Energy dependence for directed and elliptic flow in intermediate-energy heavy ion collisions *

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Abstract: Differential and integrated directed flow and elliptic flow of light charged particles ($z\leqslant 2$) are studied systematically for semi-central (b=5 fm) ^{197}Au+^{197}Au collisions at incident energies from 25 to 250 MeV/nucleon by the isospin-dependent quantum molecular dynamics model. The changes of directed and elliptic flow with incident energy reflect the dynamic competition between the mean field and nucleon-nucleon collisions and also between collective rotation and expansion.

Key words: energy dependence, directed flow, elliptic flow

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1 Introduction

The study of collective flow in nucleus-nucleus collisions has been an intense field of theoretical and experimental research for the past thirty years in both nucleonic or partonic levels [1–11]. At beam energies below several GeV per nucleon, the main motivation for studying flow is the extraction of the equation of state of nuclear matter. The collective flow is determined by the complex interplay among expansion, rotation, and shadowing of spectators, and is dependent on incident energy, impact parameter, fragment types, rapidity interval and so on. Directed and elliptic flows have been measured by the FOPI, INDRA and ALADIN collaborations for ^{197}Au+^{197}Au at an energy regime from Fermi energy to relativistic energy [12, 13], and the excitation functions for integrated directed and elliptic flow have been plotted. They and Suneel Kumar et al. [14] also simulated the directed and elliptic flows with theoretical model IQMD choosing different EOS and NN cross section to fit experimental results, but not one set of parameters can meet all the results. In view of the fact that there are no systematic and comprehensive studies on transformation with beam energy for directed and elliptic flow versus rapidity and transverse momentum, we present systematic results of the directed and elliptic flow dependence on rapidity and transverse momentum for ^{197}Au+^{197}Au collisions at an energy regime from 25 to 250 MeV per nucleon using the isospin-dependent quantum molecular dynamics (IQMD) model with common parameters in this paper, and the impact dynamics transition is also discussed.

Anisotropic flows are defined as different nth harmonic coefficients v_n of the Fourier expansion for the particle invariant azimuthal distribution,

$$\frac{\mathrm{d}N}{\mathrm{d}\phi}\propto 1+2\sum_{n=1}^{\infty}v_n\cos(n\phi), \tag{1}$$

where ϕ is the azimuthal angle between the transverse momentum of the particle and the reaction plane. Anisotropic flows generally depend on both the particle transverse momentum and rapidity, and for a given rapidity the anisotropic flows at transverse momentum p_{t} ($p_{\mathrm{t}}=\sqrt{p_x^2+p_y^2}$) can be evaluated according to

$$v_n(p_{\mathrm{t}})=\langle\cos(n\phi)\rangle, \tag{2}$$

where $\langle\cdots\rangle$ denotes the average over the azimuthal distribution of particles with transverse momentum p_{t}. The anisotropic flows v_n can further be expressed in terms of single-particle averages,

$$v_1 = \langle\cos\phi\rangle=\left\langle\frac{p_x}{p_{\mathrm{t}}}\right\rangle, \tag{3}$$

$$v_2 = \langle\cos(2\phi)\rangle=\left\langle\frac{p_x^2-p_y^2}{p_{\mathrm{t}}^2}\right\rangle, \tag{4}$$

where p_x and p_y are, respectively, the projections of particle transverse momentum parallel and perpendicular to the reaction plane. Elliptic flow is considered to arise from the anisotropic pressure gradient in the overlap region at relativistic energies, and is often studied with

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mean radial velocity to explore the correlation between spacial and momentum coordinates.

2 Theoretical framework

The intermediate energy heavy-ion collision dynamics is complex since both the mean field and nucleon-nucleon collisions play the competition role. Furthermore, the isospin-dependent role should also be incorporated for asymmetric reaction systems. An isospin-dependent quantum molecular dynamics model (IQMD) has been affiliated with isospin degrees of freedom with the mean field and nucleon-nucleon collisions [15–20]. The IQMD model can explicitly represent the many-body state of the system and principally contains correlation effects to all orders and all fluctuations, and can describe the time evolution of the colliding system well. When the spatial distance Δr is smaller than 3.5 fm and the momentum difference Δp between two nucleons is smaller than 300 MeV/c, two nucleons can coalescence into a cluster[15]. With this simple coalescence mechanism, which has been extensively applied in transport theory, different sized clusters can be recognized.

In the model the nuclear mean-field potential is parameterized as

$$U(\rho,\tau_z) = \alpha\left(\frac{\rho}{\rho_0}\right)+\beta\left(\frac{\rho}{\rho_0}\right)^{\gamma}+\frac{1}{2}(1-\tau_z)V_{\rm c} +C_{\rm sym}\frac{(\rho_{\rm n}-\rho_{\rm p})}{\rho_0}\tau_z+U^{\rm Yuk}, \qquad (5)$$

where ρ_0 is the normal nuclear matter density (0.16 fm^{-3}), $\rho_{\rm n}$, $\rho_{\rm p}$ and ρ are the neutron, proton and total densities, respectively; τ_z is the zth component of the isospin degree of freedom, which equals 1 or -1 for neutrons or protons, respectively. The coefficients α, β and γ are the parameters for the nuclear equation of state. $C_{\rm sym}$ is the symmetry energy strength due to the density difference of neutrons and protons in a nuclear medium, which is important for asymmetry nuclear matter ($C_{\rm sym}=32$ MeV is used). $V_{\rm c}$ is the Coulomb potential and $U_{\rm Yuk}$ is the Yukawa (surface) potential. In the present work, we take α=124 MeV, β=70.5 MeV and γ=2 which corresponds to the so-called hard EOS with an incompressibility of K=380 MeV.

The nucleon-nucleon (NN) cross section is the experimental parametrization which is isospin dependent. The neutron-proton cross section is about three times larger than the neutron-neutron or proton-proton cross section below 300 MeV/nucleon.

3 Results and discussions

Now we move to the calculations. About 100000 ^{197}Au+^{197}Au collisions have been simulated with hard EOS and medium impact parameter b=5 fm at beam energies $E_{\rm lab}$=25,40,60,80,100,150 and 250 MeV/nucleon, respectively. In this study, we extract the physical results at 200 fm/c for light charged particles $z\leqslant2$ (LCP) when the system has been in freeze-out.

The upper panel of Fig. 1 shows the differential directed flow as a function of transverse momentum for forward mid-rapidity ($0<y<0.4$) LCP. Squares, circles, up triangles, down triangles, diamonds, left triangles and right triangles are for 25, 40, 60, 80, 100, 150 and 250 MeV/nucleon collision energies respectively. At lower energies the directed flows are negative for the negative in-plane transverse momentum due to the rotation effect, and the absolute values increase monotonically with transverse momentum increasing, and then descend with increasing $p_{\rm t}$ which may be because the high $p_{\rm t}$ particles are emitted earlier and are strongly relatively blocked by other nucleons [12]. As energy increases nucleon-nucleon collisions overcome the attractive mean field, p_x changes its sign to positive and so to the directed flow v_1, and the higher the incident energy, the greater the directed flow. If the rapidity cut changes, the values of the directed flows also change, while the patterns of v_1 curves do not change [21]. The lower panel of Fig. 1

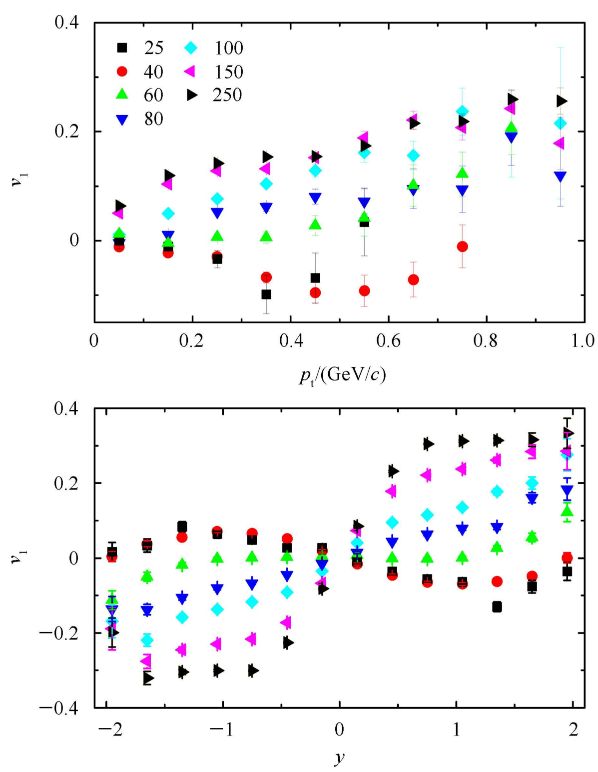

Fig. 1. The differential directed flow as a function of transverse flow for forward mid-rapidity ($0<y<0.4$) LCP and the integrated directed flow as a function of normalized rapidity for LCP at incident energies 25, 40, 60, 80, 100, 150 and 250 MeV/nucleon.

shows the directed flow integrated for LCP with all $p_{\rm t}$ as a function of normalized rapidity. It is very similar to $\langle p_x\rangle$-y distribution, which is symmetrical with the point ($y=0$, $p_{\rm t}=0$) for the symmetrical impact system and is also like the so-called 'S curve' [12]. As energy increases, the slope in the mid rapidity changes from negative for lower collision energy to positive for higher energy, and the higher the collision energy, the bigger the positive slope. It is also because the stronger compression at higher incident energy produces greater directed flow.

What is shown in Fig. 2 is similar to Fig. 1 but for elliptic flow. The upper panel of Fig. 2 shows that the elliptic flows are positive and increase monotonically as $p_{\rm t}$ increases at lower energies, and then descend with increasing $p_{\rm t}$ due to the bounce-off effect from spectators, while v_2 is negative at higher energies and the pattern of the absolute value is similar to that of lower energies. It means that the elliptic flow evolves from a preferential in-plane (rotational like) emission to an out-of-plane (squeeze-out) emission with the increase of energy, which is also because the mean field which contributes to the formation of a rotating compound system becomes less important and the collective expansion process based on the nucleon-nucleon scattering becomes predominant [14]. It also shows that the higher energy collision owns a greater magnitude of the elliptic flow for the stronger compression. The lower panel shows the integrated elliptic flow versus rapidity. The integrated elliptic flow is positive and one-peak shape symmetric with $y=0$ at lower energies. As energy increases the peak becomes gradually lower, and becomes flat, and the v_2 value equals 0 at about 100 A MeV incident energy which is in accordance with other results of the so-called transition energy for elliptic flow [12, 13]. Then, the peak becomes negative and turns into a valley, and two peaks are formed near $y=\pm1.3$. The negative elliptic flow in mid-rapidity may be the result of predominant nucleon-nucleon scattering including squeeze-out and shadowing effects, i.e., the compressed matter is pushed out of the way by the still incoming matter and is shadowed by the spectators resulting in the out-of-plane emission [14]. It also reflects that the valley is deeper for higher incident collision which owns a more significant squeeze-out effect.

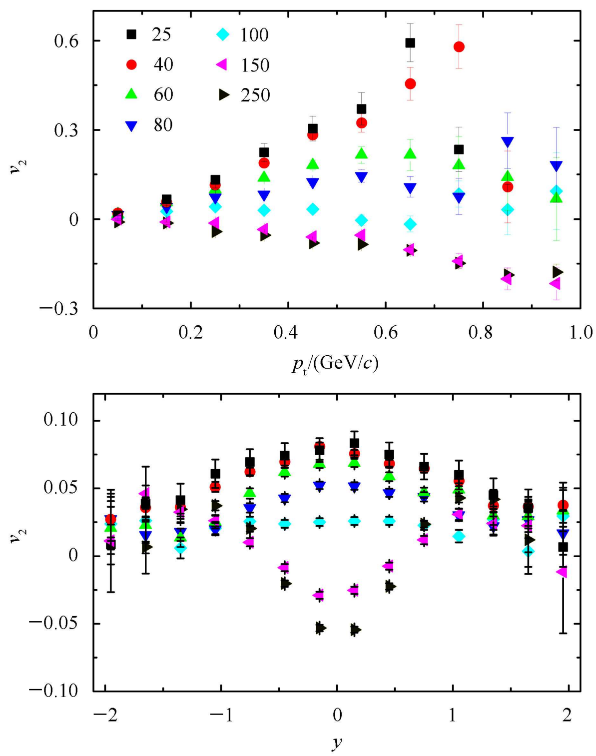

Fig. 2. The differential elliptic flow as a function of transverse flow for forward mid-rapidity ($0<y<0.4$) LCP and the integrated directed flow as a function of normalized rapidity for LCP at incident energies 25, 40, 60, 80, 100, 150 and 250 MeV/nucleon.

4 Summary

We have investigated the behaviors of directed and elliptic flows as functions of transverse momentum and normalized rapidity for light charged particles $z\leqslant2$ at medium collision parameter (b=5 fm) for the simulations of ^{197}Au+^{197}Au at incident energies of 25, 40, 60, 80, 100, 150 and 250 MeV/nucleon using the IQMD model. It is shown that the directed flow at forward rapidity is negative and the elliptic flow is positive at lower energies such as 25 and 40 A MeV, but as incident energy increases v_1 tends to be positive while v_2 changes to be negative. The rapidity dependent directed flow is an 'S curve', while the elliptic flow is one-peak shape in mid-rapidity at lower incident energies but a valley in mid-rapidity and two peaks in large rapidity at higher energies. It has been exposed that the change of directed flow is the result of nucleon-nucleon collisions overcoming the mean field, and the transformation of elliptic flow is invoked by fireball expansion conquering compound system rotation as increasing collision energy.

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