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Time Dependence of Elliptic Flow in Ultrarelativistic Au+Au Collisions*

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Abstract The freeze-out time dependence of the elliptic flow and the transverse radius $r_{\rm T}$ dependence of elliptic flow at different freeze-out time are studied for non-central Au+Au collisions at $\sqrt{s_{\rm NN}}$=200 GeV with the Relativistic Quantum Mocular Dynamics model. We get the results that the elliptic flow decreases with the freeze-out time and the correlation between the elliptic flow and the transverse radius changes with the freeze-out time what could be explained with the pressure gradient. The transverse expansion velocity of particles emitted at the freeze-out time is adopted as a signal of the pressure gradient.

Key words relativistic heavy-ion collisions, elliptic flow, transverse velocity, pressure gradient, freeze-out time

1 Introduction

The study of properties of extremely hot and dense nuclear matter and the search for anticipated transition to a deconfined phase of Quark Gluon Plasma(QGP) are two of the main objectives of heavy-ion experiments at ultrarelativistic energies[1]. Both theorists and experimentalists are looking for genuine QGP fingerprints, that can not be masked or washed out by processes on a hadronic level. In the collision of two relativistic nuclei, a hot and dense system of partonic matter may form. At present, the expansion of highly compressed nuclear matter in the direction perpendicular to the beam axis of the colliding heavy-ions, known as collective flow, is believed to be one of the most promising signals to detect the nature of the constituents and the equation of state of the system in the early stage of the reaction[2]. The elliptic flow is one kind of the collective flow[3—5]. It describes the anisotropy of the transverse momentum distribution of particles emitted from non-central collisions. Elliptic flow is a fundamental observable since it directly reflects the rescattering among the produced particles. Rescattering transfers the initial spacial anisotropy of the nuclear overlap region in the transverse plane to the observed momentum anisotropy. For a given initial spatial deformation, the density of particles is so intense that the matter in the reaction zone reaches a state of local thermal equilibrium. Since the spatial anisotropy is largest at the beginning of the evolution, elliptic flow is especially sensitive to the early stage of the system's evolution[6, 7]. A measurement of elliptic flow thus provides access to the fundamental thermalization time scale in the early stage of a relativistic heavy-ion collisions[8—10].

Elliptic flow of charged particles is among the first signals measured at Relativistic Heavy Ion Collider(RHIC) at Brookhaven Nationaliy Laboratory[11]. A lot of work concerning the centrality, the

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(pseudo) rapidity, and especially the transverse momentum is done to study Au+Au collisions at $\sqrt{s_{\rm NN}}$=130GeV[5] and $\sqrt{s_{\rm NN}}=200$GeV[4].

Experimental data from RHIC Au+Au collisions for identified particles[3, 4] demonstrate that the differential elliptic flow signal $v_2(p_{\rm T})$, with $p_{\rm T}$ up to 1.5GeV/c, shows a behavior expected from hydrodynamic model calculations. Above 1.5GeV/c, the data deviate from hydro predictions. The underlying microscopic mechanism of the production of elliptic flow needs continued work to be done. Now many microscopic models based on transport theory are able to reproduce, at least quanlitatively, many features of v_2. In this work, we study elliptic flow with the Relativistic Quantum Mocular Dynamical(RQMD) model[12]. Transverse expanding velocity is a signal of the pressure gradient. The freeze-out time dependence of elliptic flow and the differential elliptic flow $v_2(r_{\rm T})$ are analyzed in this paper.

The RQMD model is a semi-classical microscopic approach which combines classical propagation with stochastic interactions[12]. Color strings and ropes model the prehadronic stage in 1+1 dimensions. Fragmentation and decay lead to a production of particles. Overlapping strings do not fragment independently from each other but form ‘ropes’, chromoelectric flux-tube whose sources are charge states in higher dimension representations of color $SU(3)$. RQMD is a full transport theoretical approach for reactions between nuclei (and elementary hadrons) starting from the initial state before the overlapping to the final state after the strong interactions have ceased (freeze-out). The model is well established and has been used successfully to describe many observables measured at SPS bombarding energies over a wide range of projectile-target combinations. To investigate the development of elliptic flow, Au+Au collisions with an impact parameter between 5fm< b <8fm are generated at $\sqrt{s_{\rm NN}}=200$GeV.

2 The anisotropic transverse velocity

In heavy-ion collisions, the density distribution of the particles of the colliding source is not uniform: the number density and energy density of the particles are highest in the core of the created fireball in relativistic nuclear collisions. There is an angular dependence of the matter density gradient. This leads to the generation of the pressure gradient. Therefore, during the evolution of the colliding source, besides the thermal behavior, the source also undergoes a collective expanding. The mean transverse expanding velocity of the particles is a siganal of the pressure gradient[13]. In the following analysis, the transverse velocity of particles at the freeze-out is defined by

$$\beta_{\rm T}(r_{\rm T})=\left\langle\frac{\boldsymbol{p}_{\rm T}\cdot\boldsymbol{r}_{\rm T}}{E\ r_{\rm T}}\right\rangle, \quad (1)$$

where $\boldsymbol{r}_{\rm T}$ and $\boldsymbol{p}_{\rm T}$ are the transverse position and the transverse momentum of a particle, respectively, and E denotes its energy. The $\langle\cdots\rangle$ means averaging the particles on the shell with the radius r_T. In this analysis, the z-axis applied is directed along the beam in the coordinate space and the impact parameter direction is labeled as x-axis. The reaction plane is composed of the x-axis and z-axis. The y-axis is perpendicular to the reaction plane, and the x-axis and the y-axis make up of the transverse plane.

Figure 1 shows the transverse velocity $\beta_{\rm T}$ as a function of the freeze-out time of particles which are generated by RQMD model for non-central Au+Au collisions at $\sqrt{s_{\rm NN}}=200$GeV. The $\beta_{\rm T}$ is calculated by the Eq. (1). For the colliding source, the local equilibrium may be reached in the midrapidity region. Thus, the rapidy of particles used here is spread over $-1<y<1$ with $p_{\rm T}<1.5$GeV/c. As can be seen in Fig. 1, the later the particles freeze-out, the smaller their transverse velocity. This suggests that the pressure

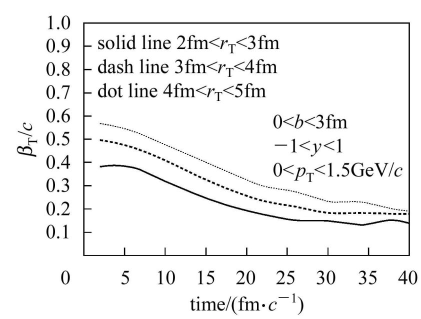

Fig. 1. The freeze-out time dependence of the transverse velocity for freeze-out particles in $\sqrt{s_{\rm NN}}$ = 200GeV Au+Au non-central collisions.

gradient of the source decreases with freeze-out time, and the particles with the largest transverse velocity carry the information of the evolution of the source at the early stage. Fig. 1 also shows that the transverse velocity of freeze-out particles increases with their radius.

3 The time analysis of elliptic flow

In non-central relativistic heavy-ion collisions the colliding energy is very high, so that the spectators leave the reaction region quickly. The overlapping area of two nuclei has a characteristic almond shape. The pressure gradient converts the original spatial anisotropy of the system into momentum anisotropy. The distribution of the final particles can be described with an azimuthal Fourier expansion.

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

where ϕ is the azimuthal angle of the emitted particle momentum relative to the reaction plane. The elliptic flow is defined as the second harmonic coefficient v_2[14]. It measures the eccentrity of the particle distribution in the momentum space and can be calculated by $v_2=\langle\cos(2\phi)\rangle$, where $\langle\cdots\rangle$ denotes averaging the $\cos(2\phi)$ of all the selected particles in one event. During the evolution the spacial anisotropy diminishes and the process of generating anisotropies in momentum space quentches itself. When the source becomes spherical, the elliptic flow stops developping. Therefore, v_2 carries information about the earlier phase of ultrarelativistic heavy-ion collisions. It is necessary to analyze the temporal structure of the elliptic flow's evolution. Fig. 2 shows the elliptic flow as a function of the freeze-out time. One can clearly observes a strong correlation between freeze-out time and elliptic flow. Note that the particles emitted from the source at the early stage have the strongest elliptic flow, while later on the flow of the particles is significantly reduced. This is a result of the fact that the pressure gradient and the anisotropy of the pressure gradient of the colliding source are both the biggest at the early stage. The freeze-out time dependence of elliptic flow demonstrates that the elliptic flow mainly carries the information of the early stage of the evolution of the source. It also should be noted that the elliptic flow is very small above $t\sim$20fm/c. This also shows that the change of the anisotropy of the freeze-out particles in coordinate space is very fast. The initial almond shape of the source will quickly change into isotropic. The v_2 of freeze out particles at early stage can't be regarded as absolute collective flow. Here the elliptic flow v_2 is mainly used to characterize the anisotropy of the distribution of freeze out particles in momentum space. And the anisotropy is related to the pressure gradient. The analysis about freeze out time dependence of elliptic flow in detail can be found in previous work[15]. To study the formation of elliptic flow, the elliptic flow v_2 as a function of the transverse freeze-out radius r_T is analyzed. The radius dependence of elliptic flow at different freeze-out time for non-central Au+Au collisions at $\sqrt{s}=200$GeV is plotted in Fig. 3. Here the top picture shows a peak shape of the radius dependence of elliptic flow for particles with a freeze-out time up to $t\sim 10$fm/c. The value of the elliptic flow v_2 increases from about 4% to 10% with the transverse freeze-out radius up to $r_\mathrm{T}\sim 3.5$fm. The value of elliptic flow v_2 decreases from 10% above $r_\mathrm{T}\sim$3.5fm and reaches zero at $r_\mathrm{T}\sim$7fm. As mentioned above, elliptic flow is driven by the anisotropy of the pressure gradient which is caused by the initial almond shape of the colliding source. Therefore, Fig. 3(a) shows that the anisotropy of the pressure gradient changes with the transverse freeze-out radius r_T. To get the effect of freeze-out time on r_T differential elliptic flow $v_2(r_\mathrm{T})$, Fig. 3(b) describes the r_T differential elliptic flow $v_2(r_\mathrm{T})$ with freeze-out time t between 10fm/c~40fm/c. As can be seen from Fig. 3(b), the value of elliptic flow v_2 increases with transverse radius r_T and then reaches saturation at $r_\mathrm{T}\sim$5fm. The value of saturation for the elliptic flow $v_2(r_\mathrm{T})$ is 2% which is smaller compared to the biggest value of Fig. 3(a). When comparing Fig. 3(a) to Fig. 3(b), it can be seen that up to $r_\mathrm{T}\sim 5$fm the elliptic flow decreases with freeze-out time for the same transverse radius. The particles mainly freeze-out with $r_\mathrm{T}<$5fm for noncentral Au+Au collisions at $b=5\sim$8fm. This suggests that the elliptic flow v_2 of freeze-out particles decreases with the increasing of freeze-out time. This can also directly be seen from Fig. 2. It also should be noted that at $r_{\mathrm{T}} < 2$fm the elliptic flow of freeze-out particles is less than zero at late stage. This will be explained in the following part.

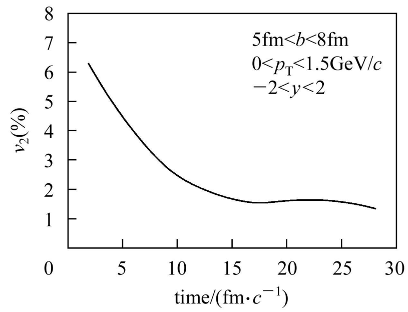

Fig. 2. The freeze-out time dependence of the elliptic flow for freeze-out particles in $\sqrt{s_{\mathrm{NN}}} =$ 200 GeV Au+Au non-central collisions.

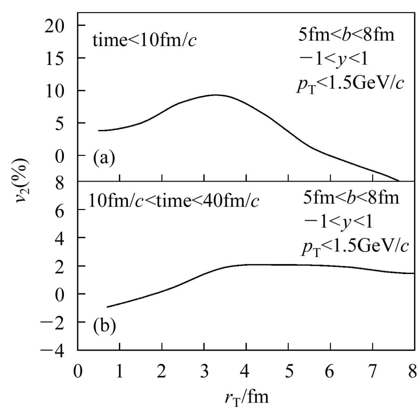

Fig. 3. The radius dependence of the elliptic flow for different freeze-out time in $\sqrt{s_{\mathrm{NN}}} =$ 200GeV Au+Au non-central collisions. Top: The freeze-out time for particles is less than 10fm/c; bottom: The freeze-out time for particles is between 10fm/c and 40fm/c.

4 The differential elliptic flow

The transverse radius r_{T} differential elliptic flow $v_2(r_{\mathrm{T}})$ at different freeze-out time should be related to the pressure gradient. The transverse velocity is the signal of the pressure gradient. Fig. 4 shows the transverse radius r_{T} dependence of the transverse velocity at different time. As can be seen in Fig.4(a) and Fig. 4(b), the transverse velocity increases with r_{T} and then reaches saturation in both early and late stage of the evolution of the colliding source. In the following part, β_x denotes the velocity of in-plane direction, β_y denotes the velocity of out-of-plane direction. Fig. 4(a) presents that at early stage, there is $\beta_x/\beta_y > 1$ at r_{T} <3.5fm, and $\beta_x/\beta_y < 1$ at r_{T} >3.5fm. The transverse velocity is isotropic at r_{T} ~3.5fm. It provides information about the pressure gradient. It demonstrates that at early stage, with r_{T} <3.5fm the pressure gradient in in-plane direction is bigger than that in out-of-plane direction, while with r_{T} >3.5fm the former is smaller than the latter. The changes in anisotropy of the pressure gradient for different radius regions are related to the spacial anisotropy. Because of the almond shape of the source, in collisions with impact parameter b ~7fm, the density of particles in in-plane direction is much less than that in out-of-plane direction at r_{T} >3.5fm at early stage. Thus, the pressure gradient is bigger in the out-of-plane direction for $r_{\mathrm{T}} > 3.5$fm than that in the in-plane direction at early stage. On the other hand, Fig. 4(b) shows that there is β_x/β_y >1 for r_{T} up to 5fm at the late stage. Above r_{T} ~5fm the transverse velocity becomes isotropic and reaches saturation. This suggests that up to r_{T} ~5 fm the out-of-plane pressure gradient is bigger than that in-plane, while above r_{T} ~5 fm the pressure gradient becomes small and isotropic, what leads to the saturation of elliptic flow as a function of radius. Now the character of Fig. 3(b) that the elliptic flow $v_2 < 0$ at $r_{\mathrm{T}} < 2$fm could be explained like that: the density of particles in the in-plane direction is diluted more than that in out-of-plane direction at

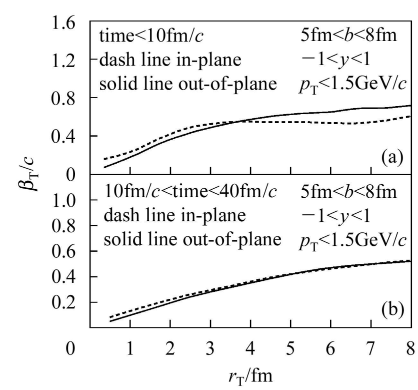

Fig. 4. The radius dependence of radial velocity in different direction in $\sqrt{s_{\mathrm{NN}}} =$ 200GeV Au+Au non-central collisions. Top:freeze-out time for particles is less than 10fm/c; bottum:freeze-out time for particles is between 10fm/c and 40fm/c.

$r_{\rm T} < 2$fm due to $\beta_x/\beta_y > 1$. Although the pressure gradient in in-plane direction is bigger than that of out-plane direction at $r_{\rm T} < 2$fm at late stage, the elliptic flow of freeze-out particles is still less than zero at radius $r_{\rm T} < 2$fm. This shows that the pressure gradient and density of the source are both important to the generation of the elliptic flow. From the analysis we can get the result that the correlation between anisotropy and transverse radius changes with the evolution of the source and that can be studied with the transverse expanding velocity.

5 Conclusion

We studied the freeze-out time dependence of elliptic flow, and the freeze-out radius dependence of elliptic flow in different time ranges. The radius dependence of transverse velocity can be seen as the result of the pressure gradient. The study shows that the elliptic flow decreases with the freeze-out time. The elliptic flow carries the information of the early stage. At the early stage of the evolution of the source, the radius dependence of elliptic flow shows a peaked shape in the late stage, the elliptic flow increases with radius until it reaches saturation. This could be explained with the anisotropy of the pressure gradient as a function of the transverse radius changes with freeze-out time. The microscopic mechanism of pressure gradient needs further study.

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超相对论Au+Au碰撞中椭圆流的时间依赖*

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摘要 用相对论量子分子动力学(RQMD)模型模拟了质心系束能量为$\sqrt{s_{\rm NN}}$=200GeV的Au+Au非对心碰撞,研究了椭圆流对末态粒子冻出时间的关系.研究了在不同的阶段,椭圆流对末态粒子位置的关系.结果表明椭圆流随冻出时间的单调递减,椭圆流对横向半径的关系随冻出时间发生变化.用压力梯度对所得结果进行了分析.径向速度用来表征压力梯度.

关键词 相对论重离子碰撞 椭圆流 横向速度 压力梯度 冻出时间

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