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Anisotropic Transverse Flow and Multiparticle Azimuthal Correlation in Heavy Ion Collisions*

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Abstract The transverse anisotropy of particle emission is studied and a clear signature of the multipartiple azimuthal correlation is evidenced in Au + Au collisions at 600*A* MeV within the Quantum Molecular Dynamics (QMD) model. The study indicates that the behaviour of elliptic flow in different events reflects the spatial anisotropy and the extent of particle rescatterings in the collisions.

Key words directed flow, elliptic flow, azimuthal correlation

High energy heavy ion collisions provide a unique possibility to study nuclear matter at high densities and at high temperatures in the laboratory. It remains an experimental and theoretical challenge to extract information about the initial conditions from the particle distributions at freezeout[1]. Since the pressure gradient perpendicular to the collision axis causes various transverse collective flows, such as radial flow, directed flow, and elliptic flow, in nuclear collisions, these flows observed in the final state are expected to carry the information about the nuclear equation of state and the in-medium nucleon-nucleon cross section[2,3]. Until now, the study of the flow in high energy nuclear collisions is attracting large attention from both experimentalists and theorists.

The anisotropic transverse flow has been studied most commonly by analyzing the Fourier expansion of the azimuthal distribution of the particles[4,5]. Such study requires an event-plane reconstruction in each event, but further averaging over many events in order to obtain a statistically relevant measurement of the flow. In past years, either directed flow or the elliptic flow was studied separately in some papers[6,7], but the combined researches are still very few. In this paper, we describe a method to study the azimuthal correlation between the two anisotropic components of the transverse flow and analyze the final state azimuthal fluctuation in heavy-ion collisions. We will show that the study of multiparticle azimuthal correlation can offer information about space-time evolution of the system. The studies presented in this paper are performed within the QMD model.

In an actual experiment, the reaction plane is not known exactly. Empirically, the azimuthal distribution of the final state particles can be parametrized by Fourier series[8]:

$$\rho(\phi) = \frac{a_0}{2\pi}\left[1 + 2\sum_{n=1}^{\infty}(x_n\cos n\phi + y_n\sin n\phi)\right], \quad (1)$$

where ϕ is the azimuthal angles of the emitted particle in a certain coordinate system in which the beam direction is defined as z-axis, and a_0 is a normalization factor. The azimuthal anisotropy can be studied by the Fourier coefficients x_n and y_n. The first and second harmonics in the Fourier expansion are related to the directed flow and the elliptic flow component, respectively.

The values of x_n and y_n can be calculated from experimental data event by event[8,9]:

$$x_n = \frac{1}{a_0}\int_0^{2\pi}\rho(\phi)\cos(n\phi)\mathrm{d}\phi = \langle\cos n\phi\rangle,$$

$$y_n = \frac{1}{a_0}\int_0^{2\pi}\rho(\phi)\sin(n\phi)\mathrm{d}\phi = \langle\sin n\phi\rangle.$$

From these, one can construct the vectors $\boldsymbol{Q}_n$ defined as

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$$Q_n = Q_n(e_x \cos\phi_n + e_y \sin\phi_n), \quad (2)$$

where $Q_n = \sqrt{x_n^2 + y_n^2}$, $\phi_n = \frac{1}{n}\arctan\frac{y_n}{x_n}$ and $0 \le n\phi_n < 2\pi$. It should be indicated that the direction of vector Q_n is defined modulo $\frac{2\pi}{n}$. For each event, the two anisotropic components of transverse flow, the directed flow and the elliptic flow, can be described by the vectors Q_1 and Q_2, respectively. The multiparticle azimuthal correlation function $C(\beta)$ can be constructed as follows:

$$C(\beta) = \frac{\pi}{M}\frac{\mathrm{d}M}{\mathrm{d}\beta}, \quad (3)$$

where M is the number of events and β is the angle between the vectors Q_1 and Q_2,

$$\beta = \arccos\left(\frac{Q_1 \cdot Q_2}{Q_1 Q_2}\right). \quad (4)$$

Theoretically, the value of β should be 90° for negative elliptic flow and 0° or 180° for positive elliptic flow. Fig.1 shows the azimuthal correlation function for protons from QMD calculations for Au + Au collisions at 600 A MeV and the impact parameters $b = 6$fm. The vectors Q_1 and Q_2 were calculated using protons within normalized rapidity regions of $\left|\left(\frac{y}{y_{\text{beam}}}\right)_{\text{cm}}\right| > 0.3$ and $\left|\left(\frac{y}{y_{\text{beam}}}\right)_{\text{cm}}\right| < 0.25$, respectively. The fact that the distribution is not flat confirms the multiparticle azimuthal correlation. The enhancement at $\beta = 90°$ reflects the fact that the elliptic flow is negative for the collisions on an average. The width of the peak indicates that an azimuthal fluctuation exists in the collisions.

Fig.1. The correlation function $C(\beta)$ for protons.

tuation, we sort out the events according to the multiparticle azimuthal correlation. Since the azimuthal angle of Q_2 is defined modulo π, the range of $0 \le \beta < \pi/2$ is divided into four equall intervals. The azimuthal angle distributions of the protons with respect to the reaction plane at midrapidity $\left(\left|\left(\frac{y}{y_{\text{beam}}}\right)_{\text{cm}}\right| < 0.25\right)$ for the four groups of events are shown in Fig.2. It can be seen that the events with different values of β give very different elliptic flow. Peaks in Fig.2(a) and Fig.2(b) located near 0° and 180° indicate that the long axes of the ellipses lie in the reaction plane. For the events in Fig.2(c) and Fig.2(d), the protons are preferentially emitted perpendicular to the reaction plane. The elliptic flow changes sign from positive to negative as the value of β increase from 0° to 90°.

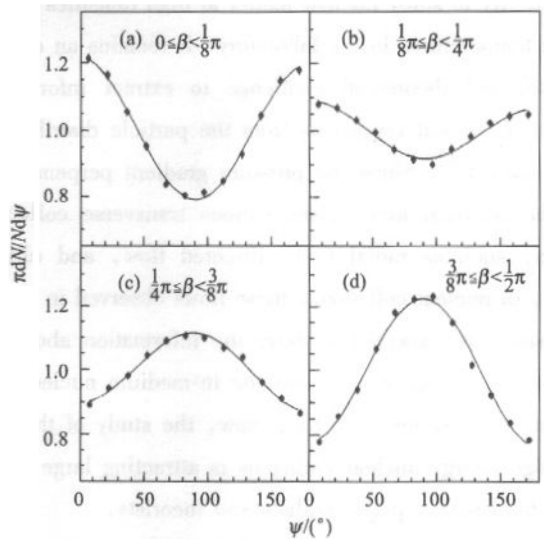

Fig.2. The normalized distributions of azimuthal angle ψ for protons in Au + Au collisions at 600 A MeV.

The elliptic flow results from a competition between the early "squeeze-out" when compressed matter tries to move out in the direction perpendicular to reaction plane and the late-stage in-plane emission associated with the shape of the participant zone[10,11]. The particle rescatterings in the evolving system convert the initial spatial anisotropy into the momentum anisotropy. The spatial anisotropy in general decreases with system expansion, thus quenching this effect and making elliptic flow particularly sensitive to the early stages of the system evolution. The azimuthal asymmetry of the source can be defined as[5]

$$\delta = \frac{R_y^2 - R_x^2}{R_y^2 + R_x^2} \tag{5}$$

where $R_x = \langle x^2 \rangle^{1/2}$ and $R_y = \langle y^2 \rangle^{1/2}$ describe the geometrical size of the system in the transverse direction, and the

Initially, the value of δ is

ameter.

source expands δ decrease because the average velocities in x-direction are larger than those in y-direction. Taken the averages in Eq. (5) over the points of last interaction

we calculate the freeze-out

-0.005 ± 0.001, 0.016 ± 0.001, 0.062 ± 0.001 and 0.085 ± 0.001 for event groups a, b, c and d, respectively. Our results indicate that the collective transverse expansion in coordinate space affects the azimuthal distributions of the final state particles in momentum space and a space-momentum correlation would develop. The behaviour of elliptic flow in different events depends on the evaluation of event-by-event dynamical fluctuations. It reflects the spatial anisotropy and the extent of rescatterings, or the particle density in the transverse. This provide a new opportunity to correlate phenomena related to azimuthal anisotropies with the initial energy density.

Generally, the azimuthal distribution of particle emission with respect to the reaction plane can be described by the truncated Fourier expansion[7]

$$dN/d\psi = v_0(1 + v_1\cos\psi + v_2\cos 2\psi). \tag{6}$$

The smooth curves in Fig. 2 are obtained using this fit function. For symmetric collisions, v_1 is an odd function of the center-of-mass rapidity, its value is zero within the error bars at midrapidity. The second Fourier coefficient v_2 commonly used to quantify elliptic flow. The sign and magnitude of v_2 reflects the result of a competition between the early "squeeze-out" perpendicular to the reaction plane and the later in-plane emission of nucleons. Fig. 3 shows the elliptic flow of protons at midrapidity as a function of β in different transverse momentum (p_t) regions for 600 A MeV Au + Au collisions with $b = 6$fm.

The distributions in Fig. 3 clearly show an increasing squeeze-out effect as the transverse momentum increases.

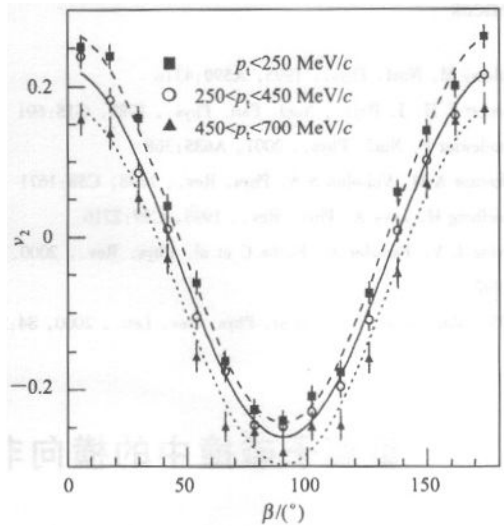

Fig. 3. The elliptic flow parameter v_2 of protons as a function of β in Au + Au collisions at 600 A MeV.

This is due to the fact that high p_t particles can only be produced through the most violent collisions in the early stage of the reaction[11,12]. These particles can only retain their high transverse momenta by escaping from the reaction zone along the direction perpendicular to the reaction plane without suffering much rescatterings. The low p_t particles have undergone a sufficiently large number of rescatterings. The early pressure created in the participant region can be revealed more clearly by the particles with high transverse momenta.

In summary, we have investigated directed flow and elliptic flow for protons in Au + Au collisions at 600 A MeV within QMD model. A clear signature of multiparticle azimuthal correlation between the two anisotropic components of the transverse collective flow was evidenced in noncentral collisions. The study indicated that the behaviour of elliptic flow in different events depend on the evaluation of event-by-event dynamical fluctuations. The collective transverse expansion in coordinate space affects the azimuthal distribution of the final state particles in momentum space and the space-momentum correlation would develop. The elliptic flow of protons with high transverse momenta is much more sensitive to the early pressure created in the participant region.

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重离子碰撞中的横向非对称流与多粒子方位角关联*

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摘要 非对心重离子碰撞中,横向非对称核物质流的存在引起了末态的多粒子方位角关联. 对600*A* MeV Au + Au碰撞的QMD模拟数据分析表明,不同事件中侧向流与椭圆流在横向上的夹角存在明显的涨落,多粒子方位角关联揭示了相互作用区域核物质运动的空间-动量相关性. 椭圆流对碰撞系统的演化过程反映敏感,在中间快度区域,不同事件中椭圆流的差别与反应过程中粒子经历再散射的情况有关.

关键词 侧向流 椭圆流 方位角关联

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