Relative Space-Time Asymmetries in Pion and Nucleon Production in Noncentral Nucleus-Nucleus Collisions at High Energies

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(Received 2 September 1997)

We propose the use of ratios of the pion-proton correlation functions evaluated under different conditions to study the relative space-time asymmetries in pion and proton emission (pion and nucleon source relative shifts) in high energy heavy ion collisions. We address the question of the noncentral collisions, where the sources can be shifted spatially relative to each other both in the longitudinal and in the transverse directions in the reaction plane. We use the RQMD event generator to illustrate the effect and the technique. [S0031-9007(97)04801-1]

PACS numbers: 25.75.Gz, 24.10.Lx

The importance of the study of the space-time structure of particle emission in heavy ion collisions has been emphasized repeatedly. In general the question of the corresponding measurements splits into two: measurements of the extent (size) of the emission zone for each particular particle species and the measurement of the relative location of the sources of different particles. Measurements of the size of the effective source could be addressed in principle by two (identical) particle interferometry. At present, particle sources are studied intensively by this method both in elementary particle and heavy ion collisions [1–3]. On the other hand, the question of the relative space and time asymmetry in the production of different particles (source shifts) remains almost unexplored, although this question is very important for an interpretation of the experimental data within different models (for example, the ones which require particle thermalization, chemical equilibration, etc.).

An important first step in the investigation of source shifts in space and time was done in Ref. [4], where nonidentical particle correlation functions were proposed as a tool for the study of time delays in the emission of different particle species. This observation was based on analytical calculations [5,6] of the final state interaction contribution to the correlation function. Recently, a more detailed investigation of the possibilities provided by the correlations of nonidentical particles to study asymmetries in particle production in relativistic heavy ion collisions was attempted [7].

Here, we use the $\pi^{\pm}p$ correlations to study asymmetries in the pion and nucleon (proton) production in noncentral nucleus-nucleus collisions at high energies. To be specific, we investigate particle production in the rapidity region close to the projectile rapidity in Au + Au collisions at AGS energies. We select the rapidity region where proton directed flow is most pronounced [8], and where it is natural to expect that proton and pion sources could be shifted relative to each other not only in the longitudinal (z) direction but also in the flow direction (along or opposite to the impact parameter vector; $+x$ or $-x$ directions, below).

Two-pion interferometry of noncentral collision and its relation to anisotropic flow was addressed earlier in [9]. In particular, it was noted that the pion source looks different from different directions with respect to the reaction plane angle, in part due to the fact that the pion source is screened by nucleons in the direction of nucleon flow. This implies that the pion source is effectively shifted with respect to the proton source. This observation was supported [9] by the analysis of the pion source shape in RQMD generated events. Recent experimental results on anisotropic flow of pions and nucleons [8] confirm this picture. The observed flow of protons and pions looks very different, and this difference agrees with the assumption of pion screening by nucleons. More importantly, pions of different charge at very low transverse momenta flow in the opposite directions. This fact is naturally explaned by a Coulomb interaction with the protons, assuming that the pion and proton sources are shifted in space. In the current paper we show how such shifts could be detected and measured experimentally using pion-proton correlations, determined mainly by two-particle final state interactions.

Referring for the quantitative description of final state interaction contributions to the correlation function to the original papers [4–7,10–12], here we discuss it qualitatively. Such a discussion will help us explain and justify the techniques used below.

Any two-particle (both identical and nonidentical) correlation function is mainly sensitive to the distance between particles at the moment when the second particle is produced. (Here and in the discussion below we mean particles at freeze-out, that is at the point of last interaction.) Such a separation can be written as

$$\tilde{\mathbf{r}}_{12} \approx (\mathbf{r}_1 - \mathbf{r}_2) - \mathbf{V}(t_1 - t_2), \qquad (1)$$

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where we introduce the notations $\mathbf{r}$, t for the space and time position of particle production, and $\mathbf{V} = (\mathbf{p}_1 + \mathbf{p}_2)/(E_1 + E_2)$ for the pair velocity. The difference between identical and nonidentical particle correlations (except quantum statistics effects, which are not essential for the current study) comes from the fact that the correlation function in the case of nonidentical particles in general depends on the orientation of the relative velocity $\mathbf{v} \equiv \mathbf{p}_1/E_1 - \mathbf{p}_2/E_2$ (that is, the correlation function is different for the cases of $\mathbf{v}$ and $-\mathbf{v}$), while for identical particles such a dependence is averaged out due to the symmetry of the system.

The dependence of the nonidentical two-particle correlation function on the relative velocity becomes clear if one recollects that nonidentical two-particle correlations are mostly due to two body interactions in the final state. The impact of the two body final state interaction obviously is different for particles (at the instant of both of them are created) moving, in the particle pair rest frame, toward each other or moving in the opposite directions. If the centers of the effective sources of two-particle species are shifted, then the dependence of the correlation function on the orientation of the relative velocity with respect to the shift becomes obvious. Suppose that particles of type "2" are produced on average at $z_2 > z_1$ (for simplicity assume also that $t_2 \approx t_1$). Then, selecting the pairs with $v_{1,z} > v_{2,z}$ one would select the pairs which move on average toward each other (in the pair rest frame) and the corresponding final state interaction would be stronger. (In this simplified consideration we neglect possible differences between particle velocities at the moment of production and the measured ones). Depending on the type of final state interaction the correlation function would decrease or increase. Studying the orientation of the relative velocity to which the correlation function is the most sensitive one could find the orientation of the shift in space.

It is natural to study the two nonidentical particle ($\pi^\pm p$) correlations in the pair rest frame and as a function of $\mathbf{k}^*$, half of the particle relative momentum in this system ($\mathbf{k}^* = \mathbf{p}_\pi = -\mathbf{p}_p$). In the region of small values of k^* (much less than the inverse size of the particle source) the final state interaction of two charged particles is dominated by the Coulomb interaction. In this case the correlation function can be written in analytical form [5,10–12], which makes it possible to estimate the ratio of the correlation functions evaluated under different conditions. If we denote the correlation functions for two different cases, for example, $k_i^* > 0$ and $k_i^* < 0$, as $R_i^{(+)}$ and $R_i^{(-)}$, then in the limit of small k^* [7],

$$\frac{R_i^{(+)}}{R_i^{(-)}} \approx \frac{a + 2\langle r^* \rangle + 2\langle \mathbf{r}^*\mathbf{k}^*/k^* \rangle^{(+)}}{a + 2\langle r^* \rangle + 2\langle \mathbf{r}^*\mathbf{k}^*/k^* \rangle^{(-)}} \approx \frac{1 + 2\langle \mathbf{r}^* \rangle \langle \mathbf{k}^*/k^* \rangle^{(+)}/a}{1 + 2\langle \mathbf{r}^* \rangle \langle \mathbf{k}^*/k^* \rangle^{(-)}/a} \approx 1 + 2\langle \mathbf{r}^* \rangle_i/a\,, \quad (2)$$

where a is the Bohr radius (for the $\pi^\pm p$ system $a \approx \pm 222$ fm) and $\mathbf{r}^*$ is the relative separation in particle production points. Then, $\langle \mathbf{r}^* \rangle$ is the shift between sources in the pair rest frame, the quantity of interest. It should be mentioned, that in the derivation of Eq. (2) it is assumed that $\langle r^* \rangle \ll |a|$, and that $|\mathrm{Re}\, f| \ll |a|$, where f is the strong s-wave pion-proton scattering amplitude. [The correlation function then reduces (see, for example, Eqs. (1) and (5) in [4]) to: $R = A_c(\eta) \times \langle |F(-i\eta, 1, i\rho)|^2 \rangle$, where $A_c(\eta) = 2\pi\eta/[\exp(2\pi\eta) - 1]$ is the modulus squared of the nonrelativistic Coulomb wave function at the origin, $F(\alpha, 1, z) = 1 + \alpha z + \alpha(\alpha + 1)(z/2!)^2 + \dots$ is the confluent hypergeometrical function, $\eta = 1/(k^* a)$ and $\rho = k^* r^* + \mathbf{k}^*\mathbf{r}^*$. Equation (2) immediately follows from the substitution, in the considered limit, of the confluent hypergeometrical function with its linear approximation: $F \to 1 + \rho\eta = 1 + (k^* r^* + \mathbf{k}^*\mathbf{r}^*)/(k^* a)$.] The average in formula (2) is taken over all pairs from the corresponding subsample. It was also used that in the limit of $k^* \ll \langle p_t \rangle$, $\langle \mathbf{r}^* \rangle \langle \mathbf{k}^*/k^* \rangle^{(\pm)} = \pm\langle \mathbf{r}^* \rangle_i/2$ for the above defined cuts on k_i^*.

For the current study we use the RQMD v1.08 [13] event generator to simulate Au+Au collision at 11.4 GeV/nucleon. We select *particles* in the rapidity region $2.8 < y_{\mathrm{lab}} < 3.2$ and within a relatively narrow sector in azimuthal space, such that $p_x > 0$ and $|p_y/p_x| < 0.5$. We create two event subsamples in accordance with the orientation of the reaction plane: "$\Psi_r = 0$" (in this case nucleons flow in the positive x direction) and "$\Psi_r = \pi$" subsamples. The relative shifts between pion and proton sources for both cases are presented in Table I as calculated both in the center of mass system of colliding nuclei and in the particle pair rest frame. In the RQMD generated events we observe strong momentum-position correlations in particle production (especially for pions); the values presented in the table correspond to the average of the production points over the particles which contribute to the pairs with $k^* < 15$ MeV. This restriction limits significantly the effective transverse momentum range of pions, decreasing its average value in the sample. For both subsamples the average components of the pair velocity in the center

TABLE I. The mean values of spatial and temporal shifts (in fm) of pion and proton sources for two different orientations of the reaction plane in the center of mass frame of the colliding nuclei (upper half) and in the pair rest frame (lower half).

	$\langle x_\pi - x_p \rangle$	$\langle y_\pi - y_p \rangle$	$\langle z_\pi - z_p \rangle$	$\langle t_\pi - t_p \rangle$
$\Psi_r = 0$	−4.7	0.1	−8.3	−3.7
$\Psi_r = \pi$	1.5	0.1	−7.1	−2.8

	$\langle x_\pi^* - x_p^* \rangle$	$\langle y_\pi^* - y_p^* \rangle$	$\langle z_\pi^* - z_p^* \rangle$	$\langle t_\pi^* - t_p^* \rangle$
$\Psi_r = 0$	−5.8	0.1	−12.3	10.3
$\Psi_r = \pi$	0.9	0.2	−10.5	8.3

of mass system of colliding nuclei are $V_z \approx 0.89$ and $V_x \approx 0.17$.

We analyze approximately 200×10^3 pairs in each of the subsamples, the typical statistics for modern experiments. Our goal is to show the sensitivity of the πp correlation function to the shifts presented in Table I.

Below we consider only the $\pi^+ p$ correlation function (which *decreases* with the strength of the interaction), the results for $\pi^- p$ case would be very similar taking into account the change in sign of the Coulomb interaction, which dominates at low values of the particle relative velocity. The correlation functions are evaluated by weighting the simulated particle pairs with the modulus squared of the two-particle wave function $\psi^S_{-\mathbf{k}^*}(\mathbf{r}^*)$ averaged over the spin S of the pair. [Note that the two-particle amplitude $\psi^S_{-\mathbf{k}^*}(\mathbf{r}^*)$ is often substituted by the usual wave function $\psi^S_{\mathbf{k}^*}(\mathbf{r}^*)$ (see, for example [2,11]). This substitution is of no importance for identical particles or in the case of a symmetric distribution of the relative coordinates $\mathbf{r}^*$. However, it may be seen from Eq. (2) that it would lead to the incorrect sign of the asymmetry contribution in the ratio R_i^+/R_i^-.] The corresponding wave functions are calculated in accordance with the Lednicky-Lyuboshitz [5] formulas taking into account both the Coulomb as well as the strong interaction in the final state. In Fig. 1 we show the correlation functions calculated for the "$\Psi_r = 0$" event subsample for two sets of cuts $k_x^* > 0$ ($k_x^* < 0$) and $k_z^* > 0$ ($k_z^* < 0$). Note that these cuts approximately correspond to the cuts in the laboratory system $v_{\pi,x} > v_{p,x}$ ($v_{\pi,x} < v_{p,x}$) and $v_{\pi,z} > v_{p,z}$ ($v_{\pi,z} < v_{p,z}$), respectively. The correspondence would be strict if one selected the coordinate system with one of the axes parallel to the pair velocity. The ratios of the correlation functions are also shown in the same figure. One can see that the correlations are stronger in the cases of $k_z^* > 0$ and $k_x^* > 0$, which clearly indicates that the proton source is shifted relative to the pion source to positive z^* and positive x^* values. The magnitude of the difference in the cases of cuts on k_z^* and k_x^* shows that the shift in z direction is larger than the one in x direction.

In Fig. 2 we show the analogous plots for the "$\Psi_r = \pi$" subsample. Note the difference in Figs. 1 and 2 concerning the cut on k_x^*. It reflects the fact that the relative shift between pion and proton sources has changed sign (and value), and the proton source is now to the "left" relative to the pion source. The change in the correlation function, from "k_x^*" cuts, although small in magnitude, is statistically significant; shown in Fig. 3 are the correlation functions on a different scale.

Qualitatively the results of the $\pi^+ p$ correlation analysis show unambiguously the correct relative location of pion and proton sources. Quantitatively the agreement with the approximate formula (2) is also very good. In accordance with (2), each one Fermi of the shift leads to a change of approximately 0.9% in the ratio of the corresponding correlation functions at small values of k^*. From Table I one would expect the following values for the ratios of the correlation functions at small values of k^*: in the case of "$\Psi_r = 0$" the ratio $R_z^{(-)}/R_z^{(+)} \approx 1.11$ and $R_x^{(-)}/R_x^{(+)} \approx 1.05$; in the case of "$\Psi_r = \pi$", $R_z^{(-)}/R_z^{(+)} \approx 1.09$ and $R_x^{(-)}/R_x^{(+)} \approx 0.99$. The correlation function ratios shown in Figs. 1–3 agree with these numbers quite well.

In the current paper we have analyzed the correlation function in the particle pair rest frame. The source shifts extracted are those in this frame. Although, in principle, the correlation function is sensitive to the time shift between the sources [5,6] in this system, the sensitivity is very weak and can be neglected under the condition of $|t^*| \ll \mu r^{*2}$ (μ is the reduced mass). Physically, one of the reasons for this is the very small particle relative velocity in this frame $\mathbf{v}^* \approx \mathbf{k}^*/\mu$; the relative space separation between particles changes on average very little during the time $\Delta t = t^*$ provided that $k^*/\mu|\Delta t| \ll |\langle \mathbf{r}^* \rangle|$.

If one considers space and time shifts in the laboratory system (or in the center of mass of the colliding nuclei system) then the correlation function depends on all four shifts, but all four of them cannot be extracted from three possibly measured ratios of the correlation functions, exactly the same problem observed in two-

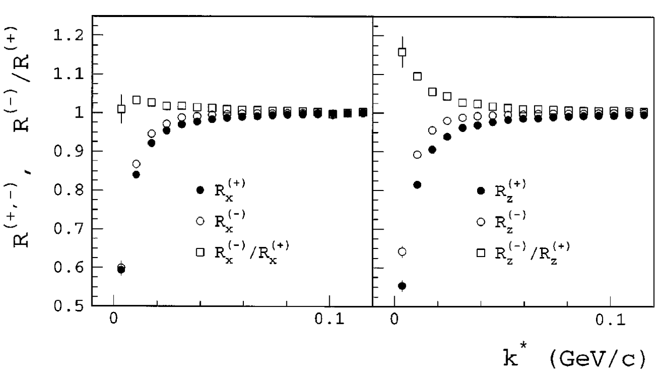

FIG. 1. The correlation functions $R^{(+)}_{x,z}$ ($k^*_{x,z} > 0$) and $R^{(-)}_{x,z}$ ($k^*_{x,z} < 0$) for the event subsample "$\Psi_r = 0$".

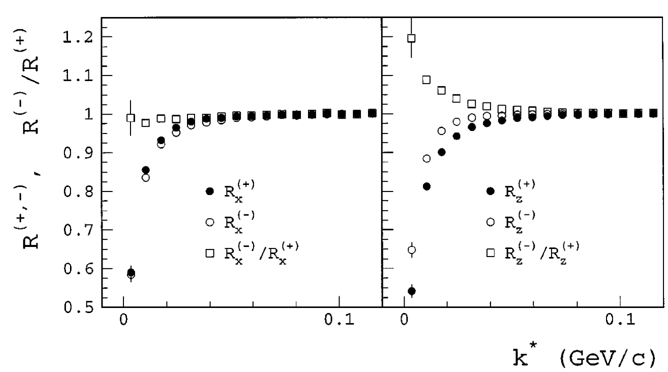

FIG. 2. The same as Fig. 1 for the event subsample "$\Psi_r = \pi$".

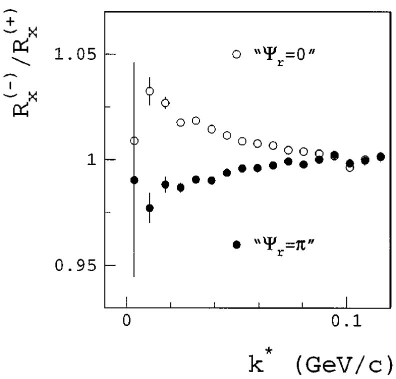

FIG. 3. The ratios of the correlation function $R_x^{(-)}$ and $R_x^{(+)}$ for two event subsamples "$\Psi_r = 0$" and "$\Psi_r = \pi$".

particle interferometry. To extract all shifts in this case one needs to make additional assumptions, for example, that the shifts do not depend on the velocity of the pair. Such questions are beyond the scope of this publication.

We have shown that important information on the relative shifts between pion and proton sources can be obtained by comparing the πp correlation functions evaluated at different conditions. The good *quantitative* results achieved in the application of the method to the RQMD generated events give a hope that the same technique can be successfully applied to the data.

Two of the authors (S. V. and R. L.) wish to acknowledge the support and hospitality of the Nuclear Theory and the Relativistic Nuclear Collisions groups of the Nuclear Science Division of the Lawrence Berkeley National Laboratory during their visit to LBNL. This work was supported in part by the U.S. DOE Contract No. DE-AC03-76SF00098 and by GA AV Czech Republic, Grant No. A1010601.

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