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Absorption Correlation in Pion Interferometry Analyses

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The effect of absorption on the analyzed results of pion interferometry is studied. The removal of this effect is investigated using a VUU simulation. Data for collisions of 1.8 *A* GeV Ar+Pb at the Bevalac streamer chamber are analyzed. The spatial parameter of the source extracted from pion interferometry is less than the true value due to the absorption correlation. The effect of the absorption correlation can be eliminated by properly constructing the background.

Key words: pion interferometry, azimuthal distribution, absorption collection, correlation function.

1. INTRODUCTION

Bose-Einstein correlations among identical pions result in an enhancement of the correlation function in the region of small relative momentum. The fact that the enhancement is closely related to the space-time structure of the pion-emitting source is the basis of pion interferometry [1-4]. Pion interferometry has been extensively used to extract information on the space-time evolution and degree of coherence of the pion-emitting source, and on the dynamics of the reaction mechanism [5]. However, the complexity of heavy-ion collisions, arising from factors such as final state interactions, nuclear shadowing, and averaging over different impact parameters and event topologies, may obscure

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the interpretation of the analyzed results of pion interferometry [6]. It is necessary to understand these various factors, and correct them where appropriate, in order to obtain reliable information about the space-time structure of the pion-emitting source from pion interferometry.

Recently, a preferential emission of pions toward the lighter projectile side and anisotropy of the azimuthal distribution for pions over the whole region of rapidity in mass-asymmetric nucleus-nucleus collisions has been reported. It has been indicated that this mainly comes from the shadowing effect of the heavy target spectator [7-9]. The strong absorption of pions originally emitted towards the side of the heavy target spectator results in an increased probability to observe pions directed toward the lighter projectile. Consequently, a correlation independent of Bose-Einstein statistics is observed among the pions (called absorption correlation). Because the absorption correlation causes the momenta of pions in the final state to be correlated in addition to the Bose-Einstein symmetrization, the study of the following questions becomes very important. Can the absorption correlation affect the interpretation of the analyzed results of pion interferometry? How should the effect of absorption correlation on the analyzed results of pion interferometry be eliminated?

In this paper, we first briefly review the two-pion correlation function and experimental data for 1.8 A GeV Ar+Pb from the Bevalac streamer chamber. Then, the method to eliminate the effect of absorption correlation from pion interferometry for VUU simulations is proposed in Section 3. The data for 1.8 A GeV Ar+Pb from the Bevalac streamer chamber are analyzed in Section 4. Finally, the conclusions are given in Section 5.

2. TWO-PION CORRELATION FUNCTION

Bose-Einstein correlations exist among identical pions. Assuming that the emitting pion may be described by a plane wave function $\psi_p(x)$ and denoting the spatial distribution function of the pion-emitting source by $\rho(x)$, the two-pion correlation function takes the form [1,2]:

$$C(p_1,p_2) = \frac{\int d^4x d^4y \rho(x)\rho(y) \left| \psi_{p_1}(x)\psi_{p_2}(y) + \psi_{p_2}(x)\psi_{p_1}(y) \right|^2}{\int d^4x \rho(x)\psi^*_{p_1}(x)\psi_{p_1}(x) \int d^4y \rho(y)\psi^*_{p_2}(y)\psi_{p_2}(y)}$$

$$= 1 + \frac{|\tilde{\rho}(p_1,p_2)|^2}{\tilde{\rho}(p_1,p_1)\tilde{\rho}(p_2,p_2)}, \tag{1}$$

where $\tilde{\rho}(p_1, p_2) = \int \rho(x)\psi^*_{p1}(x)\psi_{p2}(x)d^4x$ is the Fourier transform of $\rho(x)$.

The functional form of the correlation function depends on the form of the source density distribution $\rho(x)$. Assuming that the source density is a Gaussian distribution, if the coherence of the source is taken into account, the two-pion correlation function can be written as [1-3]:

$$C(q,q_0) = 1 + \lambda \exp(-q^2R^2/2 - q_0^2\tau^2/2), \tag{2}$$

where q and q_0 are the relative momentum and relative energy of the pions; R and τ are the spatial parameter and the lifetime parameter of the source; λ is the coherence parameter.

In data analysis, the two-pion correlation function is defined as [2,3]:

$$C(p_1,p_2) = \kappa \frac{\mathrm{Cor}(p_1,p_2)}{Uncor(p_1,p_2)}, \tag{3}$$

where Cor(p_1,p_2) is the number of correlated-pion pairs constructed by selecting two negative pions from the same event; Uncor(p_1,p_2) is the number of background pion pairs constructed by selecting each pion in the pair from a different event with the same multiplicity, and κ is a normalization constant. Fitting the data given by Eq.(3) with the correlation function form of Eq.(2), the parameters of the source can be extracted.

The data sample for this investigation comes from a streamer chamber experiment at the Bevalac for central collisions of 1.8 A GeV Ar+Pb. The events selected by the trigger correspond, in a geometric picture, to central collisions with impact parameter less than 5.0 fm. A momentum cut ($p_{lab} \geq 100$ MeV/c) has been imposed to remove the effect of multiple scattering in the target, and possible electron contamination of the negative pion sample. After the kinematic selection, there are 3200 events with negative pion multiplicity $M_{\pi^-} \geq 2$. The average observed π^- multiplicity is 9.0 and the total number of correlated pion-pairs is 98500. Details of this experiment have been reported earlier [3]. Because the lifetime parameter in Eq.(2) is not sensitive in the interferometry analysis for our Bevalac streamer chamber data [3], we fix its value at $\tau = 0$.

3. ABSORPTION CORRELATION

In mass-asymmetric nucleus-nucleus collisions, the stronger absorption of pions at the side of heavy target spectator brings about the anisotropy of the azimuthal distribution of pions in the final state. The azimuthal distribution of the pions can be written as [8,9]:

$$\frac{dN}{d\phi} = A[1 + \xi \cos(\phi - \psi)], \tag{4}$$

where ϕ is the azimuthal angle of pions in the final state, ψ is the azimuth of the reaction plane, ξ is an asymmetric factor, and A is a normalization constant.

The anisotropic absorption of pions in the final state results in an increased probability to observe pions direeted toward the lighter projectile, and absorption correlation is observed among the pions. Gyulassy suggested [10] that such an absorption reduces the single-pion wave functions, $\psi_p(x)$, by a factor $f(p_i, \Theta_i, \phi_i - \psi)$, where Θ_i and ϕ_i are the polar angle and azimuthal angle of the momentum vector p_i for the i-th pion, and ψ is the azimuth of the reaction plane. Denoting the correlation function after introducing the factor $f(p_i, \Theta_i, \phi_i - \psi)$ by C_f, we can write

$$\begin{aligned} C_f(\boldsymbol{p}_1, \boldsymbol{p}_2) &= \frac{f^2(p_1,\theta_1,\phi_1 - \psi)f^2(p_2,\theta_2,\phi_2 - \psi)}{f^2(p_1,\theta_1,\phi_1 - \psi_1)f^2(p_2,\theta_2,\phi_2 - \psi_2)} C(\boldsymbol{p}_1, \boldsymbol{p}_2) \\ &= R(\boldsymbol{p}_1, \boldsymbol{p}_2)C(\boldsymbol{p}_1, \boldsymbol{p}_2), \end{aligned} \tag{5}$$

where ψ_i represents the azimuth of the reaction plane for the event from which the i-th pion in the background is selected. $R(p_1,p_2)$ is a correction factor, which reflects the absorption correlation among the pions in the final state. It can be seen from Eq.(5) that if the reaction planes are measured event-by-event and the events are rotated so that their reaction planes are parallel to each other, then $\psi = \phi_1 = \phi_2$ and $R(p_1,p_2) = 1$; then the influence of the absorption correlation on two-pion interferometry would be removed.

In the VUU model [11], the reaction plane is known *a priori*. The VUU data can be used to estimate the effect of the absorption correlation on the analyzed results from two-pion interferometry for 1.8 A GeV Ar+Pb collisions. The pions are treated as classical particles in the VUU model, and it is necessary to impose Bose-Einstein symmetry on the pions produced in VUU simulations to reflect that they are bosons for interferometry analyses. We record momenta of the final state pions and the space-time location where they were created. Using the method proposed by Humanic [12], correlated pion pairs are formed as follows. First each pion pair is randomly selected, and then weighted by the factor.

$$W(\boldsymbol{p}_1, \boldsymbol{p}_2) = |\psi_{\boldsymbol{p}_1}(x_1)\psi_{\boldsymbol{p}_2}(x_2) + \psi_{\boldsymbol{p}_1}(x_2)\psi_{\boldsymbol{p}_2}(x_1)|^2.$$

Table 1
The analyzed results of two-pion interferometry for VUU simulation of 1.8 A GeV Ar+Pb collisions.

	(a)			(b)		
	R(fm)	λ	$<r>$(fm)	R(fm)	λ	$<r>$(fm)
Soft	5.92±0.23	0.98±0.07	6.68±0.26	5.34±0.20	0.95±0.07	6.02±0.23
Hard	6.19±0.24	1.00±0.08	6.98±0.27	5.39±0.22	0.96±0.07	6.08±0.25

(a) is for the reaction planes parallel to each other, and (b) is for randomly rotating the reaction plane of each event about the beam direction.

The background pion pairs are constructed by the following two methods:

a) Each pion for constructing a background pion pair is randomly selected from a different VUU event, with all reaction planes parallel to each other. The pions in such a background sample have the same azimuthal distribution as in a sample of pion-pairs with the absorption correlation present.

b) We rotate each VUU event about the beam direction through a random angle so that the azimuthal distribution of their reaction planes is uniform. Each pion constructing a background pion pair is selected from a different event so that the background is similar to that used in the previous experimental analyses of pion interferometry.

Table 1 shows the analyzed results from two-pion interferometry for "soft" and "hard" VUU simulations for 1.8 A GeV Ar+Pb collisions. The number of correlated pion pairs is 6×10^5, which is 6 times the statistics number for our Bevalac streamer chamber data. The number of background pairs is about 20 times that of the correlated pairs, and the form of correlation function used for analyses is Eq.(2).

Because the extracted spatial parameter from two-pion interferometry reflects the average radius of the pion source [4], we list the fitted spatial parameter R and the corresponding average radius $<r>$ in Table 1. On the other hand, the average radius of the source is directly calculated from the VUU model, which for "soft" and "hard" VUU simulations are 6.65±0.06 fm and 6.95±0.06 fm respectively. It can be seen that the average radius of the source obtained from two-pion interferometry with the reaction planes aligned parallel is consistent with the directly-calculated average radius within statistical errors, and the effect of the absorption correlation is removed. It also can be seen that the absorption correlations decrease the extracted spatial parameter of the source from the usual two-pion interferometry analyses, and the deviation is about 5%. The influence of the absorption correlation on the coherence parameter is negligible at the present level of statistical accuracy.

4. ANALYSES OF DATA SAMPLE

In data analyses, the reaction plane for an event can be estimated from the transverse momenta of nucleons emitted in the collision [13]. For the data sample of 1.8 A GeV Ar+Pb collisions at the Bevalac streamer chamber, in which only negative pions have been measured, the average observed π^- multiplicity is 9. There is a large dispersion between the estimated reaction plane and the true one if the estimated of reaction plane is made only by using the transverse momenta of pions. It has been demonstrated [8,14] that the reaction plane for an event may be estimated from the transverse momenta of pions only if the negative pion multiplicity $M_{\pi^-} > 9$. Therefore, it is difficult to eliminate the effect of absorption correlation for this experimental data sample by the method of rotating the events to align their estimated reaction planes parallel to each other.

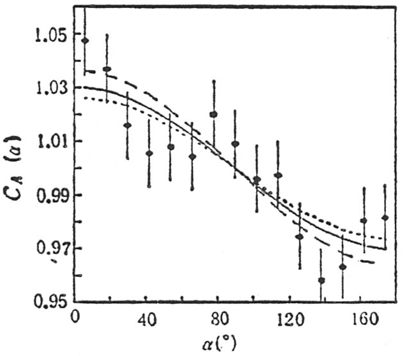

Fig. 1
Azimuthal correlation function $C_A(\alpha)$ for the observed collisions of 1.8 *A* GeV Ar+Pb (solid line) and for "soft" (dotted line) and "hard" (dashed line) VUU simulations.

Constructing the background sample after aligning the reaction planes parallel corresponds to rotating the azimuthal angle of each pion in the background sample to achieve the same asymmetric azimuthal distribution of pions as that of pions in the experimental data sample. Therefore, if the azimuthal distribution of pions in the experimental data sample is known, a new background sample can be constructed by randomly rotating the azimuthal angle of each pion in the usual background according to this distribution so that the effect of the absorption correlations can be corrected without finding the reaction plane for each event. On the other hand, using the method of the azimuthal correlation function [8,15], the asymmetric factor ξ in Eq.(4) can be calculated and the azimuthal distribution of the pion in the final state can be determined without the measurement of the reaction plane for each event.

The azimuthal correlation function is defined as [8,15]:

$$C_A(\alpha) = \frac{P(\alpha)}{PM(\alpha)}. \tag{6}$$

where $P(\alpha)$ is the distribution probability of α, which is the angle between the transverse momenta of two pions in an event. $P(\alpha)$ can be obtained from Eq.(4):

$$P(\alpha) = A^2[1 + 0.5\xi^2\cos(\alpha)]; \tag{7}$$

$PM(\alpha)$ is the distribution probability of α for Monte Carlo events which are generated by randomly mixing pions from different events. Using Eq.(6) to analyze the experimental data for collisions of 1.8 *A* GeV Ar+Pb at the Bevalac streamer chamber and the "soft" and "hard" VUU simulations of the correspondent collisions, we obtain the results:

Figure 1 shows the fitted curves and the experimental data. The values of the asymmetry factor ξ are the same within statistical errors for the experimental data and for the "soft" and "hard" VUU simulations, which implies that the absorption is the main course of the preferential emission for the pions over the whole region of rapidity.

In pion interferometry analyses, the new background sample can be constructed as follows. First, each pion in a background pion-pair is randomly selected as usual from a different event with the same multiplicity. Then maintaining the magnitude and the polar angle of the momentum vector for each pion in the background unchanged, the azimuthal angle is randomly sampled according to the asymmetric azimuthal distribution of pions in the final state and is reassigned to each pion to form a new background pion-pair. Using such a background sample to analyze the VUU simulations, the results are:

$$\text{Soft } \xi = 0.23 \pm 0.02,$$
$$\text{Hard } \xi = 0.27 \pm 0.02,$$
$$\text{Exp. } \xi = 0.25 \pm 0.02.$$

The values for the source parameters are consistent with the calculated results in Table 1 in the case of the reaction planes aligned parallel within statistical errors, and the effect of the absorption correlation is removed.

For collisions of 1.8 A GeV Ar+Pb at the Bevalac streamer chamber, the fitted results from the usual method of two-pion interferometry are [3]

$$\text{Soft } R = 5.93 \pm 0.22 \text{ fm}, \quad \lambda = 1.01 \pm 0.07,$$
$$\text{Hard } R = 6.11 \pm 0.26 \text{ fm}, \quad \lambda = 0.97 \pm 0.08.$$

After removing the influence of the absorption correlation, the fitted results are

$$R = 5.53 \pm 0.38 \text{ fm}, \quad \lambda = 0.99 \pm 0.13,$$
$$R = 5.87 \pm 0.43 \text{ fm}, \quad \lambda = 1.02 \pm 0.15.$$

It can be seen that the influence of the absorption correlation is unobservable for our Bevalac streamer chamber data at the present level of experimental accuracy.

5. CONCLUSIONS

In relativistic mass-asymmetric nucleus-nucleus collisions, absorption correlation among the pions caused by the shadowing effect of the heavy target spectator results in that the extracted spatial parameter of the source from pion interferometry will be less than the true value. In order to obtain reliable information about the space-time structure of the source from pion interferometry, it is essential to eliminate the effect of the absorption correlation by choosing proper ways to construct the background sample. The new background sample can be constructed by the following two methods. One way is that the reaction plane for each event is determined at first, and then each pion in a background pion-pair is randomly selected from a different event after rotating the events to align their reaction planes parallel to each other. The alternative way to construct the background is that the azimuthal angle of momentum for each pion in the usual background is randomly reassigned according to the asymmetric azimuthal distribution of pions in the final state determined by the method of the azimuthal correlation function. The latter one does not depend on the measurement of the reaction planes and can be used to correct the influence of the absorption correlation when the reaction planes for events can not be determined or the dispersion of the estimated reaction planes is large. The analyses from the "soft" and "hard" VUU simulation and from experimental data at the Bevalac streamer chamber show that the spatial parameter of the source extracted from the usual analyses of pion interferometry is less than the true value due to the absorption correlation. The deviation is about 5% for collisions of 1.8 A GeV Ar+Pb. The influence of absorption correlation can not be detected for our Bevalac streamer chamber data at the present level of experimental accuracy. With increased statistics in the future experiments, it will be important to take the effect of various possible correlations besides the Bose-Einstein symmetrization into account for pion interferometry analyses to obtain the correct information about the space-time picture of the emitting source.

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