# Photon interferometry and size of the hot zone in relativistic heavy ion collisions

Jan-e Alam,[1] Bedangadas Mohanty,[1] Pradip Roy,[2] Sourav Sarkar,[1] and Bikash Sinha[1,2]
[1]*Variable Energy Cyclotron Centre, Kolkata 700064, India*
[2]*Saha Institute of Nuclear Physics, Kolkata 700064, India*
(Received 6 March 2003; published 22 May 2003)

The parameters obtained from the theoretical analysis of the single-photon spectra observed by the WA98 Collaboration at Super Proton Synchrotron (SPS) energies have been used to evaluate the two-photon correlation functions. The single-photon spectra and the two-photon correlations at relativistic heavy ion collider (RHIC) energies have also been evaluated, taking into account the effects of the possible spectral change of hadrons in a thermal bath. We find that the ratio $R_{side}/R_{out}\sim 1$ for SPS and $R_{side}/R_{out}<1$ for RHIC energy.

DOI: 10.1103/PhysRevC.67.054902 PACS number(s): 25.75.Gz, 12.38.Mh

## I. INTRODUCTION

Two-particle intensity interferometry along with the analysis of single-particle spectra has been widely used for a quantitative characterization of the hot zone created by the collision of two heavy ions at high energies. The method was first applied to measure the angular diameter of stars and other astronomical objects using the measurements based on two-photon correlations known as Hanbury Brown–Twiss (HBT) correlations [1]. Later in the field of particle physics, two-pion correlations were used to obtain the spatial extent of the fireball in proton-antiproton reactions [2]. In high energy heavy ion collisions, two-particle (e.g., pions, kaons, etc.) correlations have been extensively studied both experimentally [3–5] and theoretically [6,7] to obtain direct information about the size, shape, and dynamics of the source at freeze-out. This is usually done via selection of transverse momentum and rapidity of the correlated particles. Compared to two-particle correlation, the three-particle correlation has been shown to provide additional information on chaoticity and asymmetry of the source emission [8]. Recently, it has been argued that spatial separation between sources of different species can be extracted from nonidentical particle correlation functions, hence these can provide an independent cross-check of the transverse flow prescription [9]. One of the major limitations of carrying out the correlation studies with hadrons appearing at the final state is that the information about the possible early dense state of matter is diluted or lost through rescattering. Although, some calculations suggest that the ratio of the radius of the source along the direction of the total transverse momentum ($\vec{K}_T$) of the two detected particles to the source radius perpendicular to $\vec{K}_T$ and the beam direction, as a function of transverse momentum, can provide useful information [10]. However, the results at relativistic heavy ion collider (RHIC) where quark-gluon plasma (QGP) is expected to be formed are not encouraging for the above signal [4,5]. Investigations to understand the partonic effects on the interferometry with final state particles (pions) at RHIC [11] are being pursued. HBT interferometry as a sensitive probe of the QCD equation of state and hence formation of QGP has been discussed in Refs. [10–12]. It has been argued [13,14] that in contrast to hadrons, two-particle intensity interferometry of photons that are produced throughout the space-time evolution of the reaction and which suffer almost no interactions with the surrounding medium can provide information on the history of the evolution of the hot matter created in heavy ion collisions.

From the experimental point of view, photon interferometry encounters considerable difficulties compared to hadron interferometry due to small yield of direct photons from the early hot and dense region of the matter and the associated large background of photons, primarily from the electromagnetic decay processes of hadrons at freeze-out [15]. However, recent calculations demonstrate that it is still possible to experimentally filter out the correlations of photons from the hot and dense zone from those arising due to the residual correlations of decay photons. This can be done by studying photon interferometry as a function of invariant relative momentum of the two photons [16]. One expects the photons coming from the early stage of the reactions to contribute predominantly to the region of small invariant relative momentum.

The aim of the present work is to first analyze the single-photon spectra observed by the WA98 Collaboration [15] in Pb+Pb interactions at SPS energies. In the next step, we evaluate the two-photon correlations with the initial conditions, equation of states (EOS), and freeze-out conditions which reproduce the photon spectra mentioned above. The EOS used here [17] contains all hadrons upto mass $\sim$2.5 GeV [18]. The freeze-out conditions are fixed from the study of hadronic spectra measured by the NA49 Collaboration [19]. The effects of the possible spectral modifications of hadrons in a thermal bath on the single-photon spectra and two-photon correlations have been included. The results at RHIC energy for the single-photon distributions and two-photon correlations are also presented.

It is necessary to point out here that our calculation contains some significant improvements over the previous works [13,14]. The correlation function evaluated here (i) contains contributions from two-loop calculations of photon emission rate [20]; (ii) emission rate from hadronic matter contains in-medium effects; (iii) the EOS contains all hadronic degrees of freedom upto mass $\sim$2.5 GeV; and (iv) the initial conditions, freeze-out conditions, and the EOS reproduce the WA98 single-photon spectra [15] and NA49 hadronic spectra. Moreover, in Ref. [14] where the correct definition of the Bose-Einstein correlation (BEC) was used, the space-time evolution was only one dimensional.

The paper is organized as follows. In the following section we give a general discussion on the correlation function and the associated kinematics. This is followed by the section that deals with the space-time evolution. Section IV deals with the results. First we present the results for SPS energies. Then we discuss the single-photon spectra and two-photon correlations at RHIC energies. In Sec. V we summarize our findings.

## II. CORRELATION FUNCTION

The BEC function for two identical particles is defined as

$$C_2(\vec{k}_1,\vec{k}_2)=\frac{P_2(\vec{k}_1,\vec{k}_2)}{P_1(\vec{k}_1)P_1(\vec{k}_2)}, \tag{1}$$

where $\vec{k}_i$ is the three-momentum of the particle $i$ and $P_1(\vec{k}_i)$ and $P_2(\vec{k}_1,\vec{k}_2)$ represent the one- and two-particle inclusive photon spectra, respectively. These are defined as

$$P_1(\vec{k})=\int d^4x\,\omega(x,k) \tag{2}$$

and

$$P_2(\vec{k}_1,\vec{k}_2)=P_1(\vec{k}_1)P_1(\vec{k}_2)+\int d^4x_1 d^4x_2\,\omega(x_1,K)\,\omega(x_2,K)\cos(\Delta x^\mu \Delta k_\mu), \tag{3}$$

where $K=(k_1+k_2)/2$, $\Delta k_\mu=k_{1\mu}-k_{2\mu}=q_\mu$, $x$ and $k$ are the four-coordinates of position and momentum, respectively, and $\omega(x,k)$ is the source function, which defines the average number of particles with four-momentum $k$ emitted from a source element centered at the space-time point $x$. $\omega(x,k)$ is actually the thermal emission rate of photons per unit four volume. For the QGP phase at a temperature $T$, this is given by [21,22,20]

$$\omega(x,k)=\frac{5}{9}\frac{\alpha\alpha_s}{2\pi^2}T^2(x)e^{-k/T(x)}\left\{\ln\left[\frac{2.912k}{g^2T(x)}\right]+\frac{4(J_T-J_L)}{\pi^3}\left(\ln 2+\frac{k}{3T(x)}\right)\right\}, \tag{4}$$

where $\alpha=1/137$, $\alpha_s$ is the strong coupling constant, $J_T=4.45$, and $J_L=-4.26$. Note that $C_2$ is independent of the strong coupling constant. For photon emission from a hot hadronic gas, we have considered a host of reaction processes involving $\pi$, $\rho$, $\eta$, and $\omega$ mesons as well as from the decay of the $\rho$ and $\omega$ [21]. For the details on the evaluations of the photon emission rate from a hadronic gas we refer to Refs. [23,24]. The effects of the intermediary $a_1$ meson have also been considered in evaluating the photon emission rate [25,26].

We shall be presenting the results in terms of difference in rapidity ($\Delta y$) of the two photons, outward ($q_{out}$), sideward ($q_{side}$), and invariant momentum differences ($q_{inv}$) of the two photons, which are defined as

$$q_{out}=\frac{\vec{q}_T\cdot\vec{K}_T}{|K_T|}=\frac{(k_{1T}^2-k_{2T}^2)}{\sqrt{k_{1T}^2+k_{2T}^2+2k_{1T}k_{2T}\cos(\psi_1-\psi_2)}}, \tag{5}$$

$$q_{side}=\left|\vec{q}_T-q_{out}\frac{\vec{K}_T}{K_T}\right|=\frac{2k_{1T}k_{2T}\sqrt{1-\cos^2(\psi_1-\psi_2)}}{\sqrt{k_{1T}^2+k_{2T}^2+2k_{1T}k_{2T}\cos(\psi_1-\psi_2)}}, \tag{6}$$

$$q_{inv}=\sqrt{-2k_{1T}k_{2T}[\cosh(y_1-y_2)-\cos(\psi_1-\psi_2)]}, \tag{7}$$

where $\vec{q}_T=\vec{k}_{1T}-\vec{k}_{2T}$, $\vec{K}_T=(\vec{k}_{1T}+\vec{k}_{2T})/2$ with the subscript $T$ indicating the transverse component, $y_i$ is the rapidity, and $\psi_i$'s are the angles made by $k_{iT}$ with the $x$ axis. One also defines another kinematic variable $q_{long}$ as

$$q_{long}=k_{1z}-k_{2z}=k_{1T}\sinh(y_1)-k_{2T}\sinh(y_2). \tag{8}$$

It may be mentioned that the BEC function has values $1\leqslant C_2(\vec{k}_1,\vec{k}_2)\leqslant 2$ for a chaotic source. These bounds are from quantum statistics. While the radius corresponding to $q_{side}$ ($R_{side}$) is closely related to the transverse size of the system, the radius corresponding to $q_{out}$ ($R_{out}$) measures both the transverse size and duration of particle emission [6,7]. So studying $R_{side}/R_{out}$ will indicate the duration of particle emission [27–29]. These source dimensions can be obtained by parametrizing the calculated correlation function with the empirical Gaussian form

$$C_2=1+\exp(-R_{out}^2q_{out}^2-R_{side}^2q_{side}^2-R_{long}^2q_{long}^2)\,. \tag{9}$$

A gross idea of the source size can also be inferred from $R_{inv}$, which is defined as

$$C_2=1+\exp(-R_{inv}^2q_{inv}^2). \tag{10}$$

## III. SPACE-TIME EVOLUTION

To compare transverse momentum spectra of a photon with the experiments, we have to convolute the static emission rate [fixed temperature, e.g., given by Eq. (4)] by the space-time evolution from the formation to the freeze-out state. This is done solving the relativistic hydrodynamical equations in (3+1) dimensions [30] with boost invariance along the longitudinal direction [31]. One then needs to specify the following: the initial temperature and the time when the hot system reaches a state of thermodynamic equilibrium, the EOS that guides the rate of expansion/cooling, and the freeze-out temperature when the system decouples into free-streaming hadrons. We will not discuss here the details on the EOS, initial conditions, and the modification of the hadronic masses in a thermal bath because these topics had been discussed in our earlier works in great detail, which will be appropriately referred below. For SPS conditions we will assume a hot hadronic gas in the initial state with temperature dependent masses of the constituent hadrons, which expands and cools till freeze-out. The two-photon correlations at SPS energies will also be given for a possible phase transition scenario, i.e., when QGP is formed at the initial state. The EOS used here is given in Ref. [17]. The initial conditions are similar to Refs. [32,33]. The variation of hadronic masses (except pseudoscalar) with temperature follows universal scaling law proposed by Brown and Rho (BR) [34]. It is necessary to point out that a substantial amount of literature is devoted to the calculation of effective masses of hadrons in the medium. Our principal motivation for choosing the BR conjecture is that this has been used successfully to explain the WA98 photon spectra [32] and CERES/NA45 [35] low mass dilepton spectra [36,37]. For higher collision energies, i.e., at RHIC we will consider a situation where QGP is formed in the initial state, then the quark matter evolves with time to a hadronic phase via an intermediate mixed phase in a first order phase transition scenario. The mixed phase is a mixture of both quark matter and hadronic matter, with the fraction of quark matter decreasing with time to zero when the phase transition is complete. The hot hadronic gas then expands till the system freezes out. The initial condition for the SPS and RHIC energies in terms of the initial temperature ($T_i$) is set from the number of particles per unit rapidity at the midrapidity region for those energies according to the following equation:

$$T_i^3 = \frac{2\pi^4}{45\zeta(3)} \frac{1}{\pi R_A^2 \tau_i 4 a_k} \frac{dN}{dy}. \tag{11}$$

$a_k = \pi^2 g_k/90$ is determined by the statistical degeneracy ($g_k$) of the system formed after the collision. Taking the particle multiplicity per unit rapidity at midrapidity to be 700 for SPS, we get $T_i = 200$ MeV with the formation time ($\tau_i$) taken as 1.0 fm/$c$. With a multiplicity of 1100 for Au+Au collisions at RHIC, we get $T_i = 264$ MeV for an initial time of 0.6 fm/$c$ [38]. The critical temperature ($T_c$) is taken to be 170 MeV [39] here. The freeze-out temperature ($T_f$) is taken to be 120 MeV for both SPS and RHIC energies; a value that describes the transverse momentum distributions of hadrons produced [40]. Let us now turn to the EOS which plays a central role in the space-time evolution we have considered. For the hadronic phase, the EOS corresponds to that for the hadronic gas with particles of mass up to 2.5 GeV and includes the effects of nonzero widths of various mesonic and hadronic degrees of freedom [17]. The velocity of sound ($c_s^2$) corresponding to this EOS at freeze-out is about 0.18 [17] (the value corresponding to a free gas of massless particles being 0.33). We emphasize that the medium modifications of the constituent hadrons play a nontrivial role in the estimation of the quantities mentioned above. Of special interest is the velocity of sound and the estimation of the initial temperature for the hot hadronic gas considered at SPS. These have been exhaustively dealt with in a number of our earlier works [17,26,32,40] and we do not repeat them here. With these inputs we have performed a (3+1)-dimensional hydrodynamic expansion. The solution of the hydrodynamic equations has been used to evaluate the space-time integration involved in Eqs. (2) and (3).

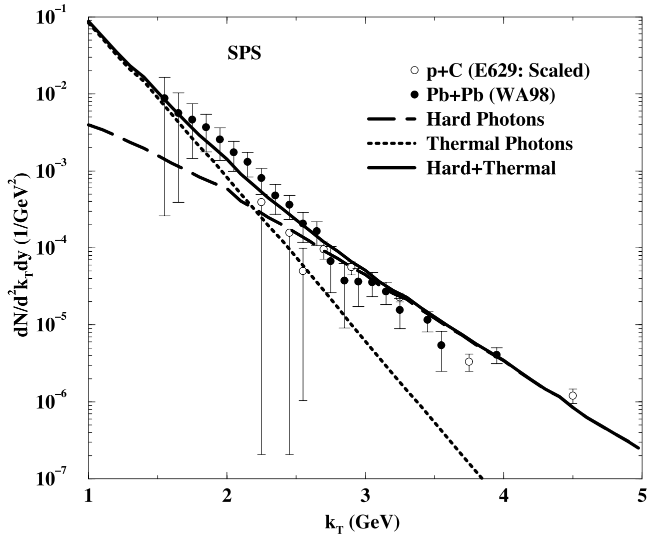


FIG. 1. Single-photon spectra at SPS.

## IV. RESULTS

In this section we present the results of two-photon interferometry. We shall first present the results for SPS energies and then give our predictions for RHIC. In both cases, we will first start with the single-photon spectra and then present the two-photon correlation as a function of $\Delta y$, $q_{out}$, $q_{side}$, and $q_{inv}$. At the SPS energies we present the two-photon correlation results using the inputs that reproduce the measured single-photon spectra [15], as mentioned before. For RHIC, our predictions are based on the same model as the one that explains the SPS data, but for different initial conditions as expected at RHIC energies.

Figure 1 shows the single-photon yield measured by the WA98 experiment at CERN SPS, as a function of transverse momentum. The contributions from hard scattering of partons (hard photons) and from a hot hadronic gas (thermal photons) have been shown separately. The hard photon contribution has been normalized to reproduce the scaled $p+C$ data [41] as well as the scaled $p$-$p$ data [42] ($p$-$p$ data are not shown here; please see Ref. [32]). The experimental results of the WA98 Collaboration show some "excess" photons over the hard photons for $1.5 \leq p_T(\mathrm{GeV}) < 2.5$ GeV, which we argue to originate from a thermal source either of QGP or hot hadronic gas of initial temperature 200 MeV (see also Refs. [32,33] for details). In the present work we have evaluated the thermal photon from a hot hadronic gas with its mass reduced according to the universal scaling scenario [34]. The combined result of hard and thermal photons is found to explain the data reasonably well.

From the expressions given in Eqs. (5)–(7), one can see that several combinations can be made in the variables $y$, $\psi$, and $k_T$ to present the results for two-photon correlation. For simplicity, we will present all two-photon correlation results for direct photons with momentum around 2 GeV/$c$, since it lies in the range of momentum where excess direct photons have been observed at the SPS energies. We take $\psi_2 = 0$ and $y_2 = 0$ for all cases. We vary $\psi_1$ and $y_1$ wherever necessary.

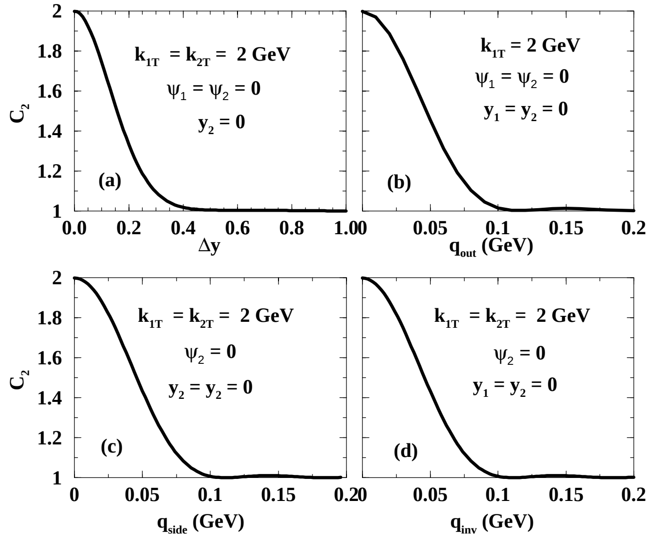


FIG. 2. Correlation function $C_2$ as a function of $\Delta y$, $q_{out}$, $q_{side}$, and $q_{inv}$ for Pb+Pb collisions at 158*A* GeV at SPS.

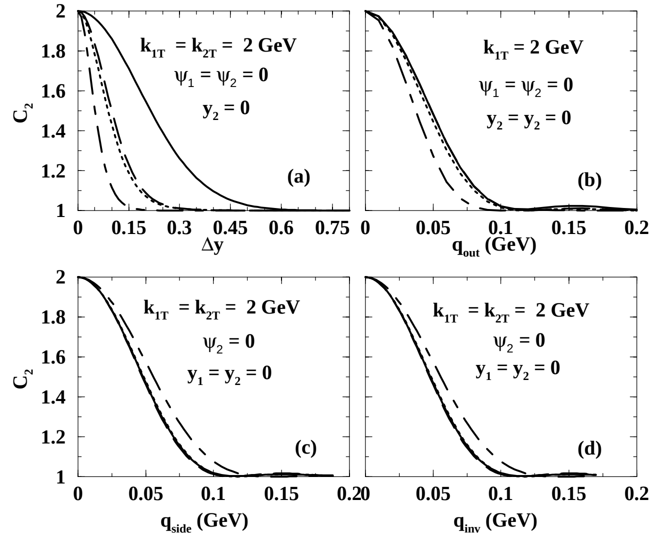


FIG. 3. Correlation function $C_2$ as a function of $\Delta y$, $q_{out}$, $q_{side}$, and $q_{inv}$ for Pb + Pb collisions at 158*A* GeV at SPS. Solid (dashed) line indicates results for QGP (mixed) phase and dot-dashed (dotted) line represents correlation function for hadronic (sum) phase.

Figures 2(a)–2(d) show the variation of the correlation strength ($C_2$) as a function of $\Delta y$, $q_{out}$, $q_{side}$, and $q_{inv}$ for various phases (sum≡QGP+mixed+hadrons). The HBT radii of the evolving hot hadronic matter (denoted by Hadron*, indicating that the masses of the hadrons are modified in the medium according to BR scaling) is shown in Table I. Please note that to get the quantity $R_{long}$ in the longitudinally comoving system (LCMS) of reference one should multiply the numbers given in Table I by cosh($y_K$), where $y_K$ is the rapidity corresponding to the momentum $K$ defined in Sec. II. We would like to mention here that the HBT radii give the length of homogeneity of the source and this is equal to the geometric size if the source is static. However, for a dynamic source, e.g., the system formed after ultrarelativistic heavy ion collisions, the HBT radii are smaller than the geometric size (see Refs. [28,43–45]).

Our earlier analysis [32] shows that the WA98 single-photon spectra can be explained by two different kinds of initial states: (i) hot hadronic gas, with the masses of the hadrons varying according to BR scaling hypothesis or (ii) QGP, which is created initially. It is rather difficult to distinguish between the two at present. Therefore, in the following we show the results on two-photon correlation functions for case (ii) also. In Fig. 3 the variation of the two-photon correlations is depicted in a scenario when QGP is formed initially at SPS. The initial conditions here are similar to those of Ref. [32]. The HBT dimensions extracted from these correlation functions are shown in Table I. The difference in the correlation function as a function of $q_{out}$ for QGP and the mixed phase is negligible. When plotted as a function of $q_{side}$ [Fig. 3(b)] the correlation function for QGP, mixed phase, and the sum almost overlap. The width of the correlation function for the hadronic phase is the largest as compared to the other phases. The HBT dimensions satisfy the relation $R_{side}/R_{out}\sim 1$ for the correlation functions denoted by "sum" in Table I. This is irrespective of the formation of QGP or hot hadronic gas with the mass of the hadrons (except pseudoscalar) approaching zero at the initial temperature. Although the latter scenario is closely related to the chiral/deconfinement phase transition, it is very difficult at this stage to draw a firm conclusion.

TABLE I. Values of the various parameters (in fm) of the correlation functions in the forms given in Eqs. (9) and (10) for SPS and RHIC energies at a transverse momentum of 2 GeV.

| | | $R_{inv}$ | $R_{out}$ | $R_{side}$ | $R_{long}$ |
|---|---|---|---|---|---|
| SPS | Hadron* | 3.7 | 3.6 | 3.7 | 0.5 |
| | QGP | 3.5 | 3.4 | 3.5 | 0.37 |
| SPS | Mixed | 3.5 | 3.4 | 3.5 | 0.8 |
| | Hadron | 3.0 | 4.5 | 3.0 | 1.5 |
| | Sum | 3.5 | 3.6 | 3.5 | 0.9 |
| | QGP | 3.5 | 3.5 | 3.5 | 0.55 |
| RHIC | Mixed | 3 | 5.4 | 3 | 2.0 |
| | Hadron | 2.7 | 6.8 | 2.7 | 2.3 |
| | Sum | 3 | 5.5 | 3 | 1.6 |

Figure 4 shows our predictions for the single-photon spectra at RHIC energies. Here the thermal photons contain contributions from QGP, mixed, and the hadronic phases. The results show a clear dominance of the thermal photon over the hard photons for $p_T<3$ GeV. We calculate the two-photon correlation at RHIC energies with the inputs that are used to evaluate the single-photon spectra as a function of $\Delta y$, $q_{out}$, $q_{side}$, and $q_{inv}$.

Figure 5(a) shows the variation of $C_2$ as a function of $\Delta y$, for two photons with momentum of 2 GeV/$c$. We have taken $\psi_1=\psi_2=0$ for simplicity. The contributions from all the three phases are shown. We observe that the width of the

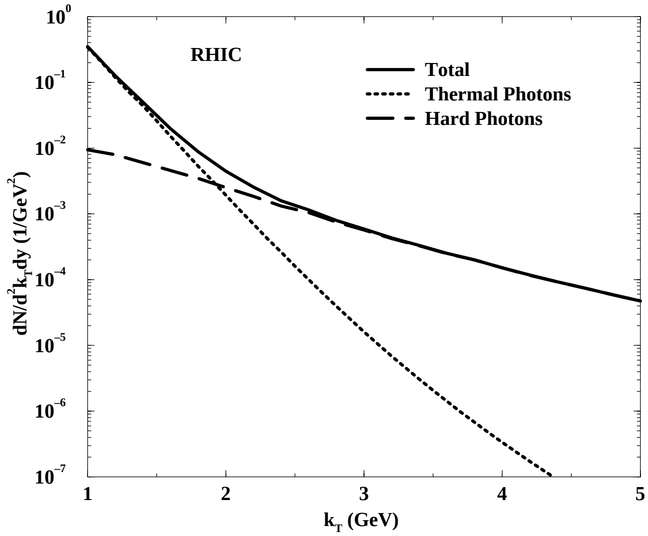


FIG. 4. Single photon spectra from Au+Au collisions at RHIC energies.

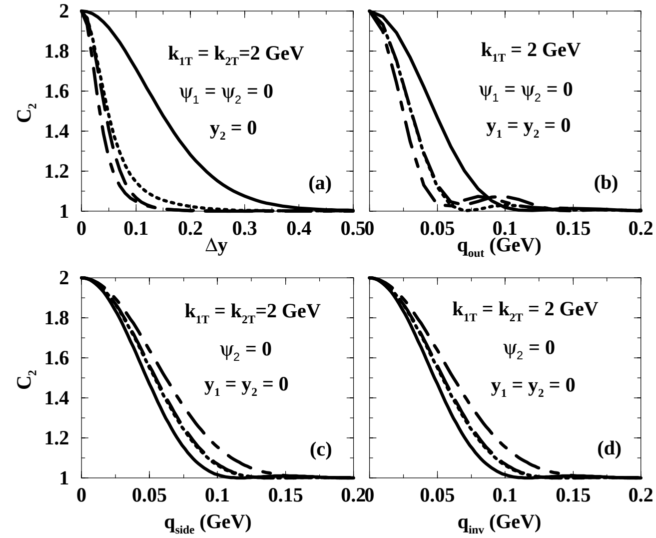


FIG. 5. Correlation function $C_2$ as a function of $\Delta y$, $q_{out}$, $q_{side}$, and $q_{inv}$ for Au+Au collisions at 200*A* GeV at the RHIC. Solid (dashed) line indicates results for QGP (mixed) phase and dot-dashed (dotted) line represents correlation function for hadronic (sum) phase.

correlation function is largest for the QGP phase followed by that from the mixed phase and then the hadronic phase. The inverse will reflect the corresponding HBT radii of the source. Figure 5(b) shows the variation of $C_2$ with $q_{out}$, for $y_1=y_2=0$, $\psi_1=\psi_2=0$, and $k_{1T}=2$ GeV. The contributions of all three phases are shown. One observes that the $C_2$ variation is similar for the three phases and is similar to that for the case with $\Delta y$, but the widths are considerably smaller. Figure 5(c) shows how $C_2$ varies with $q_{side}$ for all the three phases as well as the sum. For this case we have taken $y_1=y_2=0$, $\psi_2=0$, and $k_{1T}=k_{2T}=2$ GeV. The trend in the variation of the width for the three phases has reversed. The width of $C_2$ distribution for QGP is smallest, followed by that for the mixed phase and then the hadronic phase. Figure 5(d) shows how $C_2$ varies with $q_{inv}$ for all the three phases as well as the sum. For this case we have taken $y_1=y_2=0$, $\psi_2=0$, and $k_{1T}=k_{2T}=2$ GeV. The trend in the variation of the width for the three phases is similar to that for the case of $q_{side}$.

## V. SUMMARY

The two-photon correlation functions have been evaluated for SPS and RHIC energies. Constraints from the experimentally observed single-photon spectra have been used to evaluate the correlation functions at SPS energies. Predictions for both the single-photon spectra and the two-photon correlation functions have also been given at RHIC energies. The values of HBT radii extracted from the two-photon correlation functions show that $R_{side}/R_{out}\sim 1$ irrespective of the formation of QGP or hadronic gas with reduced mass initially for SPS and $R_{side}/R_{out}<1$ for RHIC energy.

## ACKNOWLEDGMENT

One of us (B.M.) is grateful to the Board of Research on Nuclear Science and Department of Atomic Energy, Government of India for financial support.

[1] R. Hanbury Brown and R. Q. Twiss, Nature (London) **178**, 1046 (1956).
[2] G. Goldhaber, T. Goldhaber, W. Lee, and A. Pais, Phys. Rev. **120**, 300 (1960).
[3] Th. Alber *et al.*, NA35 Collaboration, Z. Phys. C **66**, 77 (1995).
[4] C. Adler *et al.*, STAR Collaboration, Phys. Rev. Lett. **87**, 082301 (2001).
[5] K. Adcox *et al.*, PHENIX Collaboration, Phys. Rev. Lett. **88**, 192302 (2002).
[6] U. Heinz and B.V. Jacak, Annu. Rev. Nucl. Part. Sci. **49**, 529 (1999).
[7] U.A. Weidemann and U. Heinz, Phys. Rep. **319**, 145 (1999).
[8] I.V. Andreev, M. Plumer, and R.M. Weiner, Int. J. Mod. Phys. A **8**, 4577 (1993); M.M. Aggarwal *et al.*, WA98 Collaboration, Phys. Rev. Lett. **85**, 2895 (2000).
[9] F. Retiere, STAR Collaboration, nucl-ex/0212026.
[10] S. Soff, S.A. Bass, and A. Dumitru, Phys. Rev. Lett. **86**, 3981 (2001).
[11] Z. Lin, C.M. Ko, and S. Pal, Phys. Rev. Lett. **89**, 152301 (2002).
[12] S. Soff, S.A. Bass, D.H. Hardtke, and S.Y. Panitkin, Phys. Rev. Lett. **88**, 072301 (2002).
[13] D.K. Srivastava and J.I. Kapusta, Phys. Lett. B **307**, 1 (1993); Phys. Rev. C **48**, 1335 (1993); Phys. Lett. B **319**, 407 (1993).
[14] A. Timmermann, M. Plumer, L. Razumov, and R.M. Weiner, Phys. Rev. C **50**, 3060 (1994).
[15] M.M. Aggarwal *et al.*, WA98 Collaboration, Phys. Rev. Lett.

**85**, 3595 (2000).
[16] D. Peressounko, Phys. Rev. C **67**, 014905 (2003).
[17] B. Mohanty and J. Alam, nucl-th/0301086.
[18] R.M. Barnett *et al.*, Particle Data Group, Phys. Rev. D **54**, 1 (1996).
[19] H. Appelshäuser *et al.*, NA49 Collaboration, Phys. Rev. Lett. **82**, 2471 (1999).
[20] P. Aurenche, F. Gelis, H. Zaraket, and R. Kobes, Phys. Rev. D **58**, 085003 (1998).
[21] J.I. Kapusta, P. Lichard, and D. Seibert, Phys. Rev. D **44**, 2774 (1991).
[22] R. Baier, H. Nakkagawa, A. Niegawa, and K. Redlich, Z. Phys. C **53**, 433 (1992).
[23] S. Sarkar, J. Alam, P. Roy, A.K. Dutt-Mazumder, B. Dutta-Roy, and B. Sinha, Nucl. Phys. **A634**, 206 (1998).
[24] P. Roy, S. Sarkar, J. Alam, and B. Sinha, Nucl. Phys. **A653**, 277 (1999).
[25] J.K. Kim, P. Ko, K.Y. Lee, and S. Rudaz, Phys. Rev. D **53**, 4787 (1994).
[26] J. Alam, S. Sarkar, P. Roy, T. Hatsuda, and B. Sinha, Ann. Phys. (N.Y.) **286**, 159 (2000).
[27] M. Herrmann and G.F. Bertsch, Phys. Rev. C **51**, 328 (1995).
[28] S. Chappman, P. Scotto, and U. Heinz, Phys. Rev. Lett. **74**, 4400 (1995).
[29] S. Pratt, Phys. Rev. D **33**, 1314 (1986).
[30] H. von Gersdorff, M. Kataja, L. McLerran, and P.V. Ruuskanen, Phys. Rev. D **34**, 794 (1986).
[31] J.D. Bjorken, Phys. Rev. D **27**, 140 (1983).
[32] J. Alam, S. Sarkar, T. Hatsuda, T.K. Nayak, and B. Sinha, Phys. Rev. C **63**, 021901(R) (2001).
[33] J. Alam, P. Roy, S. Sarkar, and B. Sinha, nucl-th/0106038.
[34] G.E. Brown and M. Rho, Phys. Rev. Lett. **66**, 2720 (1991).
[35] G. Agakichiev *et al.*, CERES Collaboration, Phys. Lett. B **422**, 405 (1998).
[36] G.Q. Li, C.M. Ko, and G.E. Brown, Phys. Rev. Lett. **75**, 4007 (1995); G.Q. Li, C.M. Ko, G.E. Brown, and H. Sorge, Nucl. Phys. **A611**, 539 (1996).
[37] S. Sarkar, J. Alam, and T. Hatsuda, nucl-th/0011032.
[38] A. Dumitru and D.H. Rischke, Phys. Rev. C **59**, 354 (1999).
[39] F. Karsch, hep-ph/0103314.
[40] B.K. Patra, J. Alam, P. Roy, S. Sarkar, and B. Sinha, Nucl. Phys. **A709**, 440 (2001).
[41] M. McLaughlin *et al.*, E629 Collaboration, Phys. Rev. Lett. **51**, 971 (1983).
[42] D.L. Adams *et al.*, E704 Collaboration, Phys. Lett. B **345**, 569 (1995).
[43] S. Pratt, T. Csörgo, and J. Zimanyi, Phys. Rev. C **42**, 2646 (1990).
[44] G. Bertsch, P. Danielwicz, and M. Herrmann, Phys. Rev. C **49**, 442 (1994).
[45] B.R. Schlei and N. Xu, Phys. Rev. C **54**, R2155 (1996).