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Nuclear collective flows as a probe to the neutron–proton effective mass splitting

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ABSTRACT

The isospin-dependent quantum molecular dynamics model is used to investigate the nuclear collective flow observables in semicentral ^{197}Au+^{197}Au collisions at 400*A* MeV. It is found that the calculated results can reproduce both the experimental data and the other theoretical calculations. We find that the cluster production influences the rapidity dependence of directed flow of protons but less influences the results of tritons. Neutron–proton differential collective flows have larger values when taking the neutron effective mass less than the one of protons as compared with the case of neutron effective mass greater than the one of protons at larger rapidities and transverse momenta. Thus neutron–proton differential collective flows are proposed to be a useful probe to the neutron–proton effective mass splitting and the momentum-dependent symmetry potential.

The nuclear symmetry energy usually consists of the kinetic energy, the local symmetry potential energy and nonlocal symmetry potential energy. The local symmetry potential energy refers to the density-dependent and momentum-independent part while the nonlocal symmetry potential energy refers to the momentum-dependent part. A lot of theoretical approaches [1–11] and experimental data [10–16] have been devoted to the study of the nuclear symmetry energy at both subsaturation and suprasaturation densities in the past years, for the recent reviews, see Refs. [1,2,17,18]. However, in those theoretical models, the importance of the nonlocal symmetry potential energy is seldom stressed and even it is not included in some of the models. Recent studies [19–24] have demonstrated that the results with and without the nonlocal symmetry potential energy are very different.

In the non-relativistic transport model, the nucleon effective mass measures the momentum-dependent nucleon single-particle potential. The nonlocal symmetry potential energy is closely related to the neutron–proton effective mass splitting $m_n^* - m_p^*$ with m_n^* and m_p^* representing the neutron and proton effective masses, respectively. Different signs of the $m_n^* - m_p^*$ correspond to different nonlocal symmetry potentials [22,25]. Therefore, we have to constrain the sign of the $m_n^* - m_p^*$ before constraining the nonlocal symmetry potential energy. Unfortunately, up to now, constraints on the $m_n^* - m_p^*$ are still very controversial. Predictions using various approaches diverge quite widely especially at densities far away saturation point. Recently, by using the current constraints on the symmetry energy and its slope values at saturation density ρ_0, Li et al. have obtained the mean values of the $m_n^* - m_p^*$ at ρ_0, that is, $m_n^* - m_p^* = 0.27\delta$ [26]. However, the values of the $m_n^* - m_p^*$ at abnormal densities are unknown. Observables sensitive to the $m_n^* - m_p^*$ are needed to be found theoretically and the corresponding experimental data are needed to be analysed.

Nuclear collective flows have been found to be a useful tool for extracting information on both the isospin symmetric part [27,28] and the isospin asymmetric part [10,22,29–33] of the nuclear equation of state (EoS). In general, the flow observables are obtained from the Fourier expansion of the azimuthal distribution [34]:

$$f(y, p_t) \propto 1 + 2v_1\cos(\phi) + 2v_2\cos(2\phi), \tag{1}$$

where y is the rapidity along beam direction and $p_t = \sqrt{p_x^2 + p_y^2}$ the transverse momentum. ϕ is the azimuthal angle of the concerned emitted particle with respect to the reaction plane. $v_1 = \langle p_x/p_t\rangle$ is the directed flow and $v_2 = \langle (p_x^2 - p_y^2)/p_t^2\rangle$ the elliptic

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flow, where the angular bracket stands for an average over all concerned particles in a given event.

In this Letter, based on the isospin-dependent quantum molecular dynamics model (IQMD) [35–37], by calculating the rapidity and transverse momentum dependence of the v_1 and v_2 in semicentral ^{197}Au+^{197}Au collisions at 400A MeV, it is found that the theoretical results can reproduce both the experimental data reported by the FOPI Collaboration and the one obtained by the IQMD model used by Hartnack et al. [16]. Furthermore, the neutron–proton differential collective flows are found to show a clear signal of the $m_n^* - m_p^*$. They have larger values for the case of $m_n^* < m_p^*$ with respect to that of $m_n^* > m_p^*$ in the larger rapidity and transverse momentum regions.

Most of details of the IQMD model used in the present work can be found in Refs. [35–37]. We improve the model through incorporating the isospin-dependent momentum dependent interaction. In the present model, the Hamiltonian H is expressed as

$$H = T + U_{\rm Coul} + \int V(\rho) d\mathbf{r}, \tag{2}$$

where T is the kinetic energy and $U_{\rm Coul}$ the Coulomb potential energy. $V(\rho)$ is the nuclear potential energy density functional, which is written as

$$V(\rho) = \frac{\alpha}{2}\frac{\rho^2}{\rho_0} + \frac{\beta}{\gamma+1}\frac{\rho^{\gamma+1}}{\rho_0^{\gamma}} + \frac{g_{\rm sur}}{2}\frac{(\nabla\rho)^2}{\rho_0} + E_{\rm sym}^{\rm loc}(\rho)\rho\delta^2, \tag{3}$$

with

$$E_{\rm sym}^{\rm loc}(\rho) = \frac{1}{2}C_{\rm sym}\left(\frac{\rho}{\rho_0}\right)^{\gamma_s}, \tag{4}$$

and

$$E_{\rm sym}^{\rm loc}(\rho) = A_{\rm sym}\left(\frac{\rho}{\rho_0}\right) + B_{\rm sym}\left(\frac{\rho}{\rho_0}\right)^2. \tag{5}$$

The parameters α, β and γ are taken as −390 MeV, 320 MeV and 1.14, respectively, and the corresponding compressibility is 200 MeV [38]. $g_{\rm sur}$ is taken as 130 MeV fm^5. The first and second terms in Eq. (3) are the two-body and three-body terms, respectively. The third one is the surface term and the last one corresponds to the symmetry energy. Eq. (4) gives a hard, linear and soft symmetry energy when $\gamma_s = 2, 1, 0.5$, respectively. Eq. (5) corresponds to a supersoft symmetry energy.

A momentum-dependent energy density functional is included in the model, which reads [25]

$$V_{mdi} = \frac{1}{2\rho_0}\sum_{\tau,\tau',\tau\neq\tau'} C_{\tau,\tau'}\int\int\int d\mathbf{p}d\mathbf{p}'d\mathbf{r} f_\tau(\mathbf{r},\mathbf{p}) \times \ln^2\left[0.0005\left(\mathbf{p}-\mathbf{p}'\right)^2+1\right] f_{\tau'}\left(\mathbf{r},\mathbf{p}'\right), \tag{6}$$

where $C_{\tau,\tau} = 1.57(1-x)$ and $C_{\tau,\tau'} = 1.57(1+x)$. The two sets of coefficient values of $A_{\rm sym}, B_{\rm sym}$, $C_{\rm sym}$ and x are 43, −16.75, 52.5 MeV and −0.65, and 32.41, −20.65, 23.52 MeV and 0.65 corresponding to the mass splittings $m_n^* > m_p^*$ and $m_n^* < m_p^*$, respectively, which gives opposite mass splitting but quite similar density dependence of the symmetry energy. From Eq. (6) one can get the symmetry energy contribution from the momentum-dependent potential part.

In Fig. 1, we show the Lane potentials as a function of momentum for the two different density-dependent symmetry energies and mass splittings at $\rho = 2\rho_0$. From Fig. 1, we can see that neutrons will suffer more repulsive force for the case of $m_n^* < m_p^*$ with respect to the one of $m_n^* > m_p^*$ in larger momentum region. There is a crossing of two Lane potentials for the different density-dependent symmetry energies. Moreover, it is found that the momentum value of the crossing point for the hard density-dependent symmetry energy is larger than the one of the supersoft one. This reflects the fact that, in high density region ($\rho = 2\rho_0$), the density-dependent symmetry energy plays a more important role than the momentum-dependent symmetry energy. For instance, at $k = 2$ fm^{-1} for the hard density-dependent symmetry energy (top panel of Fig. 1), it is expected that neutrons suffer more repulsive force for the case of $m_n^* < m_p^*$ than the one of $m_n^* > m_p^*$ if we do not consider the effects of the density-dependent symmetry energy. However, the values of the density-dependent symmetry energy which corresponds to the case of $m_n^* > m_p^*$ are larger than the one of $m_n^* < m_p^*$ at $\rho = 2\rho_0$. Thus total effects are more repulsive force to neutrons for the case of $m_n^* > m_p^*$ with respect to the one of $m_n^* < m_p^*$ as shown in the top panel of Fig. 1.

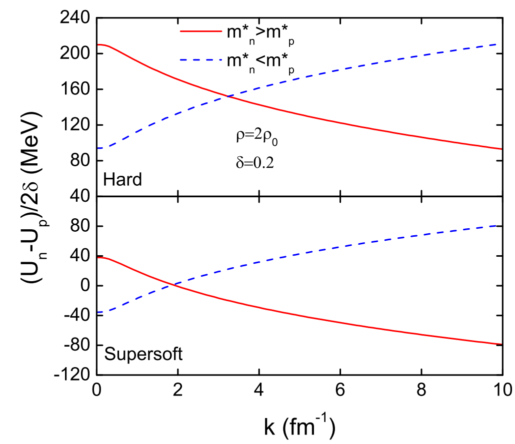

Fig. 1. (Colour online.) Lane potential as a function of momentum for different density-dependent symmetry energies and neutron–proton effective mass splittings.

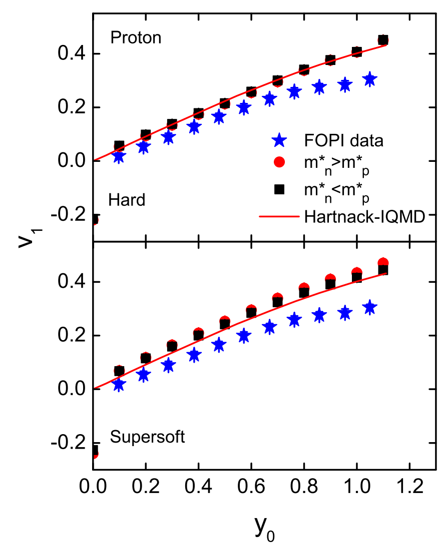

Fig. 2. (Colour online.) Directed flow of protons as a function of reduced rapidity for ^{197}Au+^{197}Au collisions at 400A MeV with centrality $0.25 < b_0 < 0.45$ and transverse 4-velocities cut $u_{t0} > 0.4$. The results are calculated by using hard (upper panel) and supersoft (bottom panel) density-dependent symmetry energy and different neutron–proton effective mass splittings in the framework of the IQMD model. The data and results of the IQMD model used by Hartnack et al. are taken from Ref. [16].

Shown in Fig. 2 is the rapidity dependence of directed flow, $v_1(y_0)$, of protons produced in ^{197}Au+^{197}Au collisions at 400A MeV with centrality $0.25 < b_0 < 0.45$ and cut $u_{t0} > 0.4$. Here $b_0 = b/b_{max}$ is the reduced impact parameter with $b_{max} = 1.15 \times$