N/Z dependence of balance energy as a probe of symmetry energy in heavy-ion collisions

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Introduction

The equation of state (EOS) of symmetric nuclear matter is well understood due to extensive efforts of nuclear physics community for the past few decades. Nowadays, the nuclear EOS of asymmetric nuclear matter has attracted lot of attention. The EOS of asymmetric nuclear matter can be described approximately by:

$$E(\rho,\delta) = E_0(\rho,\delta=0) + E_{sym}(\rho)\delta^2 \qquad (1)$$

where $\delta = \frac{\rho_n-\rho_p}{\rho_n+\rho_p}$ is isospin asymmetry, $E_0(\rho, \delta)$ is the energy of pure symmetric nuclear matter and $E_{sym}(\rho)$ is the symmetry energy with $E_{sym}(\rho_0)$ = 32 MeV is the symmetry energy at normal nuclear matter density. The symmetry energy is $E(\rho,1)$ - $E_0(\rho,0)$, ie. difference between energy per nucleon between pure neutron matter and symmetric nuclear matter. Symmetry energy is important not only for the nuclear physics community as it sheds light on the structure of radioactive nuclei, reaction dynamics induced by the rare isotopes but also to the astrophysicists as it acts as a probe for understanding the evolution of massive stars and the supernova explosion [1, 2]. Experimentally, symmetry energy is not a directly measurable quantity and has to be extracted from the observables which are related to the symmetry energy. Therefore, a lot of observables have been proposed in recent past which act as a probe of symmetry energy and its density dependence [3]. Collective transverse in-plane flow has been studied for past three decades and also being used to explore the isospin dependence of EOS [4, 5]. The energy dependence of collective flow led its disappearance at balance energy E_{bal}. In the present study, we propose N/Z dependence of E_{bal} as a probe of symmetry energy and its density dependence. The present study is carried within the framework of isospin-dependent quantum molecular dynamics (IQMD) model [6].

Results and Discussions

We simulate the reactions of Ca+Ca having N/Z varying from 1.4 to 2.0 in small steps of 0.2, viz. $Ca^{48}+Ca^{48}$, $Ca^{52}+Ca^{52}$, $Ca^{56}+Ca^{56}$, and $Ca^{60}+Ca^{60}$ at impact parameter of $\hat{b}$=0.2-0.4. We use a soft EOS along with anisotropic standard isospin- and energy-dependent nn cross section $\sigma = 0.8\ \sigma_{NN}{}^{free}$ [5]. The cross sections for neutron-neutron collisions are assumed to be equal to the proton-proton cross sections. Fig. 1 (a) displays the N/Z dependence of E_{bal} for Ca+Ca (solid circles) throughout the isotopic series. We find that E_{bal} decreases with increase in N/Z due to increased role of symmetry energy in systems with higher N/Z and follows a linear behaviour with N/Z. Isospin effects in collective transverse in-plane flow is due to competition between symmetry energy and isospin-dependent nn cross section. To see the dominance among these two, we switch off the symmetry energy and also make the nn cross section isospin independent, respectively. The preliminary results are displayed in Fig. 1 (a) (open circles) and (b) (open triangles) with no symmetry energy and isospin independent cross section, respectively. From the figure, we find that E_{bal} increases when we switch

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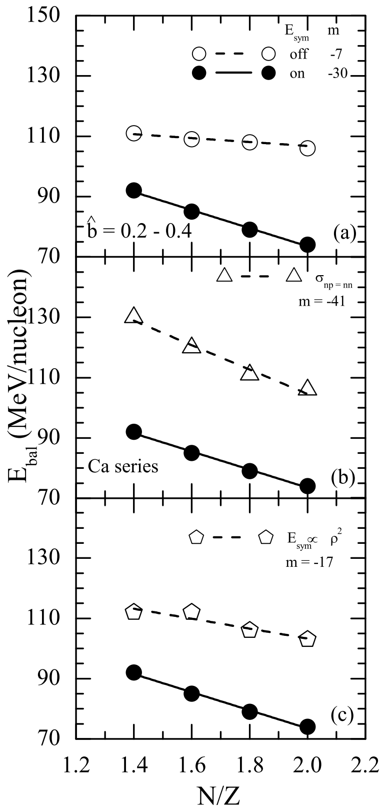

FIG. 1: N/Z dependence of E_{bal} with symmetry energy on and off, (b) isospin-dependent and independent nn cross section, and (c) $E_{sym} \propto \rho^2$. Various symbols and lines are explained in the text.

off the symmetry energy. This is due to the fact that symmetry energy contributes to repulsive potential and in the absence of symmetry potential, the collective transverse in-plane flow decreases leading to enhancement of E_{bal}. Moreover, the increase in the E_{bal} is more for higher N/Z system which is due to the increased role of symmetry energy in respective system. The behavior of E_{bal} with symmetry energy off is still linear but with reduced slope from -30 to -7. This indicates that the N/Z dependence of E_{bal} is sensitive to symmetry energy. To further strengthen our point, fig. 1 (b) shows E_{bal} with isospin independent nn cross section ,i.e. $\sigma_{np} = \sigma_{nn}$ or σ_{pp}. E_{bal} with isospin independent cross section increases which is due to the fact that isospin-dependent cross section $\sigma_{np} = 3\sigma_{nn}$ or σ_{pp}, but when we make the cross section isospin independent, the effective total cross section decreases leading to less transverse in-plane flow and hence enhancement of E_{bal}. From the figure, we also see that change in the E_{bal} is more compared to one in fig. 1 (a) pointing towards increasing role of isospin dependence of nn cross section in E_{bal}. But N/Z dependence of E_{bal} is still linear with almost the same slope as with isospin-dependent nn cross section, thus indicating almost negligible role of isospin dependence of cross section as far as the N/Z dependence of E_{bal} is concerned. This clearly demonstrates the dominance of symmetry energy in N/Z dependence of E_{bal}. To see the effect of density dependence of symmetry energy, fig. 1(c) (open pentagons) displays E_{bal} with symmetry energy $\propto \rho^2$. From the figure, we see that with $E_{sym} \propto \rho^2$, E_{bal} increases and its N/Z dependence is linear with reduced slope of -17 as compared to one with linear density dependence (solid circles) indicating that N/Z dependence of E_{bal} can act as a probe of density dependence of symmetry energy as well.

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