SENSITIVITY OF TRANSVERSE FLOW AND ITS DISAPPEARANCE TOWARDS DENSITY-DEPENDENT CROSS-SECTION*

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We study the relative role of density-dependent reduction and constant reduction of the cross-section on the mass dependence of balance energy throughout the mass range for two isobaric series corresponding to different neutron to proton contents using isospin-dependent quantum molecular dynamics model. Our study indicates that mass-dependent analysis of balance energy for semi-central collisions is almost insensitive to the choice of reduction in the cross-section. This insensitivity remains preserved for static as well as momentum-dependent soft equation of state.

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1. Introduction

The ultimate goal of nuclear physics community at intermediate energies is to understand the nuclear equation of state (EoS) as well as in-medium nucleon–nucleon (NN) cross-section. A considerable progress has been made in determining the EoS of nuclear matter, however strength of in-medium NN cross-section has still been a topic of debate. In the literature, a varieties of cross-sections have been used by various authors according to the need of their studies [1–4]. The collective transverse flow in heavy ion collisions is a measure of the pressure built up during the compression phase of a reaction, and is one of the most sensitive observable in this direction. The beam energy dependence of collective transverse flow leads to its disappearance at a particular energy termed as balance energy. The balance energy ($E_{\rm bal}$) is found to be a good probe to gather the information about NN cross-section, as it is more sensitive to the cross-section compared to different nuclear equations of state. The balance energy for more than 16 reactions

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ranging from ^{12}C+^{12}C to ^{197}Au+^{197}Au had been measured experimentally. In this direction, theoretical studies with different transport models using different EoS along with a variety of cross-sections are being done to explain the experimental data. The experimental mass dependence of balance energy was reproduced by Westfall *et al.* [5] and Magestro *et al.* [6] by using soft EoS along with 20% density-dependent reduction of the cross-section. Zhou *et al.* [7] using RVUU model asked for constant enhancement of the cross-section along with soft momentum-dependent (SMD) EoS to reproduce the measured balance energies for the same mass range as covered in Ref. [5]. On the other hand, a systematic study by Sood *et al.* [8] used hard EoS with 40 mb cross-section as well as hard momentum-dependent EoS with 50 mb cross-section. One has also studied multifragmentation and other properties at the balance point [9]. Recently, we reproduced the mass dependence of balance energy for more wider range using 20% constant reduction of the cross-section with SMD EoS [10] using isospin quantum molecular dynamics (IQMD) model. At the same time, directed flow is also found to be affected by the neutron content of the colliding pair. Puri *et al.* [11] investigated the relative contribution of the symmetry energy and isospin dependence of NN cross-section on the directed flow for isotopic pairs. However, nowhere in the literature the discussion of constant reduction of the cross-section and density-dependent reduction of the cross-section has been done simultaneously. Here, we aim to compare the role of the density-dependent reduction of the cross-section as well as constant reduction of the cross-section on the mass dependence of the balance energy throughout the mass range between 48–270 units for two isobaric series corresponding to $N/Z = 1.0$ and 1.4 using IQMD model [12]. In addition, we also study the behavior of the transverse flow towards the different cross-sections and momentum dependence of the mean field with an increase in the incident energy.

For the present study, we use Isospin-dependent Quantum Molecular Dynamics (IQMD) [12] model. Here, each nucleon propagates using the classical equations of motion under the nuclear mean field parameterized as

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

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 $t_1, \ldots, t_5$ are adjusted to the real part of the nucleonic optical potential.

2. Results and discussion

For the present study, we simulated several thousands of events of each reaction at incident energies around E_{bal} in small steps of 10 MeV/nucleon. In particular, we simulated the reactions ^{24}Mg + ^{24}Mg, ^{58}Cu + ^{58}Cu, ^{72}Kr + ^{72}Kr, ^{96}Cd + ^{96}Cd, ^{120}Nd + ^{120}Nd, ^{135}Ho + ^{135}Ho, having $N/Z = 1.0$ and reactions ^{24}Ne + ^{24}Ne, ^{58}Cr + ^{58}Cr, ^{72}Zn + ^{72}Zn, ^{96}Zr + ^{96}Zr, ^{120}Sn + ^{120}Sn, and ^{135}Ba + ^{135}Ba, having $N/Z = 1.4$, respectively. We used a soft equation of state (with and without momentum dependence) along with constant reduction (CR) read as $\sigma = 0.8\sigma_{\text{free}}$ as well as with 20% density-dependent reduction (DDR) of cross-section given by

$$\sigma = (1 - \alpha\rho/\rho_0)\sigma_{\text{free}}\,, \tag{2}$$

where $\alpha = 0.2$. The reactions were followed till the transverse in-plane flow saturates. A straight line interpolation is used to calculate the balance energy. For the transverse flow, we use the quantity *directed transverse momentum* $\langle p_x^{\text{dir}}\rangle$, which is defined in Refs. [11, 13].

In Fig. 1 (a), we display the mass dependence of balance energy, calculated using SMD EoS state along with both options of the cross-section (constant 20% reduction as well as with density-dependent 20% reduction). The calculations using CR (DDR) cross-section is shown by solid (open) symbols, whereas squares and triangles correspond to the calculations of the system having $N/Z = 1.0$ and 1.4, respectively. From the figure, we see that both options with SMD EoS results in the same E_{bal} in the case of lighter colliding pairs, whereas the difference in the balance energies starts appearing as we move towards the heavier side (compare solid and open squares). We also see that the density-dependent reduced cross-section results in the lower E_{bal} as compared to the constant reduced cross-section. This is because the density achieved in heavier systems is lower than the normal nuclear matter density (as lower incident energies and momentum-dependent interactions (MDI) are involved), which, in turn, results in less reduction of cross-section, therefore, increase in cross-section results in more transverse flow and hence will lead to lower E_{bal}. Similar trend is observed for $N/Z = 1.4$ isobaric series (see triangles in Fig. 1 (a)). Also the percentage difference in the slopes of both isobaric series calculated by $\Delta\tau(\%) = \left(\frac{\tau^{1.4}-\tau^{1.0}}{\tau^{1.0}}\right) \times 100$ using CR (15%) and DDR (19%) is almost the same.

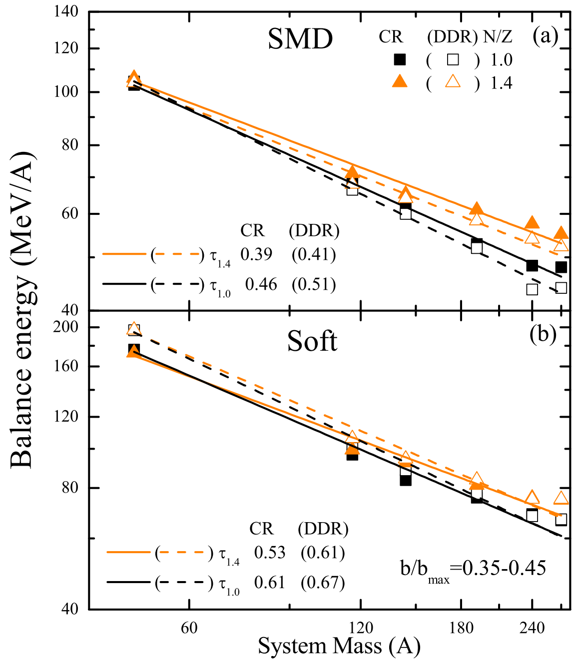

Fig. 1. Mass-dependence of balance energy using SMD (upper panel) and soft (lower panel) equation of state. Squares (triangles) symbols are for systems having $N/Z = 1.0$ (1.4). Lines represent the power law fit $\alpha\ A^{-\tau}$.

In Fig. 1 (b), we performed the same analysis but for soft EoS. Symbols have the same meaning as in Fig. 1 (a). We see that balance energies calculated using different cross-sections are different for lighter cases, whereas the difference disappears as we move to heavier side (contradictory to that observed in Fig. 1 (a)). This is due to the absence of momentum-dependent interactions (repulsive in nature) in these calculations. In Fig. 1 (a), momentum dependence of mean field, especially in lighter systems, does not let the density to be greater than one, whereas in the present case, the absence of MDI leads to higher density (*i.e.* $\rho/\rho_0 > 1$) and to the greater reduction of cross-section compared to 20% which, in turn, will increase the balance energy. On the other hand, in the heavier systems, density achieved in the reaction remains almost equal to that of the normal nuclear matter density, hence leads to only 20% reduction of cross-section and, therefore, a negligible difference in the $E_{\rm bal}$ calculated using constant reduced cross-section and as well as with density-dependent reduced cross-section in heavy colliding nuclei is observed. Here also, the percentage difference in the slopes of both isobaric series using CR (13%) and DDR (9%) is almost the same. Thus one can use any type of the reduction in the cross-section without any loss for both EoS.

As a next part of our study, we simulated the reactions of ^{24}Mg + ^{24}Mg at four different incident energies of 50, 100, 200 and 400 MeV/A using soft and SMD EoS with both the options of the nucleon–nucleon cross-section (mentioned above). In Fig. 2, we display $\langle p_x^{\rm dir}\rangle$ as a function of incident energy for both the options of the cross-section with soft (circles) and SMD (squares) equation of state. It is evident from the figure that $\langle p_x^{\rm dir}\rangle$ remains insensitive to choice of the reduction of the cross-section at low incident energies as the density achieved at these energies is almost same as that of normal nuclear matter density for both equation of states. Also DDR cross-section (see open squares and circles) leads to a lower value of $\langle p_x^{\rm dir}\rangle$ at high incident energies as compared to CR cross-section (see solid squares and circles). This is due to the fact that densities achieved at these energies are higher than those at the normal nuclear matter density and hence, leading to the reduction of cross-section by more than 20%. Also the difference is more prominent when the soft EoS is used. This is due to the repulsive nature of the MDI involved in the SMD equation of state resulting in the lower density of nuclear matter than the one achieved during the soft EoS.

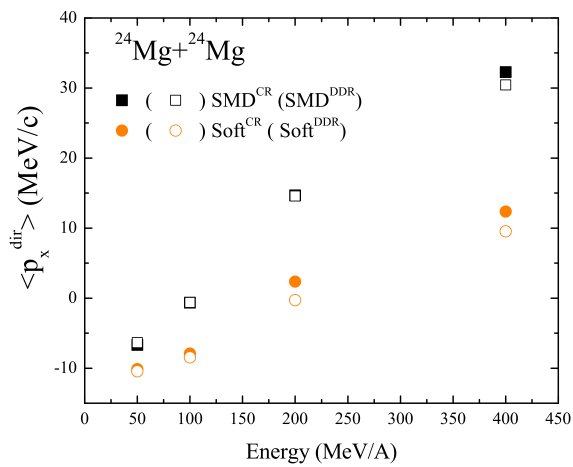

Fig. 2. (Color online) $\langle p_x^{\rm dir}\rangle$ as function of incident energy for system having mass 48 with $N/A = 1.0$.

3. Summary

In summary, we have studied the effect of density-dependent reduction as well as constant reduction of the cross-section on the balance energy for the mass range between 48–270 units for two isobaric series corresponding to $N/Z = 1.0$ and 1.4 using the SMD as well as soft equation of state. Our study indicates that SMD EoS results in the difference in the balance energies of heavier colliding nuclei, when different type of reduction factor is used, contrary to soft EoS, where difference appears in the balance energies for lighter systems. Also the effect of different types of reduction in cross-section for both EoS states was investigated on the incident energy dependence of directed flow. Our finding also showed that two different types of reduction results in more deviation when soft EoS is used as compared to SMD EoS at higher incident energies.

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