# Probing isospin effects via nuclear fragmentation

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## Introduction

Nuclear multifragmentaion offers a unique possibility to explore the behavior of nuclear equation of state of isospin asymmetric matter, and in particular, the nuclear symmetry energy. The observables sensitive to nuclear symmetry energy have been put forward in recent past such as isospin fractionation [1], isoscaling [2], isospin diffusion [3], particle production [4, 5] etc. The isospin fractionation is an unequal partitioning of neutrons and protons of isospin asymmetric system between low and high density phases and extensive studies have been carried out on this. Likewise, the fragmenting system can also be divided into low density gas phase and high density liquid phase. This gas/liquid phase has also been defined in terms of free nucleons (gas) and bound nucleons (liquid) in many studies [6]. The amount of gas and liquid content changes with beam energy as gas phase increases at higher incident energies. A transition between gas and liquid content is obtained when same is plotted as a function of beam energy and energy where liquid and gas phase have equal contribution is known as *cross-over energy* [7]. The behavior of *cross-over energy* for symmetric as well as asymmetric reactions is investigated in the present study, which is carried out using Isospin dependent Quantum Molecular Dynamics (IQMD) model [8]. Further, the role of isospin degree of freedom on the *cross-over energy* will also be studied.

## Results and discussions

We simulated the reactions of $^{50}$Cr + $^{50}$Cr ($\eta$ = 0.0), $^{40}$Ca + $^{60}$Co ($\eta$ =0.2), $^{31}$P + $^{69}$Ga ($\eta$ =0.4), $^{20}$Ne + $^{80}$Kr ($\eta$ =0.6) and $^{11}$B + $^{89}$Y ($\eta$ =0.8) at semi-central colliding geometry ($\hat{b}$ = 0.2 - 0.3) using SMD (soft momentum-dependent) equation of state. These reactions are simulated at incident energies between 120 and 700 AMeV. Here $\eta$ is varied from 0.0 to 0.8 keeping total mass of the system fixed ($A_{TOT}$ = 100). Here, we consider free nucleons (A = 1) at the freeze-out stage as gas and all other fragments (A $\geqslant$ 2) as liquid. In Fig. 1, we display the incident energy dependence of gas and liquid content for $\eta$ = 0.0 to 0.8 covering symmetric and asymmetric reactions. Open symbols correspond to the gas content of system and solid symbols represent liquid content. From the figure, we observe that the *cross-over energy* is enhanced with increase in mass asymmetry. Also we notice that the sharp increase in *cross-over energy* is obtained when we go from $\eta$ = 0.6 to 0.8. The cause of this behavior is that in symmetric and nearly symmetric reactions, there is more compression which drives the nuclear matter into the participant zone and thus more free nucleons are emitted even at lower energies while with increase in mass asymmetry, the number of nucleon-nucleon collisions are decreased causing the suppressed emission of free nucleons. Therefore, more energy is required to break the system into free nucleons and thus, cross-over is obtained at higher energies.

Next, we will check the role of isospin degree of freedom via symmetry potential and NN scattering cross-section on the *cross-over energy*. Here, we summarize our results in Fig. 2. Here, solid circles, open circles and half filled circles correspond to default calculations, calculations without symmetry potential and isospin independent cross-section, respectively. Here, we notice that the *cross-over energy* is increased in absence of symmetry potential. This is because of repulsive nature of symmetry potential and in absence of these repulsions, the multiplicity of free

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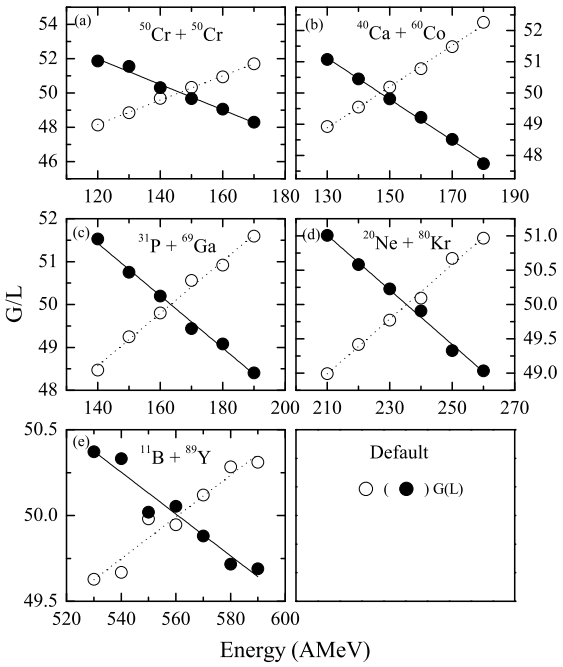


FIG. 1: The energy dependence of the gas and liquid content for the reaction pairs having mass asymmetry $\eta = 0.0$, 0.2, 0.4, 0.6 and 0.8. Various symbols are explained in the text.

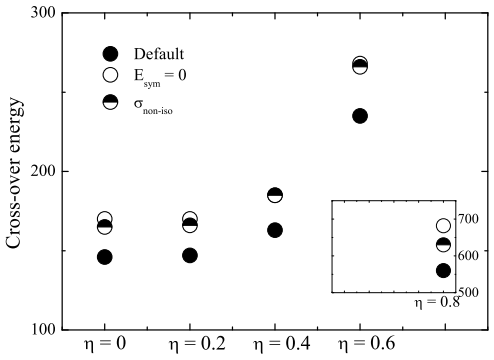


FIG. 2: The values of cross-over energy for the mass asymmetric reactions with mass asymmetry varying from 0.0 to 0.8. Various symbols are explained in the text.

nucleons decreases and thus, system requires more energy to break into free nucleons. Also, the increase in cross-over energy is observed in case of isospin independent cross-section. As the net cross-section is reduced, the number of nucleon-nucleon collisions get reduced. Therefore, the emission of free nucleons is suppressed and thus, more energy is required to break the system. Also, we notice that the rise in *cross-over energy* is more pronounced in absence of symmetry potential. Thus, we conclude that the *cross-over energy* can be a good probe to nuclear symmetry energy.

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