Photon Interferometry of Au + Au Collisions at the BNL Relativistic Heavy-Ion Collider

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We calculate the two-body correlation function of direct photons produced in central Au + Au collisions at the Relativistic Heavy-Ion Collider. Our calculation includes contributions from the early preequilibrium phase in which photons are produced via hard parton scatterings as well as radiation of photons from a thermalized quark-gluon plasma and the subsequent expanding hadron gas. We find that high energy photon interferometry provides a faithful probe of the details of the space-time evolution and of the early reaction stages of the system.

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Recent data from the Relativistic Heavy-Ion Collider (RHIC) at Brookhaven National Laboratory have provided strong evidence for the existence of a transient quark-gluon plasma (QGP). Among the most exciting findings are a strong collective flow saturating the hydrodynamic limit [1,2], a suppression of high-p_T hadrons indicative of parton energy loss [3,4], and evidence for hadronization by recombination of quarks from a deconfined phase [5]. Being of hadronic nature, these probes are necessarily affected by the late stages of the reaction and do not provide unambiguous information about the early equilibration phase. Photons and dileptons, on the other hand, decouple from the system immediately after their creation, and thus serve as complementary deep probes of the hot and dense matter. Recent studies have suggested that rescattering of partons enhances the production of photons [6,7].

One problem affecting photons is that the inclusive photon spectrum is dominated by radiative decays of long-lived hadrons (especially π^0 and η). Although the subtraction of these sources is possible with great effort, this problem severely limits the use of photons as penetrating probes. Two-photon momentum correlations do not suffer from this problem, because the geometric size of the distribution of decay vertices is extremely large on a nuclear length scale, and thus all correlations between photons from the decay of two different hadrons are confined to extremely small relative momenta. This property makes photon interferometry a promising tool for the experimental study of the preequilibrium dynamics of relativistic heavy-ion collisions.

In the present work, we employ the parton cascade model (PCM) [8,9] and ideal hydrodynamics [10] to calculate two-body quantum correlations [11] of high energy photons and show that they can provide a sensitive test of the space-time evolution of the matter in the collision zone. The peculiar features of the correlation function make it possible to differentiate between direct photons emitted in the early preequilibrium reaction phase from those produced at later times in a thermalized QGP and subsequent hadron gas. Following the early suggestion of Neuhauser [12], photon interferometry of the QGP was investigated extensively by several authors [13–18]. However, those studies focused only on photons emitted from a thermalized source. Recently, interferometry measurements with photons of transverse momenta of 100–300 MeV/c have been reported at super proton synchrotron energies [19].

Here we are primarily interested in the higher-energy photons originating in the rapidly evolving preequilibrium phase when the initial-state partons undergo multiple inelastic collisions. We use the parton cascade model to describe this phase of the collision. The basic assumption underlying the PCM is that the state of the dense partonic system can be characterized by a set of one-body distribution functions $F_i(x^\mu, p^\alpha)$, where i denotes the flavor index ($i = g, u, \bar{u}, d, \bar{d}, \dots$) and x^μ, p^α are coordinates in the eight-dimensional phase space. The time evolution of the parton distribution is described by a relativistic Boltzmann equation, whose collision term includes all scattering processes involving quarks, gluons, and photons in lowest-order quantum chromodynamics and electrodynamics. A low momentum-transfer cutoff $p_T^{\min}$ is introduced to regularize the infrared divergence of the perturbative parton-parton cross sections. Additionally, we include the branchings $q \to qg$, $q \to q\gamma$, $g \to gg$, and $g \to q\bar{q}$ following two-body collisions in the leading logarithmic approximation. The soft and collinear singularities in the showers are eliminated by terminating the branchings when the virtuality of the timelike partons drops below $\mu_0 = 1$ GeV. The present work is based on the thoroughly revised, corrected, and tested implementation VNI/BMS of the parton cascade model [8]. We already presented the rapidity distribution and the transverse momentum spectra of direct photons predicted by VNI/BMS in an earlier publication [6]. Here we explore two-photon correlations for the same model.

The PCM calculation of the hard preequilibrium photons is augmented by a hydrodynamical calculation for photon emission from a thermalized QGP and subsequently forming hadron gas. Here we employ a boost invariant hydrodynamics [10], which has been used extensively to explore photon and dilepton production and also hadronic spectra. The initial conditions are estimated from a particle rapidity density of about 1260 near $y = 0$ for a central collision of gold nuclei at $\sqrt{s_{NN}} = 200$ GeV. We assume that a chemically and thermally equilibrated plasma is formed at $\tau_0 = 0.3$ fm$/c$. We use the complete leading-order results for the production of photons from the QGP [20] and the latest results for the radiation of photons from a hot hadronic gas [21].

The upper panel of Fig. 1 shows the emission rate dN_γ/dt for photons with a transverse momentum of (1 ± 0.1) GeV$/c$ around midrapidity as a function of time. $t = 0$ is defined in the nucleus-nucleus center-of-mass frame, as the instant when the two Lorentz contracted nuclei completely overlap. Of all photons produced via hard parton scattering in the PCM, 88% are emitted within the first 0.3 fm$/c$ of the reaction. Beyond this time, due to its artificial infrared cutoffs, the PCM becomes an increasingly ineffective description of the medium evolution and does not achieve or maintain full equilibrium among the interacting partons. Assuming an initial time on the order of 0.3 fm$/c$, the hydrodynamic calculation allows for a smooth continuation of the emission rate as a function of time for the QGP and subsequent hadron gas phase. Note that the production of photons due to the primary-primary scatterings only is approximately symmetric around $t = 0$, confirming the buildup of secondary scatterings over time.

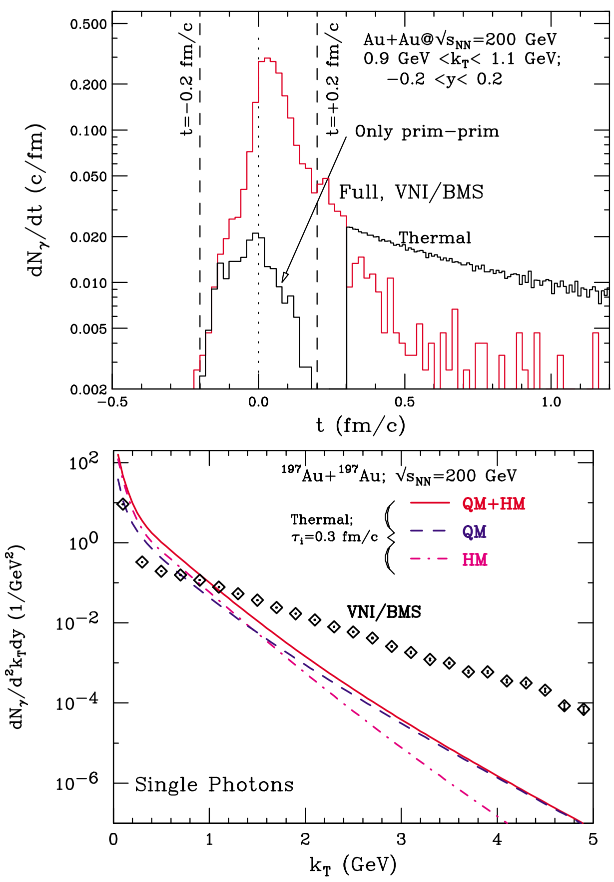

FIG. 1 (color online). Upper panel: The production rate (per event) of hard photons in a central collision of gold nuclei, at $\sqrt{s_{NN}} = 200$ GeV as a function of time in the center-of-mass system. Lower panel: Spectrum of photons from various sources: QM denotes photons emitted from a QGP and HM denotes photons emitted from a hadron gas.

The relative weight of photons emitted in the preequilibrium phase from the PCM versus those stemming from a thermalized QGP and subsequent hadron gas can be studied as a function of transverse momentum in the lower panel of Fig. 1. For a transverse momentum of $k_T = 1$ GeV$/c$, preequilibrium and thermal photons both contribute roughly 50% to the total photon yield. We therefore expect both contributions to be of importance for the calculation of the correlation function. At $k_T = 2$ GeV$/c$, however, direct photons from the PCM outweigh thermal photons by 1 order of magnitude. Here we expect only negligible contributions of thermal photons to the correlation function and a clear signal of the early photon emitting source.

The correlation between two photons with momenta $\mathbf{k}_1$ and $\mathbf{k}_2$, averaged over their spins, is

$$C(\mathbf{q}, \mathbf{K}) = 1 + \frac{1}{2} \frac{|\int d^4x S(x, \mathbf{K}) e^{ix\cdot q}|^2}{\int d^4x S(x, \mathbf{k}_1) \int d^4x S(x, \mathbf{k}_2)}, \quad (1)$$

where $S(x, \mathbf{k})$ is the photon source function for a completely chaotic source, and

$$\mathbf{q} = \mathbf{k}_1 - \mathbf{k}_2, \qquad \mathbf{K} = (\mathbf{k}_1 + \mathbf{k}_2)/2. \quad (2)$$

Our assumption of a chaotic source neglects contributions to the two photon yield by correlated two photon emission. We estimate these contributions to be small and not to influence the shape of the correlation function.

In the parton cascade model calculation, where the probability distribution of the production vertices and momenta of the photons are known, the correlation function C is calculated by following the Wigner function scheme of [22] using the HANSA code [23], i.e., by rewriting the numerator of the second term in Eq. (1) as

$$\mathrm{Num}(\mathbf{q}, \mathbf{K}) = \sum_{i,j} \cos[q(x_i - x_j)], \quad (3)$$

where the sum runs over the pairs whose individual momenta lie in a small bin around $\mathbf{K}$ of width ϵ in each of the four directions.

The emission vertices $(x, \mathbf{k})$ generated by a semiclassical transport model or the Monte Carlo sampling of emission rates generally do not represent a valid Wigner function, since the uncertainty relation $\Delta\mathbf{x}\Delta\mathbf{k} > \hbar$ is not incorporated. In order to remove this deficiency, we have smeared the emission vertices by adding random fractions of $(\hbar/p_i)$ to the emission vertices x_i [24].

We shall present our results for the correlation function $C(\mathbf{q}, \mathbf{K})$ in terms of the so-called outward, sideward, and longitudinal momentum differences. We represent the photon four-momentum in the form

$$k^\mu = (k_T \cosh y, k_T \cos\psi, k_T \sin\psi, k_T \sinh y), \quad (4)$$

where k_T is the transverse momentum, y is the rapidity, and ψ is the azimuthal angle. Using the same notation for the relative and the average momenta (2), we can write [25]

$$q_{\rm long} = |k_{1z} - k_{2z}| = |k_{1T} \sinh y_1 - k_{2T} \sinh y_2|, \quad (5)$$

$$q_{\rm out} = \mathbf{q}_T \cdot \mathbf{K}_T / K_T, \quad (6)$$

$$q_{\rm side} = |\mathbf{q}_T - q_{\rm out} \mathbf{K}_T / K_T|. \quad (7)$$

The corresponding radii for a completely chaotic source are often obtained by fitting the correlation function $C(q_{\rm out}, q_{\rm side}, q_{\rm long})$ to the functional form: $1 + (1/2) \times \exp[-(q_{\rm out}^2 R_{\rm out}^2 + q_{\rm side}^2 R_{\rm side}^2 + q_{\rm long}^2 R_{\rm long}^2)/2]$. Note that this provides that $\langle q_i^2 \rangle = 1/R_i^2$, where i = out, side, and long.

Transport calculations have employed several procedures to improve the significance of their results in order to compare with experimental data. Either the source function is parametrized, permitting an analytical evaluation of Eq. (1), or the particles generated in the calculation are "dispersed" over many particles to enhance the pair statistics. For our analysis, we have accumulated 125 000 events from VNI/BMS to make an accurate determination of the source radii possible by direct evaluation of Eq. (3). We supplement these results with photons from a Monte Carlo sampling of the hydrodynamics calculation to obtain the production vertices and momenta of the photons, which are combined with those from the PCM in our correlation analysis.

In Fig. 2 we show our results for photon momenta of $k_T = (2 \pm 0.2)$ GeV, where the high energy photons stemming from hard parton scattering completely dominate the total photon yield. We study the three-dimensional correlation function, in terms of one momentum coordinate, limiting the other two momentum coordinates to zero. The sideward radius as inferred from photons is $R_{\rm side} \approx 3.8$ fm, while the corresponding outward radius is found to be $R_{\rm out} \approx 3.7$ fm. These values are somewhat smaller than the Gaussian equivalent radius of the density distribution of a Au nucleus, reflecting the geometric shape of the colliding nuclei. The very small difference between the two radius parameters indicates a short source lifetime.

The longitudinal correlation radius is much smaller, $R_{\rm long} \approx 1.6$ fm. This is not unexpected [13] and has its origin in the fact that these photons are mostly emitted when the longitudinal extension of the system is quite small and the velocity gradients are large. We have verified that $C(q_{\rm long})$ is robust with respect to reasonable variations of the center of the rapidity window and its width, which determines ϵ. A measurement of this value of $R_{\rm long}$ would clearly identify the source of these photons as prehadronic.

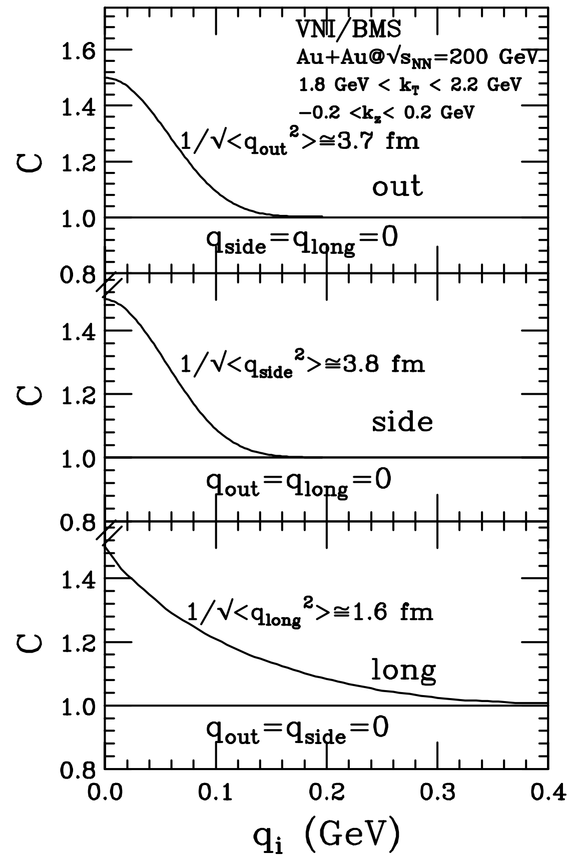

FIG. 2. The outward, sideward, and longitudinal correlations of direct photons predicted by the parton cascade model, at $K_T = 2$ GeV$/c$. The inclusion of thermal photons changes the results only marginally.

In Fig. 3 we show our results for photons at $k_T = (1 \pm 0.1)$ GeV. For this choice of k_T, preequilibrium photons and thermal ones from the QGP and hadron gas phases of the reaction contribute about equally to the yield—therefore both contributions need to be taken into account when calculating the correlation functions. As is to be expected, the radii extracted from the correlation functions lie between those of the individual contributions (thermal photons versus preequilibrium photons); however, in general, they do not reflect the average of the radii as the relative single photon yields would suggest, due to the influence of the cross term, i.e., the interference of thermal photons with preequilibrium photons.

For low k_T, thermal photons should completely dominate: at $k_T = 0.2$ GeV, our calculations predict $R_{\rm side}$ of about 5 fm, with $R_{\rm out}/R_{\rm side} \approx 2$.

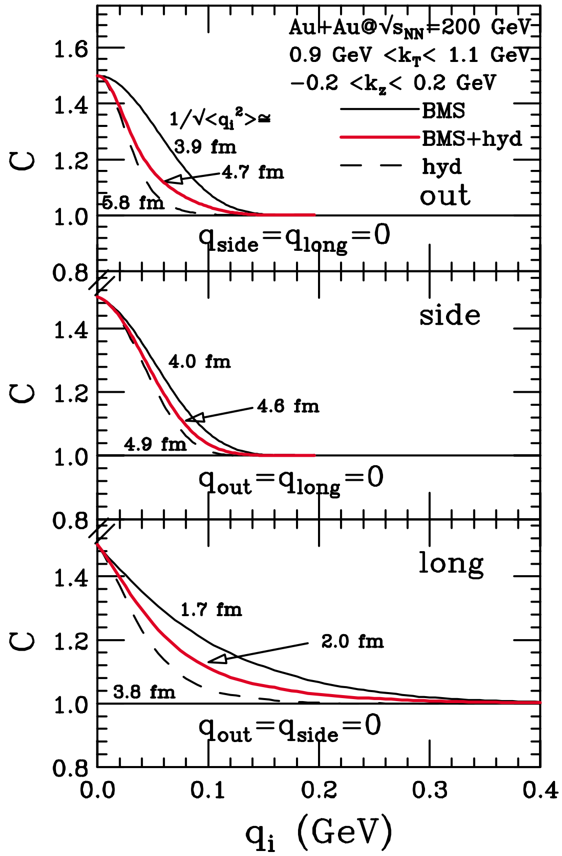

FIG. 3 (color online). Outward, sideward, and longitudinal intensity correlation of photons at 1 GeV, considering only PCM (BMS), only thermal (hyd), and all PCM + thermal photons (BMS + hyd).

In summary, we have calculated the correlation functions of high energy photons emanating from the preequilibrium stage as well as the thermal QGP and hadron gas stages of the matter formed in central Au + Au collisions at RHIC. Our study predicts that photon interferometry will reveal a small source of brief duration for photons at transverse momenta $k_T \geq 2$ GeV$/c$ due to preequilibrium emission. This contrasts with a much larger source, revealed by thermal photons at lower momenta, as they mostly originate from the QGP and hadron gas stage when the system has already expanded significantly.

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