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Multiparticle azimuthal correlations in central nucleus-nucleus collisions at high energy*

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Abstract Multiparticle azimuthal correlations in central nucleus-nucleus collisions at high energy are described by a simple formula. The calculated results are in agreement with the experimental data of carbon and oxygen induced interactions at Dubna energy. The comparison between the calculated results and experimental data shows that particles are emitted isotropically in the rest frame of the emission sources, and the emission sources have movements in momentum space.

Key words Dubna energy, nucleus-nucleus collisions, multiparticle azimuthal correlation

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1 Introduction

Relativistic nucleus-nucleus collisions at Dubna energy (a few AGeV) are very well suited for investigations of azimuthal correlations which are the subject of collective motion studies both experimentally and theoretically. It is believed that some exotic states of nuclear matter, for example the phase transition to a quark-gluon plasma [1, 2] in violent central interactions and the liquid-gas phase transition in weak peripheral excitations, can be formed in nucleus-nucleus collisions at high energy.

One of the main goals of relativistic nucleus-nucleus collision studies is to investigate nuclear matter under extreme conditions of high densities and temperatures. The most impressive results of relativistic nucleus-nucleus collision experiments are new collective phenomena discovered in these studies. The studies of multiparticle azimuthal correlations are important for understanding the space-time evolution of the collective system [3].

A lot of models have been introduced in the field of high energy collisions, for example, FRITIOF [4], VENUS [5, 6], RQMD [7–9], QGSM [10], HIJING [11–13], ARC [14–16], hydrodynamics [17, 18], thermodynamics [19, 20], and fireball [21, 22] models, etc. Different phenomenological mechanisms of initial coherent multiple interactions and baryon transports were proposed [23–25].

Recently, Liu et al. have proposed a multi-source thermal model [26–33] and described the azimuthal and multiplicity distributions of particles and projectile fragments produced in nucleus-nucleus collisions at high energies [34–39]. The model gives a simple formula for the azimuthal distributions of the particles. It is interesting for us to test the model by the multiparticle azimuthal correlations between protons and between pions in nucleus-nucleus collisions at Dubna energy.

2 The model

Let the beam direction be the $\overline{oz}$ axis and the reaction plane be the $\overline{xoz}$ plane. The momentum of the ith particle produced in an event is denoted by $\boldsymbol{P}_i$, and the corresponding transverse momentum is denoted by $\boldsymbol{P}_{i\perp}$. The analysis has been performed event by event, as in Refs. [3, 34, 35, 38, 39], and for an event we can construct the vectors:

$$\boldsymbol{Q}_{\rm B}=\sum_{y_i<\bar{y}}\boldsymbol{P}_{i\perp} \tag{1}$$

and

$$\boldsymbol{Q}_{\rm F}=\sum_{y_i>\bar{y}}\boldsymbol{P}_{i\perp}, \tag{2}$$

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where $\bar{y}$ is the average rapidity of the particles produced in the event. Let ψ be the angle between the transverse momentum of a considered particle emitted in the backward (or forward) hemisphere and the vector $\boldsymbol{Q}_{\rm B}$ (or $\boldsymbol{Q}_{\rm F}$) and φ the angle between the vectors $\boldsymbol{Q}_{\rm B}$ and $\boldsymbol{Q}_{\rm F}$ [3]. Then, the multiparticle azimuthal correlation function is constructed as $\mathrm{d}N/\mathrm{d}\psi$ and $\mathrm{d}N/\mathrm{d}\varphi$. Essentially, $\mathrm{d}N/\mathrm{d}\varphi$ measures whether the particles in the backward and forward hemispheres are preferentially emitted "back-to-back" ($\varphi=180°$) or "side-by-side" ($\varphi=0°$).

In the modelling calculations, such as in the multi-source thermal model [26–33], many emission sources of particles are assumed to form in high-energy nucleus-nucleus collisions. We assume that in the rest frame of the emission source j, the particles are isotropically emitted and the three momentum components P'_{ix}, P'_{iy} and P'_{iz} of the ith particle obey a Gaussian distribution with the same standard deviation (distribution width) σ_j. Taking into account the movement of the emission sources and the interactions between them, the particle momenta in the final states are different from those in the rest frame of the emission sources. In the investigation of the azimuthal distribution we do not need to take care of the longitudinal components of the momenta. The simplest relations between P_{ix} and P'_{ix}, as well as P_{iy} and P'_{iy} are linear

$$P_{ix}=a_xP'_{ix}+b_x\sigma_j\ , \tag{3}$$

and

$$P_{iy}=a_yP'_{iy}+b_y\sigma_j\ , \tag{4}$$

where a_x, b_x, a_y, and b_y are free parameters. Let R_1, R_2, R_3, and R_4 denote random variables distributed in [0,1], we have

$$P'_{ix}=\sqrt{-2\ln R_1}\cos(2\pi R_2)\sigma_j\ , \tag{5}$$

and

$$P'_{iy}=\sqrt{-2\ln R_3}\cos(2\pi R_4)\sigma_j\ , \tag{6}$$

because P'_{ix} and P'_{iy} obey a Gaussian distribution law.

Considering Eqs. (3)–(6), the azimuthal angle of a particle can be written as

$$\psi_i = \arctan\left(\frac{P_{iy}}{P_{ix}}\right)= \arctan\left[\frac{a_y\sqrt{-2\ln R_3}\cos(2\pi R_4)+b_y}{a_x\sqrt{-2\ln R_1}\cos(2\pi R_2)+b_x}\right]. \tag{7}$$

The angle between $\boldsymbol{Q}_{\rm B}$ and the $\overline{ox}$ axis is

$$\psi_{\rm B}=\arctan\left(\frac{Q_{{\rm B}y}}{Q_{{\rm B}x}}\right)=\arctan\left(\sum_{y_i<\bar{y}}P_{iy}\Big/\sum_{y_i<\bar{y}}P_{ix}\right), \tag{8}$$

where $Q_{{\rm B}y}=Q_{\rm B}\sin\psi_{\rm B}$ and $Q_{{\rm B}x}=Q_{\rm B}\cos\psi_{\rm B}$ are the two components of $\boldsymbol{Q}_{\rm B}$. Similarly, the angle between $\boldsymbol{Q}_{\rm F}$ and $\overline{ox}$ axis is

$$\psi_{\rm F}=\arctan\left(\sum_{y_i>\bar{y}}P_{iy}\Big/\sum_{y_i>\bar{y}}P_{ix}\right). \tag{9}$$

The angle between the transverse momentum of a particle emitted in the backward (or forward) hemisphere and $\boldsymbol{Q}_{\rm B}$ (or $\boldsymbol{Q}_{\rm F}$) is

$$\psi=|\psi_i-\psi_{\rm B}(\text{or }\psi_{\rm F})|. \tag{10}$$

The angle between the vectors $\boldsymbol{Q}_{\rm B}$ and $\boldsymbol{Q}_{\rm F}$ is

$$\varphi=|\psi_{\rm B}-\psi_{\rm F}|. \tag{11}$$

The theoretical $\overline{ox}$ axis which together with the beam direction $\overline{oz}$ defines the reaction plane is in fact the sum of $\boldsymbol{Q}_{\rm B}$ and $\boldsymbol{Q}_{\rm F}$. However, in Ref. [3] the angle between the transverse momentum of a considered particle emitted in the backward hemisphere and $\boldsymbol{Q}_{\rm B}$, as well as the angle between the transverse momentum in the forward hemisphere and $\boldsymbol{Q}_{\rm F}$ have bean measured. This indicated that two $\overline{ox}$ axes (we call them $\overline{ox'}$ axes) were used in the experiment. Both of the two $\overline{ox'}$ axes are not identical with the real theoretical $\overline{ox}$ axis. According to the experimental conditions of Ref. [3], let the direction of the vector $\boldsymbol{Q}_{\rm B}$ (or $\boldsymbol{Q}_{\rm F}$) be the $\overline{ox'}$ axis. We then have

$$\psi=\psi_i \tag{12}$$

and

$$\varphi=\psi_{\rm F}(\text{or }\psi_{\rm B})=\arctan\left(\frac{\bar{P}_y}{\bar{P}_x}\right), \tag{13}$$

where $\bar{P}_y$ and $\bar{P}_x$ are the average momentum components of particles in the forward (or backward) hemisphere. In different events, the values of $\bar{P}_y$ (or $\bar{P}_x$) are different. Let n denote the number of particles in the forward (or backward) hemisphere in an event, then

$$\varphi = \arctan\left(\frac{\sum_{i=1}^{n}P_{iy}}{\sum_{i=1}^{n}P_{ix}}\right)= \arctan\left[\frac{\sum_{i=1}^{n}a_y\sqrt{-2\ln R_3}\cos(2\pi R_4)+b_y}{\sum_{i=1}^{n}a_x\sqrt{-2\ln R_1}\cos(2\pi R_2)+b_x}\right]. \tag{14}$$

For the Dubna energy the value of n is not too high. As a first approximation and as an example we take $n=10$ for the forward (or backward) hemisphere in each event.

The above discussion shows that we can use Eqs. (12) and (14) to describe the ψ and φ distribution, $\mathrm{d}N/\mathrm{d}\psi$ and $\mathrm{d}N/\mathrm{d}\varphi$, respectively. Of course, different parameter values are needed for different collisions. The normal values of the parameters in Eqs. (12) [i.e. (7)] and (14) are $a_x=1$, $b_x=0$, $a_y=1$, and $b_y=0$. In most cases, the azimuthal correlation distributions are symmetrical around 180°. We need only $a_x\neq 1$ and $b_x\neq 0$ to describe the experimental distributions. For a symmetrical distribution, Eqs. (12) and (14) will be

$$\psi=\arctan\left[\frac{\sqrt{-2\ln R_3}\cos(2\pi R_4)}{a_x\sqrt{-2\ln R_1}\cos(2\pi R_2)+b_x}\right] \qquad (15)$$

and

$$\varphi=\arctan\left[\frac{\sum_{i=1}^{n}\sqrt{-2\ln R_3}\cos(2\pi R_4)}{\sum_{i=1}^{n}a_x\sqrt{-2\ln R_1}\cos(2\pi R_2)+b_x}\right], \qquad (16)$$

respectively. $a_x>1$ (or $a_x=1$) means that the source has an (or has no) expansion in the x direction, while $b_x>0$ (or $b_x<0$) means that the source has a movement along the positive (or negative) x direction. For an isotropic emission, $a_x=1$ and $b_x=0$. The physics condition gives $a_x\geqslant 1$.

3 Comparison with experimental data

Figure 1 presents the $\mathrm{d}N/\mathrm{d}\psi$ vs ψ for protons (a) and negative pions (b) produced in central C-Cu collisions at 3.7 AGeV. The circles and squares are the experimental data measured in the backward and forward hemispheres respectively [3]. The curves are our results calculated by the Monte Carlo method. In the calculation, we take $a_x=1$ and $b_x=0$ in Eq. (16). One can see that Eq. (16) can describe the ψ distribution in nucleus-nucleus collisions at high energy. The particles are emitted isotropically in the backward and forward hemispheres respectively.

Figure 2 presents the $\mathrm{d}N/\mathrm{d}\varphi$ vs φ for protons (a) produced in central C-Cu (circles) and C-Ne (squares) collisions and for negative pions (b) produced in central O-Pb (circles) and C-Cu (squares) collisions at 3.7 AGeV. The circles and squares are the experimental data [3]. The curves are our calculated Monte Carlo results. In the calculation we used $a_x=1$ and $b_x=-0.07$ for Fig. 2(a), $a_x=1$ and $b_x=0.08$ for O-Pb collisions in Fig. 2(b), and $a_x=1$ and $b_x=0.05$ for C-Cu collisions in Fig. 2(b). The method of χ^2 testing was used to select the parameter values. One can see that Eq. (16) can describe the φ distributions in nucleus-nucleus collisions at high energy. Our calculation shows that there is no elliptic flow in the considered collisions. For protons a negative directed

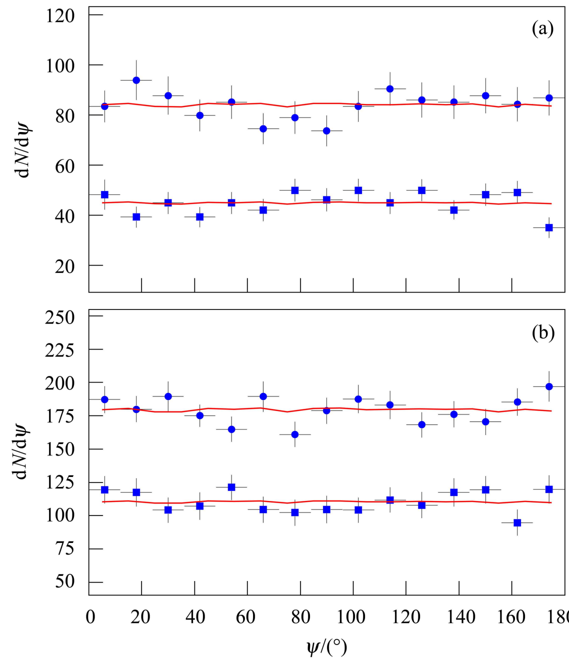

Fig. 1. $\mathrm{d}N/\mathrm{d}\psi$ vs ψ for protons (a) and negative pions (b) produced in central C-Cu collisions at 3.7 AGeV. The circles and squares are the experimental data measured in the backward and forward hemispheres respectively [3]. The curves are our calculated results.

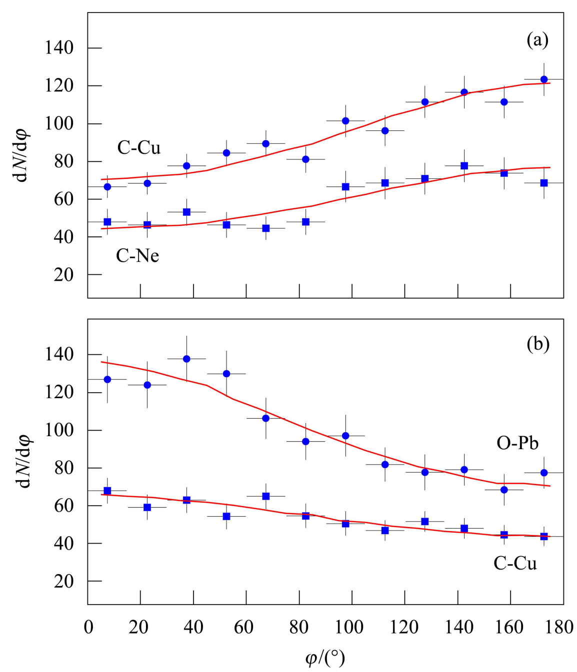

Fig. 2. $\mathrm{d}N/\mathrm{d}\varphi$ vs φ for protons (a) produced in central C-Cu (circles) and C-Ne (squares) collisions and for negative pions (b) produced in central O-Pb (circles) and C-Cu (squares) collisions at 3.7 AGeV. The circles and squares are the experimental data measured in Ref. [3]. The curves are our calculated results.

flow exists in the collisions. For negative pions a positive directed flow exists in the collisions. The directed flow means a relative movement of the emission source.

From Figs. 1 and 2 one can see that Eqs. (15) and (16) give a good description of the azimuthal correlations in nucleus-nucleus collisions at Dubna energy. Two free parameters in Eqs. (15) and (16) determine the flow characteristics. $a_x \neq 1$ means an elliptic flow, $b_x \neq 0$ means a directed flow, while $a_x = 1$ and $b_x = 0$ means no flow. The parameter values render that the source has no expansion in the four collisions. For protons produced in C-Cu and C-Ne collisions the source has a movement along the negative x direction. For negative pions produced in O-Pb and C-Cu collisions the source has a movement along the positive x direction.

In the above discussion the azimuthal distributions in high energy collisions are described in the framework of multi-source thermal model. The calculation is straightforward and simple. It is noticed that Eq. (16) is simpler than Eq. (14); and Eq. (16) seems to have an obvious physical meaning, that is, the two parameters a_x and b_x in Eq. (16) denote the expansion and movement of the source.

4 Conclusion and discussion

To conclude, we have given a formula [Eq. (14)] and described the multiparticle azimuthal correlations in nucleus-nucleus collisions at Dubna energy. The source which produces protons has a movement along the negative x direction, while the source which produces negative pions has a movement along the positive x direction. Both sources have no expansion in the x direction. Because we used $a_y = 1$ and $b_y = 0$ to obtain Eq. (16), both sources have no expansion in the y direction and movement along the positive and negative y directions.

The Dubna energy (a few AGeV) is regarded as the low end of high energies. It is expected that the maximum energy of the Cooling Storage Ring (CSR) in Lanzhou can reach the Dubna energy. The lower CSR energy can be in the range of intermediate energies. This gives us a chance to study heavy ion collisions at intermediate energy and low end of high energies at the CSR. We hope that the new experiments on multiparticle azimuthal correlations can soon be performed at the CSR and our formula [Eq. (14)] can describe the new experimental data.

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