Direct Photon Interferometry in Bi-Bi Collision at $\sqrt{s_{NN}} = 9.2$ GeV

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We consider Bose–Einstein correlations of direct photons in central Bi–Bi collisions at $\sqrt{s_{NN}} = 9.2$ GeV. Two-photon correlations are calculated in UrQMD hybrid model. Two equations of state, one with the first-order QCD phase transition and the other with the pure hadron gas, are considered to study the effects of the formation of quark-gluon plasma (QGP) and mixed phase on the observables. The extracted correlation radii in out-side-long parametrization demonstrate significant increasing in outward and longitudinal directions for the scenario including QGP, while correlations in side direction are not sensitive to the equation of the state.

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Introduction

At high energy density and temperature quantum chromodynamics (QCD) on the lattice predicts a transition from hadronic matter to the state of deconfined quarks and gluons referred as quark-gluon plasma (QGP). The properties of such a matter have been extensively studied experimentally in heavy ion collisions at SPS, RHIC, LHC etc. at different regions of net baryon density and temperature on the QCD phase diagram [1]. However, the critical point of the QCD phase diagram, at which the first-order phase transition line ends and transition becomes a crossover, has not been observed so far. Therefore, one of the key point in experimental program of NICA [2] is the exploration of the QCD phase diagram at the expected region of the critical point, covering energies $\sqrt{s_{NN}} = 3$–11 GeV.

In this paper, we investigate the photon interferometry to study the properties of QGP at NICA energies. Photon interferometry is based on the Bose–Einstein (BE) correlations, momentum correlations of particles that follow BE statistics. The BE correlations known to be a powerful experimental tool in heavy-ion physics. Hadronic BE correlations have been systematically studied over the last decades and provided comprehensive results on the space-time properties of the fireball created in a heavy-ion collision [3,4]. However, hadronic correlations reflect dimensions of the fireball at the moment of its freeze-out, while photons, being color neutral, are mostly emitted from the hottest parts of the fireball, probing the innermost hottest part of the fireball and pre-equilibrium thermalization.

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Model description

Direct photon BE correlations are calculated using UrQMD [5] hybrid model [6]. The space-time evolution of Bi–Bi collision at $\sqrt{s_{NN}} = 9.2$ GeV is modeled with ideal hydrodynamics [6]. We considered central Bi–Bi collision with the impact parameter $b = 0$ fm. The fireball in the hydrodynamic model is divided to $100\times100\times100$ cells with a cell size parameter $\mathrm{d}x = 0.2$ fm. The fluid dynamics is based on the transformation of energy, momentum and net baryon density. The equation of state (EoS) is needed as an additional input to calculate the pressure, temperature, chemical potential and QGP fraction in a cell corresponding to the energy and the baryon number densities [6]. Thus, temperature (T), chemical potential (μ_{B}), 4-velocity vector (u) and fraction of QGP (f_{QGP}) are evaluated for each cell during hydrodynamical evolution in UrQMD hybrid model. The system evolves with a time step $\mathrm{d}t = 0.08$ fm$/c$ until the energy density in all cells decreases below $5\epsilon_0$, where $\epsilon_0 = 146.5$ MeV/fm^3 is the nuclear ground state energy density. In UrQMD hybrid model the hydrodynamical evolution is calculated assuming zero viscosity of the system, which equivalent to zero mean free path.

Thermal photon emission rate $R(T(x), \mu_{\mathrm{B}}(x), p_\gamma \cdot u(x))$ is computed for each cell (in a given 4-coordinates x). Only photons emitted at the rapidly $y = 0$ are considered, correspondingly, these photons in the laboratory system have 4-momentum p_γ. The full emission rate is decomposed to contributions from QGP and HG as following,

$$R(T(x), \mu_{\mathrm{B}}(x), p_\gamma \cdot u(x)) = f_{\mathrm{QGP}} \cdot R_{\mathrm{QGP}} + (1 - f_{\mathrm{QGP}}) \cdot R_{\mathrm{HG}}, \tag{1}$$

where R_{QGP} is estimated according to [7] and R_{HG} is taken as the thermal photon production rate in hadronic reactions described in [8].

The total thermal photon yield is obtained by integrating over space-time volume of the fireball

$$E_\gamma \frac{\mathrm{d}^3 N}{\mathrm{d}p_\gamma^3} = \int \mathrm{d}^4x R(T(x), \mu_{\mathrm{B}}(x), p_\gamma \cdot u(x)) = \int \mathrm{d}^4x R(x, p_\gamma), \tag{2}$$

It has been shown (see for example [3]) that the correlation function of two-photon BE correlations (C_2) can be expressed assuming smoothness approximation as the following,

$$C_2(K, q) = 1 + \frac{1}{2} \cdot \frac{\left|\int \mathrm{d}^4x R(x, K) e^{iqx}\right|^2}{\left|\int \mathrm{d}^4x R(x, K)\right|^2}, \tag{3}$$

where $K = (p_1 + p_2)/2$ is the mean pair 4-momentum and $q = p_1 - p_2$ is the relative pair 4-momentum. Factor 1/2 appears because of the photon spin.

In this work, we use out-side-long parametrization of $q = (q^0, q_o, q_s, q_l)$ meaning that *outward* $q_o = \mathbf{q}_{\mathrm{T}} \cdot \mathbf{K}_{\mathrm{T}} / K_{\mathrm{T}}$ is collinear with transverse mean pair momentum $\mathbf{K}_{\mathrm{T}}$, *longitudinal* direction is $q_l = q_z$, *side* q_s is perpendicular to q_o and q_l, $q^0 = \mathbf{q} \cdot \mathbf{K}/K$. In this parameterization, R_l and R_o are sensitive to the source lifetime, while R_s contains only spacial information.

To investigate dependence of the photon BE correlation on the QCD phase transition, two EoS are considered. The first option, Bag model EoS [9], models the first-order QCD phase transition between HG and QGP. A system with Bag model EoS consists of QGP, mixed phase and HG, both R_{QGP} and R_{HG} contribute to the total emission rate as it is written in formula (1). A system with Hadron Resonance gas EoS [10], in its turn, consists of pure HG ($f_{\text{QGP}} = 0$) and only R_{HG} contributes to the emission rate. These two EoS are standard incorporations in UrQMD hybrid model [6].

Results

Correlation functions C_2 versus q_o, q_s and q_l at $K_{\text{T}} = 0.38$ GeV/c are presented in Fig. 1 for Bag model EoS (left) and HG EoS (right). Such correlation functions are build for a range $0 < K_{\text{T}} < 1.4$ GeV/c.

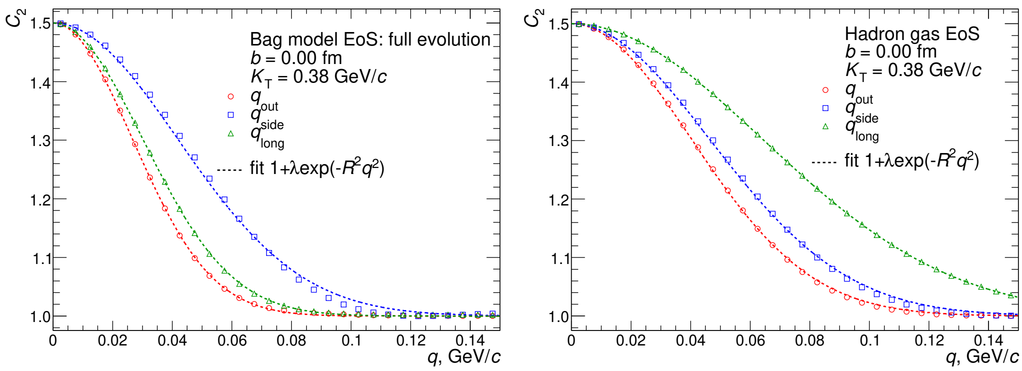

Fig. 1. Photon BE correlation functions dependending on q_o, q_s and q_l at $K_{\text{T}} = 0.38$ GeV/c for systems with Bag model EoS (left) and HG EoS (right)

The correlation functions in Fig. 1 are parametrized as

$$C_2 = 1 + \lambda \exp(-q^2 R^2), \tag{4}$$

assuming a Gaussian emitting source. From formula (4) a correlation radius R for each direction can be extracted. In a high-multiplicity environment, λ is proportional to the fraction of direct photons over inclusive photons $((N_\gamma^{\text{dir}}/N_\gamma^{\text{inc}})^2 \sim 10^{-3})$ which provides possibility to measure direct photon invariant yields [11]. Note, that because of the large lifetime of hadrons decaying into final photons, decay photons do not participate in BE correlations and result only in reduction of the correlation strength. However, in this paper we focus on calculation of correlation radii and assume $\lambda = 1/2$ (no decay photon contribution) for the simplicity.

The obtained correlation radii in out-side-long parametrization for the system with the first-order QCD phase transition (Bag model EoS) and for the pure HG system are shown in Fig. 2.

The characteristic decreasing of correlation radii with K_{T} is caused by transverse flow developed due to expansion of a system. According to Fig. 2, R_s does not change with the EoS as it depends only on spatial size of the fireball and does not convolute time component of the system. On the other

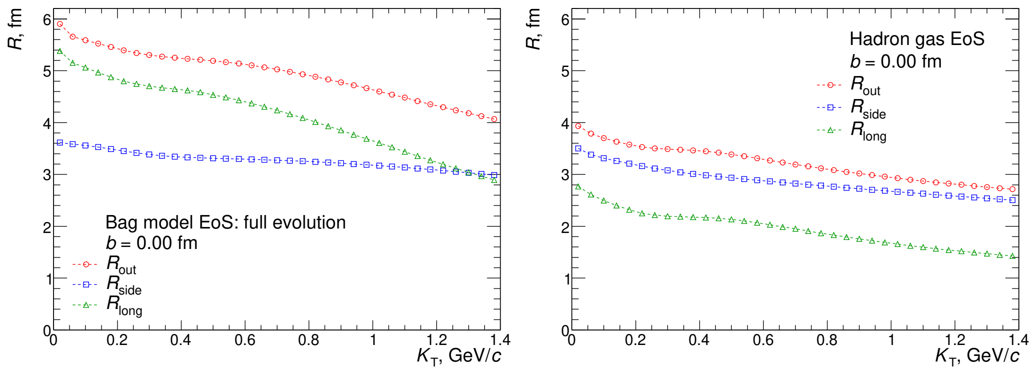

Fig. 2. Correlation radii in out-side-long parametrization as a function of K_{T} for systems with Bag model EoS (left) and HG EoS (right)

hand, R_o and R_l are larger in the scenario, including QGP. This is consistent with expectations of longer lifetime of the fireball in the case of EoS with first order phase transition, as R_o and R_l convolute spatial and time components of the system.

Summary

The BE correlations of direct photons in central (b = 0 fm) Bi–Bi collisions at $\sqrt{s_{NN}} = 9.2$ GeV are calculated in hydrodynamic approach using UrQMD. To study the effect of QGP formation, two scenarios, the first-order QCD phase transition EoS (Bag model EoS) and pure HG EoS are considered. The obtained correlation radii are decreasing with K_{T} in both scenarios according to the developing of the transverse flow in the expanding system. The side correlation radius R_s is found to be insensitive on the EoS, while R_o and R_l are increased for the case of QGP formation.

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