Squeezed back-to-back correlation of $D^0\bar{D}^0$ in relativistic heavy-ion collisions*

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We investigate the squeezed back-to-back correlation (BBC) of $D^0\bar{D}^0$ in relativistic heavy-ion collisions, using the in-medium mass modification calculated with a self-energy in hot pion gas and the source space-time distributions provided by the viscous hydrodynamic code VISH2+1. It is found that the squeezed BBC of $D^0\bar{D}^0$ is significant in peripheral Au+Au collisions at the RHIC energy. A possible way to detect the squeezed BBC in experiment is presented.

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In high-energy heavy-ion collisions, the interactions of bosons with hadronic medium before the thermal freeze-out of hadrons may cause the in-medium mass modification of bosons and then lead to a squeezed back-to-back correlation (BBC) between detected boson and antiboson \[.\] This BBC is related to the Bogoliubov transformation between the creation (annihilation) operators of the quasiparticle in medium and the detected particle \[.\] and expected to be strong for the bosons with large mass under the same mass modification \[.\] Thus the squeezed BBC is likely an observable for heavy mesons to investigate the interactions of particles with the hadronic medium.

Recently, $D$ mesons are measured in heavy-ion collisions at the Relativistic Heavy Ion Collider (RHIC) by the STAR collaboration \[8\] and at the Large Hadron Collider (LHC) by the ALICE collaboration \[9–11\], respectively. Because containing a heavy quark (charm quark), which is believed to experience the whole evolution of the quark-gluon plasma (QGP) created in relativistic heavy-ion collisions, the analyses of experimental data of $D$ mesons are of great interest. It is expected that the BBC of heavy quarks produced in the early stage of relativistic heavy-ion collisions may lead to a BBC of $D^0\bar{D}^0$ \[12\]. Because of the interactions of heavy quarks with the high density QGP and the violent expansion of QGP, the BBC of $D^0\bar{D}^0$ may exhibit different behaviors \[12–13\]. However, it should be emphasized that not only the interactions of heavy quarks with QGP but also the effects of hadronic medium on the detected $D$ meson should be considered seriously in the correlation analyses.

In Ref. \[14\], C. Fuchs, B. Martemyanov, A. Faessler, and M. Krivoruchenko calculate the in-medium self-energies of $D$ mesons at rest in a hot pion gas, induced by resonance interactions with pions. Considering that the hadronic medium is baryon dilute and meson rich in heavy-ion collisions at the RHIC and the LHC, in this study we calculate the in-medium mass shift and width of $D$ meson moving in the hot pion gas, in the FMFK framework developed in Refs. \[14, 15\].

In the FMFK framework, the self-energy $\Sigma$ of a $D$ meson in the pion gas can be written as \[14\]:

$$\Sigma = -\int A_{\pm} \frac{1}{16\pi^3 E_\pi} \frac{d^3 p_\pi}{e^{E_\pi/T} - 1},$$

(1)

for considering only the resonances with $\frac{1}{2}$ isospin. Here, the forward resonance amplitude $A_{\pm}$ can be written in the form \[14\]:

$$A_{\pm} = \sum_{j=0,1,2} \frac{8\pi\sqrt{s}}{k} \frac{(2j+1)(2j_1+1)(2j_2+1)}{(2j_1+1)(2j_2+1)} \sqrt{1+\frac{4\Gamma_j}{M_j^2}} e^{i\frac{\sqrt{4\Gamma_j}}{M_j}},$$

(2)

where $j = 0, 1, 2$ correspond to the $s$-, $p$-, and $d$-wave resonances $D^*_0$, $D^*$, and $D^*_2$ in the $D\pi$ system with masses $M_j$, partial and total widths $\Gamma_j$ and $\Gamma_j^{total}$, respectively; $j_1 = j_2 = 0$ are the spins of the $D$ and the pion, respectively, and $k$ is the c.m. momentum. The energy dependence of the widths is given by \[14\]:

$$\Gamma_j^{D\pi} = \left(\frac{k}{k_0}\right)^{2j+1} \frac{M_j^2}{s} \Gamma_j^{D\pi}/k_0,$$

(3)

where $k_0$ is the c.m. momentum when the resonance energy is its mass, and $\Gamma_j^{D\pi}$ is the on-mass-shell decay width. We list in Table I the values of $M_j$ and $\Gamma_j^{D\pi}$ for the resonances $D^*_0$, $D^*$, and $D^*_2$ \[14\]. With Eqs. \[14–16\] and the data in Table I, one can calculate the self-energy $\Sigma$ of $D$ meson in the hot pion gas.

We show in Fig. I the mass shift $\Delta M = (Re\Sigma/2M_D)$ and width $\Gamma = (-Im\Sigma/E_D)$ of $D$ meson in the hot pion

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TABLE I: Excited D-meson states which are taken into account as resonances in Dπ system.

| Resonance | $M_i$ (MeV/c^2) | $\Gamma^D_{10}$ (MeV/c^2) |
|-----------|-----------------|-------------------------|
| $D^*$     | 2008.5          | $\approx$ 0.1          |
| $D_0^*$   | 2308 $\pm$ 60   | 276 $\pm$ 99           |
| $D_2^*$   | 2461.6 $\pm$ 5.9| 45.6 $\pm$ 12.5        |

The squeezed correlation function of boson-antiboson with momenta $p_1$ and $p_2$ is defined as

$$C(p_1, p_2) = 1 + \frac{|G_s(p_1, p_2)|^2}{G_c(p_1, p_2)G_r(p_2, p_2)}, \quad (4)$$

where $G_c(p_1, p_2)$ and $G_s(p_1, p_2)$ are the so-called chaotic and squeezed amplitudes, respectively. In a homogeneous medium with volume $V$ and temperature $T$, the amplitudes $G_c(p_1, p_2) \propto V \delta_{p_1, p_2}$, $G_s(p_1, p_2) \propto V \delta_{p_1, -p_2}$, and the squeezed correlation function can be written as

$$C(p, -p) = 1 + \frac{V^2 |c_p s_{p} n_p + c_{-p} s_{-p} (n_{-p} + 1)|^2}{V^2 |n_1(p) n_1(-p)|} \equiv 1 + B(p), \quad (5)$$

where $c_p$ and $s_p$ are the coefficients of Bogoliubov transformation between the creation (annihilation) operators of the quasiparticle in medium with modified mass $m_*$ and the free observed particle, $n_p$ is boson distribution of quasiparticle, and $n_1(p) = |c_p|^2 n_p + |s_p|^2 (n_{-p} + 1)$. The function $B(p)$ is not zero only when $p_2 = -p_1$, for the homogeneous source. Thus the squeezed correlation function is also called the BBC function, which will be 1 if there is no in-medium mass modification.

For a finite source, there are still the squeezed correlations when $p_2 \neq -p_1$ but $p_2 \approx -p_1$. Considering a static source for simplicity with the same temperature and Gaussian spatial distribution with standard deviation $R [2, 3, 16]$, for $|p_1| = |p_2| = |p|$ we have

$$C(p_1, p_2) = 1 + e^{-2p^2 R^2 (1 + \cos(\alpha))} B(p) \equiv 1 + f(\alpha) B(p), \quad (6)$$

where $\alpha$ is the angle between $p_1$ and $p_2$.

We compare in Fig. 2 the functions of $f(\alpha)$ for the different values of source radius $R$ and particle momentum $p$. Here, $f(\alpha)$ decreases with increasing $R$ and $p$ for fixed $\alpha$. The squeezed correlation functions reach their maxima when $p_2 = -p_1$. There are still considerable squeezed correlations when $p_2 \neq -p_1$ but $p_2 \approx -p_1$ for small sources.

For a general particle-emitting source evolving hydrodynamically, the chaotic and squeezed amplitudes can be expressed as

$$G_c(p_1, p_2) = \int \frac{d^4 \sigma_{\mu}(r)}{(2\pi)^3} K_{1,2}^{\mu} e^{i q_{1,2} \cdot r} \left\{ |c'_{p_1, p_2}|^2 n'_{p_1, p_2} + |s'_{-p_1, p_2}|^2 [n'_{-p_1, -p_2} + 1] \right\}, \quad (7)$$

$$G_s(p_1, p_2) = \int \frac{d^4 \sigma_{\mu}(r)}{(2\pi)^3} K_{1,2}^{\mu} e^{2i q_{1,2} \cdot r} \left\{ s'_{-p_1, p_2} c'_{p_2, -p_1} \times n'_{-p_1, -p_2} + c'_{p_1, -p_2} s'_{-p_2, p_1} [n'_{p_1, -p_2} + 1] \right\}, \quad (8)$$

where $d^4 \sigma_{\mu}(r)$ is the four-dimensional element of freeze-out hypersurface, $q_{1,2}^{\mu} = p_1^{\mu} - p_2^{\mu}$, $K_{1,2}^{\mu} = (p_1^{\mu} + p_2^{\mu})/2$, and $p_i^{\mu}$ is the local-frame momentum corresponding to $p_i (i = 1, 2)$. In Eqs. (7) and (8), the quantities $c'_{p_1, p_2}$ and $s'_{p_1, p_2}$ are related to the amplitudes $c_{p_1, p_2}$ and $s_{p_1, p_2}$ of the static source through

$$c'_{p_1, p_2} = (c_{p_1, p_2} e^{i q_{1,2} \cdot p_1} + c_{-p_1, -p_2} e^{-i q_{1,2} \cdot p_1}),$$

$$s'_{p_1, p_2} = (s_{p_1, p_2} e^{i q_{1,2} \cdot p_1} - s_{-p_1, -p_2} e^{-i q_{1,2} \cdot p_1}).$$
that the spectra calculated by the VISH2+1 with measured by the STAR collaboration [7]. One can see to be 150 MeV. The experimental data of the spectra are to be 0.08 [33, 34] and the freeze-out temperature is taken

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Here, the solid and dashed lines are for the collisions in centrality intervals 0%–80% and 40%–80%, respectively, but also related to the source space-time distribution and particle momentum [2, 3].

Relativistic hydrodynamics is an efficient tool for describing the evolution of particle-emitting sources in high-energy heavy-ion collisions [18, 24]. It has been widely used to study the momentum spectra [21, 23, 25, 28], Hanbury–Brown–Twiss (HBT) radii [22, 26, 29, 30], and other observables of the final-state particles produced in relativistic heavy-ion collisions.

We plot in Fig. 3 the transverse-momentum spectra of \( D^0 \) meson for Au+Au at \( \sqrt{s_{NN}} = 200 \text{ GeV} \). Here, the solid and dashed lines are for the collisions in centrality intervals 0%–80% and 40%–80%, respectively, calculated by the viscous hydrodynamic code VISH2+1 [31] under the MC-Clib initial condition [32]. The ratio of the shear viscosity to entropy density of the QGP is taken to be 0.08 [33, 34] and the freeze-out temperature is taken to be 150 MeV. The experimental data of the spectra are measured by the STAR collaboration [7]. One can see that the spectra calculated by the VISH2+1 with \( T_f = 150 \text{ MeV} \) are approximately consistent with the data in \( p_T < 4 \text{ GeV}/c \).

![FIG. 3: (Color online) Transverse momentum spectra of \( D^0 \) meson calculated with VISH2+1 for Au+Au at \( \sqrt{s_{NN}} = 200 \text{ GeV} \). The experimental data are obtained from the STAR Collaboration measurements.](image)

For the hydrodynamic sources for Au+Au collisions at \( \sqrt{s_{NN}} = 200 \text{ GeV} \), we calculate the squeezed BBC functions \( C(\Delta \phi) \) of \( D^0 \bar{D}^0 \) as shown in Fig. 4. Here \( \Delta \phi \) is the angle between the transverse momenta of \( D^0 \) and \( \bar{D}^0 \). The dashed, solid, and dot-dashed curves represent the results calculated in the momentum re-

![FIG. 4: (Color online) Squeezed BBC functions of \( D^0 \bar{D}^0 \) for Au+Au collisions at \( \sqrt{s_{NN}} = 200 \text{ GeV} \).](image)

gions 0.55–0.65 GeV, 0.75–0.85 GeV, and 1.15–1.25 GeV, respectively, where the in-medium mass of \( D^0 \) meson, \( m_* \), is taken according to the Breit-Wigner distribution \( \mathcal{D}(m_*, \Delta M, \Gamma) = (\Gamma/2\pi)/[(m_* - \Delta M - M_D)^2 + (\Gamma/2)^2] \) with the \( \Delta M \) and \( \Gamma \) values when \( p_D = 0.6, 0.8, \) and 1.2 GeV/c, respectively. The more serious in-medium mass modification at the lower \( p_D \) (see Fig. 1) may lead to a higher squeezed BBC than that at the higher momentum. On the other hand, the more serious oscillations of single-event squeezed BBC functions at higher momentum [4] may also lead to a lower squeezed BBC after averaged over events. The squeezed BBC functions for centrality interval 40%–80% are higher than those for centrality interval 0%–80%. The reason for this is mainly that the source temporal distribution is narrow in peripheral collisions [5]. The contributions to the squeezed BBC functions at lower \( \Delta \phi \) are mainly from the more peripheral collisions, which not only have the strong squeezed BBC but also slow varying \( f(\alpha) \) functions because of the smaller source size.

Considering that the in-medium mass shift is negative, the \( D \) mesons with the in-medium masses \( m_* \) smaller than the peak of in-medium mass distribution, \( M_* \), have a large average mass difference to \( M_D \), and thus have a significant squeezed BBC [33]. We plot in Fig. 5 the squeezed BBC functions \( C(\Delta \phi) \) of \( D^0 \bar{D}^0 \) for the sources as in Fig. 4 but the in-medium masses \( m_* \) of \( D^0 \) mesons are taken according to the Breit–Wigner distribution \( m_* < M_* \). One can see that the squeezed BBC functions are more significant in this case than those in Fig. 4. The maxima of the squeezed BBC functions in Fig. 5 are about twice those in Fig. 4. Considering that the number of \( D^0 \) mesons with \( m_* < M_* \) is about half of

and \( s'_{p_1, p_2} \) are the coefficients of Bogoliubov transformation between the creation (annihilation) operators of the quasiparticles and the free particles, and \( s'_{p_1, p_2} \) is the boson distribution associated with the particle pair [2, 3]. The squeezed BBC function obtained from Eqs. (1), (7), and (8) is not only dependent on the mass modification, but also related to the source space-time distribution and particle momentum [2, 3].
the total number, the errors will increase by about $\sqrt{2}$, which is smaller than 2. Thus this way provides a possibility to detect the squeezed BBC in experiment if the in-medium mass shift can be determined by experimental measurements.

In summary, we have investigated the squeezed BBC functions of $D^0\bar{D}^0$ in Au+Au collisions at $\sqrt{s_{NN}} = 200$ GeV and in centrality intervals 0%-80% and 40%-80%. The source evolution is described by viscous hydrodynamics, VISH2 + 1 code, and the mass modifications used are calculated in the FMFK framework. It is found that the squeezed BBC of $D^0\bar{D}^0$ is observable in Au+Au collisions at the RHIC energy, especially in peripheral collisions. The squeezed BBC is obviously greater than 1 when the momenta of the two mesons are approximately antiparalleled. For a fixed angle between the momenta of the two $D$ mesons, the squeezed BBC decreases with increasing momentum. In experiment, researchers may use the $D$ mesons with the masses smaller than the maximum observed to detect the squeezed BBC and to analyze the mass modifications. On the other hand, the investigations of removing the background of heavy-quark correlations in squeezed BBC analyses will be of interest.

FIG. 5: (Color online) Squeezed BBC functions of $D^0\bar{D}^0$ for Au+Au collisions at $\sqrt{s_{NN}} = 200$ GeV, calculated with conditions $m_\ast < M_\ast < M_\ast$. 

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