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Azimuthal distributions of final-state particles and fragments and transverse structure of emission source in high-energy nucleus–nucleus collisions*

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The azimuthal distributions of final-state particles and fragments produced in high-energy nucleus–nucleus collisions are described by a modified multisource ideal gas model which contains the expansions and movements of the emission sources. The transverse structures of the sources are given in the transverse plane by momentum components p_x and p_y, and described by parameters in the model. The results of the azimuthal distributions, calculated by the Monte Carlo method, are in good agreement with the experimental data in nucleus–nucleus collisions at high energies.

Keywords: high-energy nucleus–nucleus collisions, final-state particles and fragments, azimuthal distributions, transverse structure of emission source
PACC: 2570N, 2587, 2940R

1. Introduction

Multiparticle production is an important experimental phenomenon in high-energy nucleus–nucleus collisions.[1−5] Accompanying the multiparticle production, a multifragment emission phenomenon is observed in experiments.[6−10] Generally speaking, the processes of multiparticle production and multifragment emission are different. It is difficult to describe the two processes by a unified formula.

In experimental measurements of the multiparticle production and multifragment emission, the angular distribution is easy to obtain. Especially, the azimuthal distribution is very important because it is related to the transverse motion of an interacting system. When two nuclei collide under the condition of a nonzero impact parameter, the high pressure is developed at the impact position. The matter will have a tendency to flow in the direction where the pressure gradient is larger. Therefore, the azimuthal distribution is also related to the collective flow. As the pressure is anisotropic, the azimuthal distribution is anisotropic, too.

Since the discovery of anisotropic azimuthal distribution,[11−13] many experimental results have been obtained in nucleus–nucleus collisions at intermediate and high energies. The experimental groups, e.g. the Plastic Ball experiment,[14−16] EOS,[17] FOPI,[18,19] KAOS,[20] E877,[21−25] E895,[26,27] E802 / E917,[28] E866 / E917,[29] NA49,[30] and WA98[31,32] at Bevalac / SIS (around 1A GeV), AGS (2 – 15A GeV), and SPS (40 – 200A GeV) energies have reported the azimuthal distributions of final-state particles and fragments. Meanwhile, much theoretical work has been devoted to the understanding of the mechanism responsible for the azimuthally anisotropic distributions.[33−43]

Recently, based on a multisource ideal gas model and the deformation and movement of an emission source, we have explained some experimental data in high-energy nucleus–nucleus collisions.[44−46] In this paper, based on a similar modified multisource ideal gas model, we study the transverse structure of an emission source using the azimuthal distribu-

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tions of final-state particles and fragments produced in nucleus–nucleus collisions at high energies. It is expected that the transverse structure including the expansion and movement of the emission source in the transverse plane can be extracted from the azimuthal distribution.

2. The model

Let the beam travel along the direction of the oz axis and the reaction plane be the yoz plane. Many emission sources of particles (or fragments) are assumed to form in participants (or spectators) in high-energy nucleus–nucleus collisions. We assume that a normal isotropic thermal spectrum has an expansion and a movement due to the interactions among sources. In the rest frame of the emission source i, as used in a Maxwell's ideal gas model, the three components p'_x, p'_y, and p'_z of momentum of final-state particle (or fragment) obey the Gaussian distribution and have the same standard deviation σ_i. In the investigation of azimuthal distribution, we do not need to take into account the longitudinal component of momentum.

Considering the expansion and movement of the source, the particle (or fragment) momentum components in the final state can be given by revising p'_x and p'_y. The simplest relations between p_x and p'_x, as well as p_y and p'_y are linear:

$$p_x = a_x p'_x + B_x = a_x p'_x + b_x \sigma_i, \tag{1}$$

and

$$p_y = a_y p'_y + B_y = a_y p'_y + b_y \sigma_i, \tag{2}$$

where B_x and B_y are free parameters that can be rewritten as $b_x\sigma_i$ and $b_y\sigma_i$ respectively. σ_i is the standard deviation as pointed out above, it is the parameter that characterizes the width of the momentum distribution in the source reference frame. a_x, b_x, a_y, and b_y are free parameters. We parameterize the equations so that the parameters a_x and a_y represent an expansion coefficient of the emission of the thermal source. B_x and B_y represent a displacement, while b_x and b_y represent a displacement coefficient, of the source relative to the beam axis. Because a_x and a_y represent an expansion of the source, the physical condition gives $a_x \geq 1$ and $a_y \geq 1$. There is no limitation for the values of b_x and b_y.

It seems that Eqs.(1) and (2) are in discrepancy with the conventional approach like the so-called blast wave model[47] in which Lorentz transformation is taken into account. We would like to point out that one could understand the current formalism because Eqs.(1) and (2) represented the relations of "mean" momentum between the cases of including and excluding interactions among sources in the local thermalized rest frame.[48]

Let R_1, R_2, R_3, and R_4 denote an even random variable distributed in the interval $[0, 1]$, we have

$$p'_x = \sqrt{-2\ln R_1}\cos(2\pi R_2)\sigma_i, \tag{3}$$

and

$$p'_y = \sqrt{-2\ln R_3}\cos(2\pi R_4)\sigma_i, \tag{4}$$

because p'_x and p'_y obey the Gaussian distribution. Considering Eqs.(1)–(4), in the xoy plane, the azimuthal angle can be written as

$$\begin{aligned}\phi &= \arctan\left(\frac{p_y}{p_x}\right) \\ &= \arctan\left[\frac{a_y\sqrt{-2\ln R_3}\cos(2\pi R_4) + b_y}{a_x\sqrt{-2\ln R_1}\cos(2\pi R_2) + b_x}\right].\end{aligned} \tag{5}$$

If there exists a symmetry with respect to the reaction plane, we should have $a_y = 1$ and $b_y = 0$. For an asymmetrical azimuthal distribution with respect to the reaction plane, we need one of a_x and b_x, and one of a_y and b_y, to describe the experimental data. The other two parameters (a_x and (or) a_y, or (and) b_x and (or) b_y) will be 1 or (and) 0. Or, we need three or four parameters in Eq.(5) to describe the asymmetrical distribution. We use Eq.(5) to calculate the azimuthal angle by the Monte Carlo method. The azimuthal distribution ($\mathrm{d}N/\mathrm{d}\phi$) is obtained by a statistical method. The number and excitation degrees of emission sources do not affect the azimuthal angle.

Because the parameters b_x and b_y are normalized to the width of the momentum distribution, the expression for ϕ does not contain the parameter σ_i. This allows us to describe the particle distribution in a way that is independent of the temperature of the source. The parameters B_x and B_y describe how much the source is displaced from the beam axis or what the average transverse momentum of the source is. The parameters b_x and b_y describe only the displacement coefficient of the source and depend on the temperature of the source to obtain the same transverse momentum of the source. To obtain the temperature (or σ_i), one should use the distribution of transverse momentum p_{T} ($= \sqrt{p_x^2 + p_y^2}$), but being azimuthal.

3. Comparison with experimental data

The left panel of Fig.1 shows the antiproton ($\bar{p}$) azimuthal distributions measured in the transverse momentum range $p_T < 0.5$ GeV/c and rapidity range $1.6 < y < 2.6$ for different transverse energy (E_T) bins in 11.5A GeV Au–Au collisions. The full circles are the E877 experimental data and the open circles are reflected about $\phi = 180°$.[49] The solid curves are our calculated results using the Monte Carlo method and the corresponding parameter values in Eq.(5) for each event group are given in the right panel of Fig.1. The results without source's expansion and movement are given in the left panel by the dotted lines. All calculations are done using the Monte Carlo method and for each case 10^6 particles are generated. The values of χ^2/degree-of-freedom (dof) for the fits of the solid curves in the left panel from upper to bottom are 0.045 and 0.031, respectively. To be able to easily dissect the shape of the expansion and moving emission source in the momentum space in the transverse plane that corresponds to the solid curves in the left panel, the solid curve circles are used in the right panel to represent the sources in the p_x–p_y plane and the small full circles are adopted to denote their centers. The dotted curve circles represent the original emission sources in the p_x–p_y plane and the small open circles denote their centers. Corresponding to the dotted curve circles in the right panel, the azimuthal distributions in the left panel are represented by the dotted lines. One can see an expansion of the source along the x direction and a movement of the source along the negative x direction.

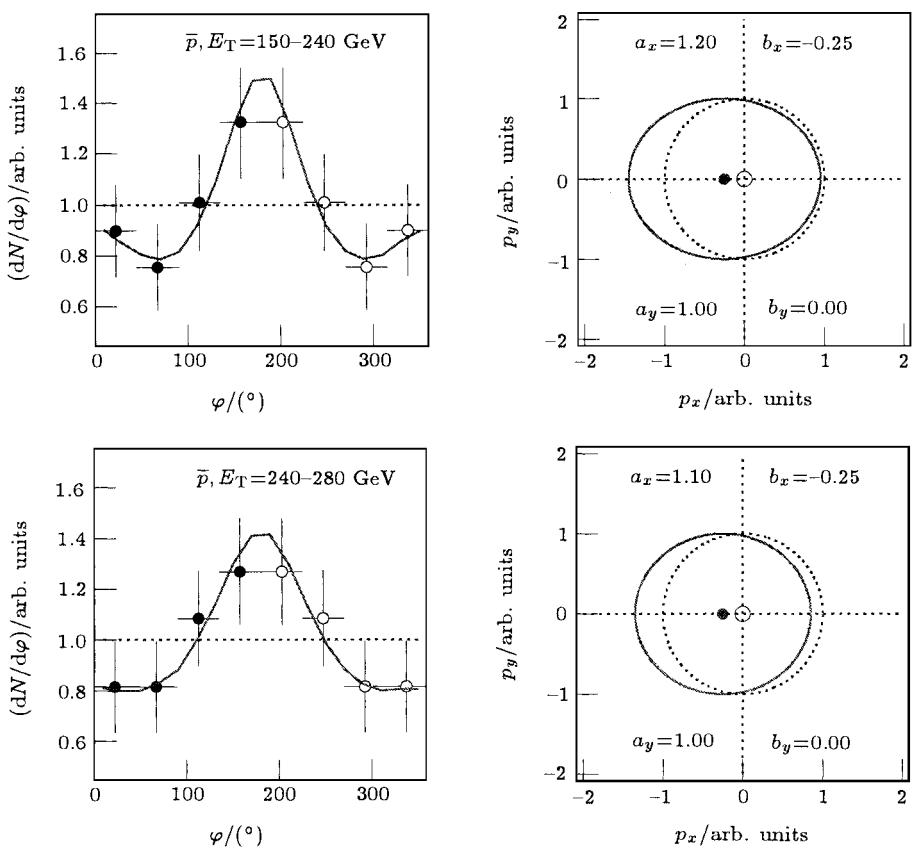


Fig.1. Left panel: Azimuthal distributions of antiprotons for different E_T bins in 11.5A GeV Au–Au collisions. The full circles denote the E877 experimental data and the open ones are reflected about $\phi = 180°$.[49] The solid and dotted curves show our calculated results using the Monte Carlo method. Right panel: Transverse structures of emission sources. The solid curve circles represent the emission sources in the p_x-p_y plane and correspond to the azimuthal distributions described by the solid curves in the left panel. The dotted curve circles represent the normal isotropic source.

The proton (p) azimuthal distributions measured in different rapidity ($y_{\rm cm}$) windows in the centre-of-mass system in 2A GeV Au–Au collisions are shown in the left panel of Fig.2. The circles denote the experimental data of the E895 Collaboration[50] and the curves show our calculated results using the Monte Carlo method. Corresponding to the continuous curves, the parameter values in Eq.(5) are given in the right panel of Fig.2. The values of χ^2/dof for the fits of the solid curves in the left panel from upper to bottom are 0.075 and 0.040 respectively. The physical meanings of curves and circles in the right panel in Fig.2 are the same as those in Fig.1. One can see an expansion of the source along the y direction and a movement of the source along the negative (upper) and positive (bottom) x directions respectively.

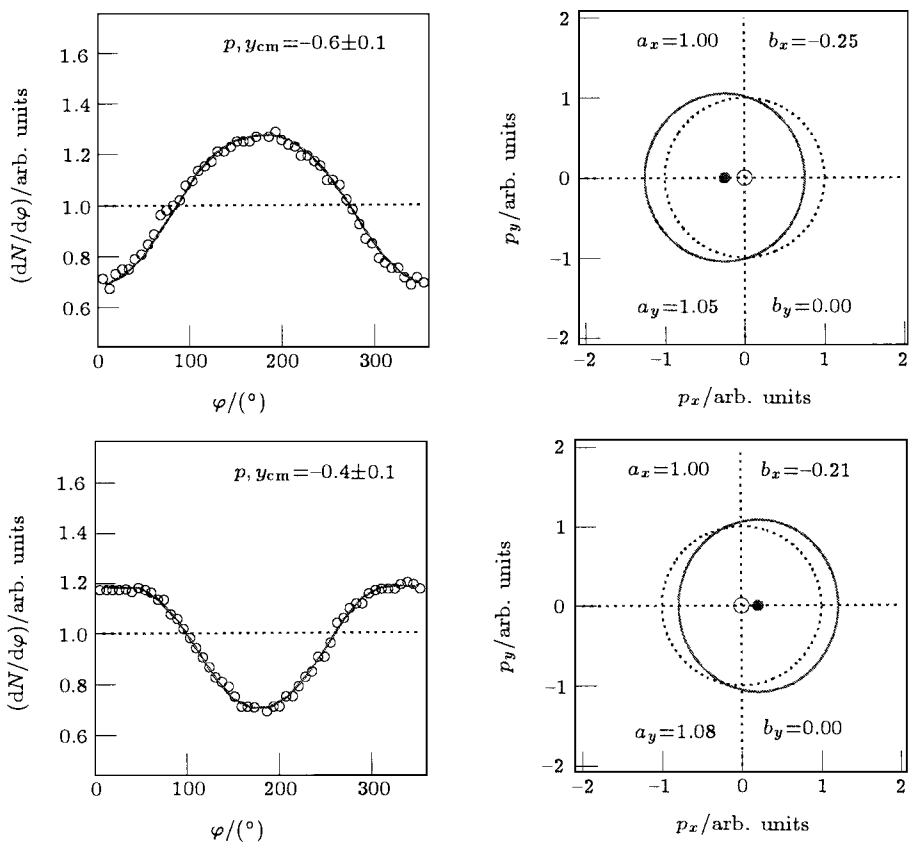


Fig.2. Left panel: Azimuthal distributions of protons in different rapidity windows in 2A GeV Au–Au collisions. The open circles denote the E895 experimental data.[50] The solid and dotted curves show our calculated results using the Monte Carlo method. Right panel: Transverse structures of emission sources. The solid curve circles represent the emission sources in the p_x–p_y plane and correspond to the azimuthal distributions described by the solid curves in the left panel. The dotted curve circles represent the normal isotropic source.

The left panel of Fig.3 shows the azimuthal distributions of projectile fragments with charge $Z \geq 2$ in 10.6A GeV Au–emulsion and 160A GeV Pb–emulsion collisions. The circles represent the E875 and EMU11 experimental data[51] and the curves indicate our calculated results using the Monte Carlo method. Corresponding to the solid curves, the parameter values in Eq.(5) are given in the right panel of Fig.3. The values of χ^2/dof for the fits of the solid curves in the left panel are 0.087 and 0.322, respectively. The physical meanings of curves and circles in the right panel in Fig.3 are the same as those in Fig.1. For 10.6A GeV Au–emulsion collisions, an expansion of the source along the x direction and a movement of the source along the positive x direction are observed in the azimuthal distribution of projectile fragments with charge $Z \geq 2$. For 160A GeV Pb–emulsion collisions, an expansion of the source along the x direction and a movement of the source along the negative x direction are observed in a similar distribution.

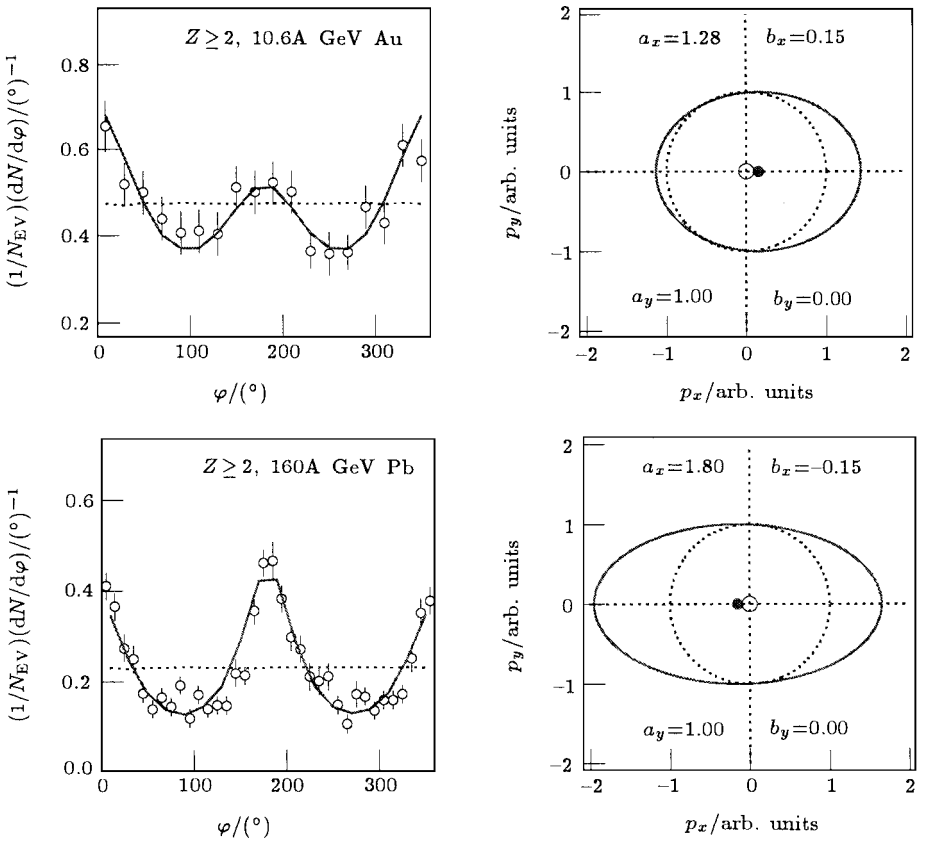


Fig.3. Left panel: Azimuthal distributions of projectile fragments with charge $Z \geq 2$ in 10.6A GeV Au–emulsion (upper panel) and 160A GeV Pb–emulsion (bottom panel) collisions. The open circles denote the E875 and EMU11 experimental data.[51] The solid and dotted curves show our calculated results using the Monte Carlo method. Right panel: transverse structures of emission sources. The solid curve circles represent the emission sources in the p_x–p_y plane and correspond to the azimuthal distributions described by the solid curves in the left panel. The dotted curve circles represent the normal isotropic source.

The azimuthal distributions of grey fragments produced in 4.5A GeV Mg–emulsion collisions are shown in the left panel of Fig.4, where the grey fragments are slow protons produced in cascade collisions in target nuclei. The circles represent the experimental data quoted from Ref.[52] and show events with different multiplicities (N_h) of target fragments. The curves indicate our calculated results using the Monte Carlo method. Corresponding to the solid curves, the parameter values in Eq.(5) are given in the right panel of Fig.4. The values of χ^2/dof for the fits of the solid curves in the left panel are 0.289, 0.441, and 0.168, respectively. The physical meanings of curves and circles in the right panel in Fig.4 are the same as those in Fig.1. One can see an expansion of the source along the x direction and a movement of the source along the positive x direction for the events with $N_h \leq 7$, an expansion of the source along both the x and y directions and a movement of the source along both the positive x and y directions for the events with $8 \leq N_h \leq 27$, and an expansion of the source along both the x and y directions and a movement of the source along the positive y direction for the events with $N_h \geq 28$.

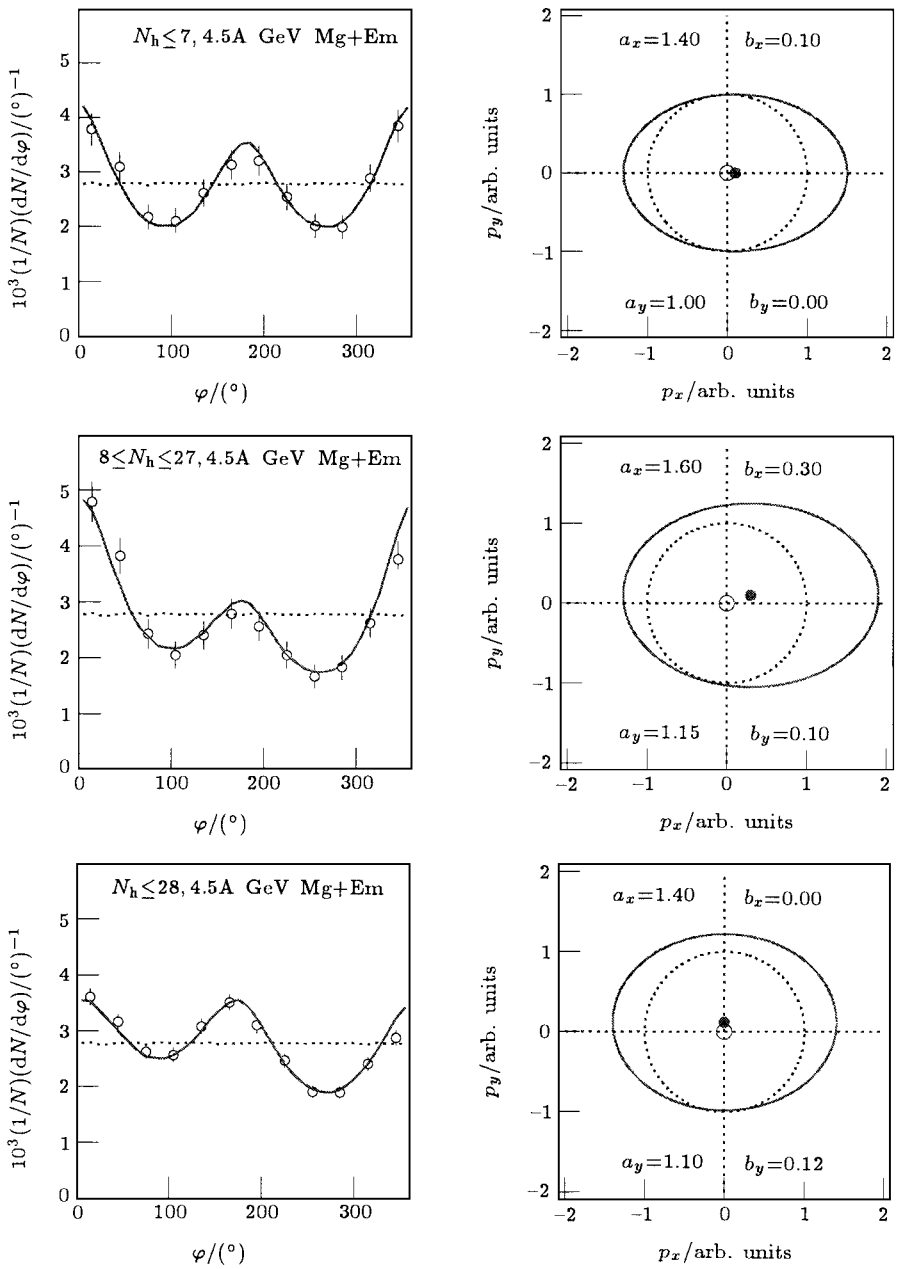


Fig.4. Left panel: Azimuthal distributions of grey fragments in different multiplicity ranges of target fragments in 4.5A GeV Mg–emulsion collisions. The open circles denote the experimental data quoted form Ref.[52]. The solid and dotted curves show our calculated results using the Monte Carlo method. Right panel: transverse structures of emission sources. The solid curve circles represent the emission sources in the p_x–p_y plane and correspond to the azimuthal distributions described by the solid curves in the left panel. The dotted curve circles represent the normal isotropic source.

To see the characteristics of Eq.(5), we plot three results of the azimuthal distribution that are described by different parameter values in the left panel of Fig.5 by the solid curves. The parameter values are given in Fig.5. The solid curve circles in the right panel of Fig.5 show the expansion and movement of emission source in the p_x–p_y plane and the small full circles denote their centers. The dotted curve circles represent the original emission sources in the p_x–p_y plane and the small open circles denote their centers. Corresponding to the solid and dotted curve circles in the right panel, the azimuthal distributions are given by the continuous and dotted curves in the left panel respectively. Figure 5 has only three examples of the results of Eq.(5). In fact, different parameter values give different azimuthal distributions. It is expected that Eq.(5) will describe many more complex structures.

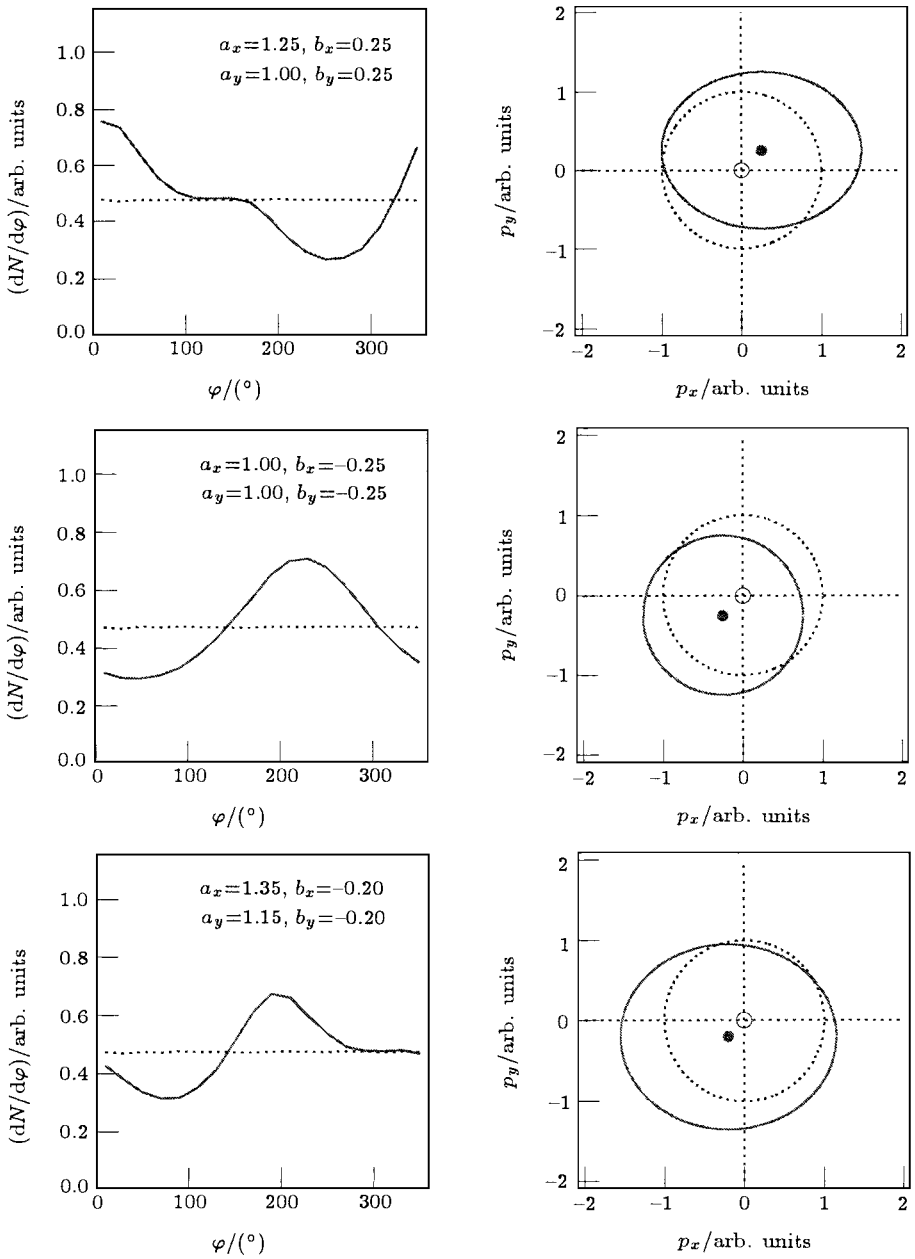


Fig.5. Left panel: Three examples of the azimuthal distribution described by Eq.(5). Right panel: transverse structures of emission sources. The solid curve circles represent the emission sources in the p_x–p_y plane and correspond to the azimuthal distributions described by the continuous curves in the left panel.

4. Discussion and conclusion

The meanings of the physical parameters are obviously explained in terms of the transverse structure of the source in high-energy nucleus–nucleus collisions. $a_x(a_y) > 1$ means that there is an expansion of the source along the $x(y)$ direction. $b_x(b_y) > 0$ and $b_x(b_y) < 0$ mean that there is a movement of the source along the positive and negative $x(y)$ directions respectively, and $b_x(b_y) = 0$ means that there is no movement along the $x(y)$ direction. The expansion and movement of the source are caused by the asymmetry in mechanics.

The parameters discussed above are related to the elliptic flow ($v_2 = \langle\cos(2\phi)\rangle$) and the directed flow ($v_1 = \langle\cos\phi\rangle$). The elliptic flow is a flow describing the expansion of the source in two opposite directions in the momentum space. The directed flow is a flow describing the movement of the source in a given direction in the momentum space. Because $a_x(a_y)$ describes the expansion of the source and $b_x(b_y)$ describes the movement of the source, we would like to say that $a_x(a_y)$ is a measure of the elliptic flow and

$b_x(b_y)$ is a measure of the directed flow.

The normal values of $a_x(a_y)$ and $b_x(b_y)$ are 1 and 0 respectively. $a_x(a_y) \neq 1$ (in fact $a_x(a_y) > 1$) means that there is an elliptic flow, and $b_x(b_y) \neq 0$ means that there is a directed flow. $a_x(a_y) = 1$ means that there is no elliptic flow, while $b_x(b_y) = 0$ means that there is no directed flow. A positive (in-plane) elliptic flow corresponds to $a_x > a_y \geq 1$, while a negative (out-of-plane) elliptic flow corresponds to $a_y > a_x \geq 1$. If $b_x(b_y) > 0$, there is a positive directed flow. If $b_x(b_y) < 0$, there is a negative directed flow. If $a_x(a_y) > 1$ and $b_x(b_y) \neq 0$, there is a mixture of an elliptic flow and a directed flow. For the case of distributions symmetrical with respect to the reaction plane which appears effectively most of the time and for which we have $a_y = 1$ and $b_y = 0$, only two parameters a_x and b_x are needed to describe the experimental data.

According to the above discussions, we would like to say that a mixture of a positive elliptic flow and a negative directed flow in the x direction is observed in azimuthal distributions of antiprotons for different E_{T} bins in 11.5A GeV Au–Au collisions (Fig.1). A mixture of a negative elliptic flow and a negative (positive) directed flow in the x direction is observed in azimuthal distributions of protons in rapidity window $y_{\mathrm{cm}} = -0.6 \pm 0.1$ ($y_{\mathrm{cm}} = 0.4 \pm 0.1$) in 2A GeV Au–Au collisions (Fig.2). For the upper (bottom) panel of Fig.3, we observe a mixture of a positive elliptic flow and a positive (negative) directed flow in the x direction. The situation of Fig.4 is more complex: all three panels show a positive elliptic flow; the upper panel shows a positive directed flow in the x direction, the bottom panel shows a positive directed flow in the y direction, while the middle panel shows a positive directed flow in both the x and the y directions.

To conclude, we have investigated the azimuthal distributions of final-state particles and fragments produced in high-energy nucleus–nucleus collisions. A modified multisource ideal gas model which contains the expansions and movements of the source gives a good description of the experimental data concerned. The formula obtained in the model does not give the azimuthal distribution directly, but the value of azimuthal angle. The azimuthal distribution can be obtained by the statistical method. It is known that the azimuthal distribution partly reflects the thermal properties of the interacting system. Our model shows that the normal isotropic thermal spectrum has an expansion and a movement. The formula is not related to the degree of excitation of the emission source, but it is based on the local equilibrium assumption.

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