \sigma_{iso})$ .

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