# Structural effects on the mass dependence of balance energy

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## Introduction

Heavy-ion collisions (HIC) at intermediate energies are used as a powerful tool to get deeper knowledge about the behavior of nuclear matter at different thermodynamical conditions. A large number of observables have been purposed to probe the nuclear matter. Among them, directed flow enjoys a special status and has been used extensively to gather the information about the equation of state (EOS) and in medium nucleon-nucleon cross-section. There are several methods used in the literature to define the nuclear transverse in-plane flow. In most of the studies, one uses ($p_x$/A) plots where one plots ($p_x$/A) as a function of $Y_{cm}/Y_{beam}$. Using a linear fit to the slope, one can define the so-called reduced flow. Alternatively, one can also use a more integrated quantity directed transverse in-plane flow "*directed transverse momentum* $\langle p_x^{dir}\rangle$" which is defined as [1]

$$\langle p_x^{dir}\rangle = \frac{1}{A}\sum_{i=1}^{A} sign\{y(i)\}p_x(i), \qquad (1)$$

where $y(i)$ is the rapidity and $p_x$(i) is the momentum of $i^{th}$ particle. The rapidity is defined as

$$y(i) = \frac{1}{2}\ln\frac{\mathbf{E}(i)+\mathbf{p}_z(i)}{\mathbf{E}(i)-\mathbf{p}_z(i)}, \qquad (2)$$

where $\mathbf{E}(i)$ and $\mathbf{p}_z(i)$ are, respectively, the energy and momentum of $i^{th}$ particle in z- direction. In this definition, all the rapidity bins are taken into account. Also the beam energy dependence of directed flow leads to its disappearance and that particular incident energy is known as energy of vanishing flow or balance energy ($E_{bal}$). The structural effects like radius and density profile of colliding nuclei can play crucial role on the reaction dynamics at intermediate energies. Yong *et al.* [2] studied the role of initialization by using different parameterizations of Skyrme forces on the symmetry energy sensitive observables in the context of IBUU model. Recently, we [3] showed the sensitivity of directed flow and its disappearance towards the structural effects via radii of colliding nuclei for the reactions of $^{12}$C + $^{12}$C and $^{197}$Au + $^{197}$Au. our findings revealed that reaction of $^{12}$C + $^{12}$C is more sensitive to the radius parameter as compared to $^{197}$Au + $^{197}$Au. So here we aim to present the systematic study of the structural effects on the mass dependence of balance energy over the entire periodic table. The present study is carried out using isospin-dependent quantum molecular dynamics model [4].

## The Model

The IQMD model has been used extensively for studying the isospin effects on large number of observables. The IQMD model is an-body theory which simulates heavy ion reaction on event by event basis, hence preserves correlations and fluctuations of a reaction. The isospin degree of freedom enters into the calculations via symmetry potential, cross-sections, and Coulomb interaction. In this model, nucleons are represented by Gaussian wave packets propagate under the baryon potential $V^{ij}$ using the classical equations of motion given by:

$$\frac{d\vec{r_i}}{dt} = \frac{d\langle H\rangle}{d\vec{p_i}}; \quad \frac{d\vec{p_i}}{dt} = -\frac{d\langle H\rangle}{d\vec{r_i}} \qquad (3)$$

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and the baryon potential is given by:

$$\begin{aligned} V^{ij}(\vec{r}\,' - \vec{r}) &= V^{ij}_{Sky} + V^{ij}_{Yuk} + \\ & V^{ij}_{Coul} + V^{ij}_{mdi} + V^{ij}_{sym} \\ &= [t_1\delta(\vec{r}\,' - \vec{r}) + t_2\delta(\vec{r}\,' - \vec{r})\rho^{\gamma-1} \\ & (\frac{\vec{r}\,' + \vec{r}}{2})] + t_3\frac{\exp(|(\vec{r}\,' - \vec{r})|/\mu)}{(|(\vec{r}\,' - \vec{r})|/\mu)} \\ & + \frac{Z_i Z_j e^2}{|(\vec{r}\,' - \vec{r})|} \\ & + t_4 \ln^2(t_5(\vec{p}\,' - \vec{p})^2 + 1)\delta(\vec{r}\,' - \vec{r}) \\ & + t_6\frac{1}{\rho_0}T_{3i}T_{3j}\delta(\vec{r_i}\,' - \vec{r_j}). \qquad (4) \end{aligned}$$

Here $Z_i$ and $Z_j$ denote the charges of $i^{th}$ and $j^{th}$ baryon, and $T_{3i}$ and $T_{3j}$ are their respective $T_3$ components (i.e., 1/2 for protons and −1/2 for neutrons). The parameters $t_1$, . . . , $t_5$ are adjusted to the real part of the nucleonic optical potential.

## Results and discussion

We simulate the reactions of $^{12}$C + $^{12}$C, $^{24}$Mg + $^{24}$Mg, $^{40}$Ca + $^{40}$Ca, $^{58}$Cu + $^{58}$Cu, $^{96}$Cd + $^{96}$Cd, $^{135}$Ho + $^{135}$Ho and $^{196}$Cf + $^{196}$Cf corresponding to N/Z =1.0 using soft momentum dependent (SMD) equation of state and reduce isospin- and energy-dependent nucleon-nucleon (nn) cross-section $\sigma = 0.8\ \sigma_{NN}{}^{free}$ at different fixed incident energies ranging between 40 MeV/A and 140 MeV/A. The calculations are performed using default liquid drop formula of the radius and reducing this radius by 10% (keeping the Fermi momentum constant) to investigate the structural effects on the balance energy. A straight line interpolation is used to calculate the $E_{bal}$.

In Fig. 1 (a), we display system size dependence of balance energy with default IQMD radius (squares) and by reducing the default radius by 10% (circles). We see that balance energy decreases with decrease in the radius due to the increase in the strength of repulsive forces ($\propto \rho/\rho_o$) with decrease in radius.

$$\Delta E_{bal}\ (\%) = \left(\frac{E_{bal}^{0.9R_{IQMD}} - E_{bal}}{E_{bal}}\right) \times 100. \qquad (5)$$

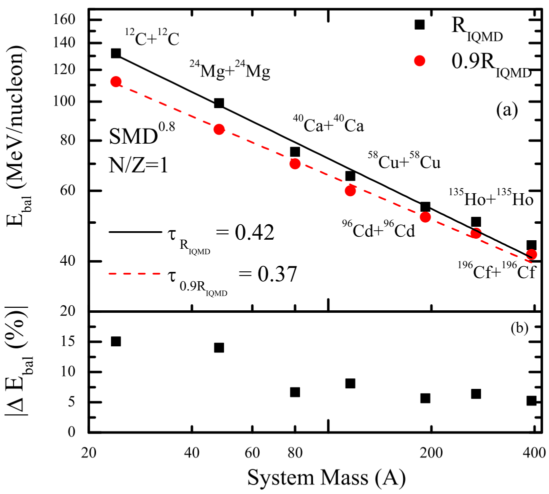


FIG. 1: The balance energy and percentage deviation as a function of total system mass. Lines represent the power law fit $\propto A^{-\tau}$. Various symbols are explained in the text.

Fig. 1 (b) displays percentage deviation of the balance energy ($\Delta E_{bal}$ (%)) (gievn by eq.(6)) calculated using 10% reduced default IQMD radius from the default IQMD calculations. We see $\Delta E_{bal}$ (%) is higher for the lighter systems compared to heavier cases. This justifies that lighter systems are more sensitive to the surface effects compared to heavier ones, and thus heavier systems remains almost unaffected by the reduction of the radius.

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## References


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