Effects of multi-collisions and surface on elliptic flow *

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Abstract The non-central Au+Au collision at center-of-mass energy $\sqrt{s_{\rm NN}} = 200$ GeV is simulated using AMPT model. It is found that both the integral and differential elliptic flow behaves differently for partons freezing out at different stages. It is shown that the integral elliptic flow of freeze-out partons decreases with time at the early stage, but increases with time at the late stage. The curve of transverse momentum distribution of elliptic flow of partons is more flatter at the early stage than at the late stage. The effect of surface emitting on elliptic flow is argued to be not neglectable.

Key words relativistic heavy-ion collisions, elliptic flow, surface emitting, many collisions

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Elliptic flow is an important experimental observable to probe the properties of matter produced at early stage in ultra-relativistic heavy ion collisions[1, 2]. The successful description to elliptic flow data at small transverse momentum ($p_{\rm T} <$ 1.5 GeV/c) using ideal relativistic hydrodynamics leads to the conclusion that a new phase of nuclear matter—deconfined and strongly interacting, which is called sQGP, has been produced in RHIC experiments[3]. However, ideal relativistic hydrodynamics could not give a good description to the distribution of elliptic flow with respect to impact parameter and transverse momentum at large transverse momentum ($p_{\rm T} > 1.5$ GeV/c)[4]. Whether the matter produced in RHIC experiments has reached to the requirement by ideal relativistic hydrodynamics, local equilibrium, is still debatable[5]. The effects of nonequilibrium on elliptic flow is being studied[6—9]. AMPT model is a transport model. Nonequilibrium effects have been included in this model self-consistently. In this paper, the possible effects of nonequilibrium on elliptic flow on partons will be studied using AMPT model.

The AMPT model includes both partonic and hadronic phase dynamics[10]. Two different scenarios, i.e., default and string melting, are implemented in the AMPT model. The string melting scenario has been used to reproduc RHIC elliptic flow data. In the string melting scenario, the initial partons are produced by converting the hadrons produced using the HIJING model[11] to their valence quarks and antiquarks with current quark masses. The collisions of the produced partons are implemented using the ZPC model[12]. Only elastic collision is included in the ZPC model with the elastic differential cross section:

$$\frac{{\rm d}\sigma}{{\rm d}t} \approx \frac{9\pi\alpha_{\rm s}^2}{2}\left(1+\frac{\mu^2}{s}\right)\frac{1}{(t-\mu^2)^2}, \tag{1}$$

and the total cross section is

$$\sigma \approx \frac{9\pi\alpha_{\rm s}^2}{2\mu^2}, \tag{2}$$

where the strong coupling constant $\alpha_{\rm s}$ is 0.47, and s and t are Mandelstam variables. μ is the screen mass and could be adjusted to fix the total cross section. The total cross section is 3 mb in pQCD calculation, but large cross section of 6-10 mb has to be used to

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describe RHIC elliptic flow data. The cross section $\sigma=10$ mb is used in this paper. When partons freeze out, two nearest quark and antiquark are combined to form a meson and three nearest quarks or antiquarks are combined to form a baryon or antibaryon, Interactions between hadrons are implemented using ART model[13]. The AMPT model has reproduced many aspects of RHIC data.

Elliptic flow results from the conversion of initial spatial anisotropy to final momentum anisotropy through the interactions among constituents of matter produced in noncentral heavy ion collisions. The spatial anisotropy is defined as

$$s_2=\left\langle\frac{x^2-y^2}{x^2+y^2}\right\rangle \tag{3}$$

and elliptic flow is

$$v_2=\left\langle\frac{p_x^2-p_y^2}{p_x^2+p_y^2}\right\rangle, \tag{4}$$

where x and y is transverse position of partons, p_x and p_y is transverse momentum component. In order to illustrate the relation between elliptic flow and the interaction among partons, the time evolution of elliptic flow of all partons at midrapidity ($|y|<1$) for Au+Au collisions at RHIC top energy $\sqrt{s_{\rm NN}}$ = 200 GeV is shown in Fig. 1. The elliptic flow is found to increase with time. This result indicates that elliptic flow increases with average collision numbers among partons. In Fig. 1, all of the partons at midrapidity, freeze-out and active, have been included to calculated time evolution of elliptic flow. Partons freezing out at different stages suffer different collision numbers. Is the behavior of time evolution of elliptic flow of freeze-out and total partons the same? The time evolution of elliptic flow for freeze-out partons are shown in Fig. 2 (solid circle). In order to make a clear comparison, elliptic flow of total partons is also plotted (solid line). Interestingly, the elliptic flow of freeze-out partons at early stage in Fig. 2 decreases with time. This result indicates that the elliptic flow of the freeze-out partons does not have the same relation with collision numbers as that of all midrapidity partons. The initial spatial distribution of matter may be the reason for this difference. At early stage of noncentral collision, the surface of matter in the x direction is larger than that in the y direction. Partons emit in the direction perpendicular to surface. Therefore, more partons emit in the x direction than in the y direction. However, the difference of matter distribution in x and y direction decreases with time. Then, elliptic flow of freeze-out partons decreases with time. In order to demonstrate this physical picture, configurations of freeze-out partons at different stages are shown in Fig. 3. It is observed that spatial anisotropy of freeze-out configuration indeed decreases with time. The results in Fig. 2 and Fig. 3 indicate that surface emitting has large contribution to integral elliptic flow at early stage.

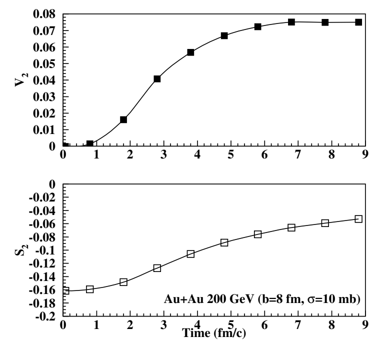

Fig. 1. Time evolution of elliptic flow and spatial anisotropy for total partons at midrapidity.

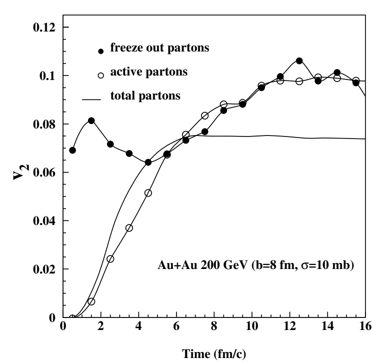

Fig. 2. Time evolution of elliptic flow for freeze-out, active, and total partons at midrapidity.

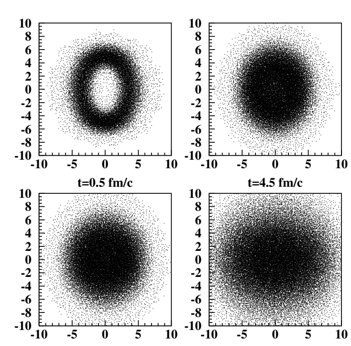

Fig. 3. Configurations of freeze-out partons at different stages.

On the other hand, with increasing the collision number between partons, the initial spatial anisotropy will be converted to momentum anisotropy sufficiently. The final elliptic flow will have more and more contributions due to this reason. The behavior of time evolution of elliptic flow of partons freezing out at late stage, shown in Fig. 2, is mainly affected by this reason. This physical picture is convinced by the time evolution of elliptic flow of active partons in Fig. 2 (empty circle). Elliptic flow of partons at late stage indeed reflects the information of interacting matter. It has been shown that the more sufficient the collisions between partons, the more the system approaches to local equilibrium[14], required by hydrodynamics. Surface emitting is a proper property of system in noncentral ultra-relativistic heavy ion collisions. Both of the surface emitting and conversion of spatial anisotropy to momentum anisotropy due to multi-collisions among partons determine the final elliptic flow.

The momentum distribution of elliptic flow $v_2(p_T)$ is proposed to be a sensitive probe to describing nonequilibrium and/or viscous properties of matter[6, 7, 14]. The curves of differential elliptic flow of partons freezing out at different stages are shown in Fig. 4. In order to demonstrate the effects of the two reasons on $v_2(p_T)$, partons freeze out before 4.5 fm/c and after 4.5 fm/c are defined as the early-stage and late-stage partons, respectively. The differential elliptic flow of these two kinds of partons is obviously different. The curve of $v_2 \sim p_T$ of the late-stage partons is more steeper. This is mainly due to the large collision numbers of these partons, which makes the system behave like hydrodynamics. The curve of $v_2 \sim p_T$ of early stage partons is found to be flat. The final momentum distribution of elliptic flow of all partons is also shown in Fig. 4 in order to compare different contributions of these two different kinds of partons. It is found that elliptic flow of early stage partons has large contribution at large transverse momentum to elliptic flow of all final partons and late stage partons dominant small transverse momentum region. The flatting of $v_2 \sim p_T$ at large p_T is an important property of differential elliptic flow data[4]. Ideal relativistic hydrodynamics could not describe this property of data. Viscous relativistic hydrodynamics is proposed to give a qualitively better description. The result shown in Fig. 4 indicates that surface emitting is an important effect on the flatting of differential elliptic flow at large transverse momentum.

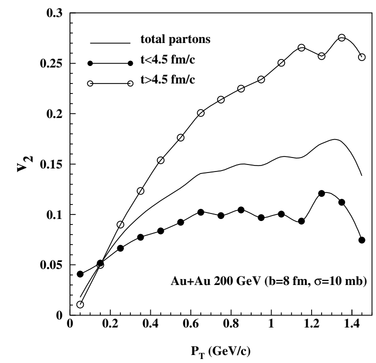

Fig. 4. Differential elliptic flow of early stage, late stage, and total partons (see text).

In summary, elliptic flow of partons is calculated using the AMPT model for Au+Au collision at $\sqrt{s_{NN}} = 200$ GeV. There are two mechanisms affecting the production of elliptic flow: the elliptic flow of partons freezing out at early stage is affected by the surface emitting effect and decreases with time; the elliptic flow of the partons freezing out at the late stage mainly results from the conversion of spatial anisotropy to momentum anisotropy through multi-collisions and increases with time. The $v_2(p_T)$ of the partons freezing out at the late stage approaches the description of hydrodynamics because of the strong interactions between partons and has large contribution to the elliptic flow of all final partons at small transverse momentum. The $v_2(p_T)$ of the partons freezing out at the early stage has large contribution to the flatting of curve at large transverse momentum.

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