Squeezed back-to-back correlations of $\phi\phi$ in Au+Au and d+Au collisions at the Relativistic Heavy Ion Collider energies

Yong Zhang$^1$ and Wei-Ning Zhang$^{1,2,*}$

$^1$School of Physics, Dalian University of Technology, Dalian, Liaoning 116024, China
$^2$Department of Physics, Harbin Institute of Technology, Harbin, Heilongjiang 150006, China

Abstract

We investigate the squeezed back-to-back correlations (BBC) of $\phi\phi$, caused by the mass modification of the particles in the source medium, in the heavy-ion collisions of Au+Au and d+Au at the Relativistic Heavy Ion Collider (RHIC) energies. The BBC functions are calculated using the modified masses extracted from experimental data and the source space-time distributions provided by the viscous hydrodynamic code VISH2+1. Our investigations indicate that the BBC of $\phi\phi$ may perhaps be observed in the collisions of d+Au and the peripheral collisions of Au+Au at the RHIC. We suggest to measure the BBC experimentally for understanding the mass modifications of the $\phi$ meson in the collisions.

Keywords: squeezed back-to-back correlation, $\phi$ meson, mass modification, Au+Au collisions, d+Au collisions

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The main goal of high-energy heavy-ion collisions is to create the matter of quark-gluon plasma (QGP), predicted by quantum chromodynamics, and study its properties [1–4]. As there are copious strange quarks $s$ and $\bar{s}$ in the QGP environment, $\phi(s\bar{s})$ meson can produce readily, bypassing the Okubo-Zweig-Izuka (OZI) rules [5]. The productions of the $\phi$ meson observed in the heavy-ion collisions at the Relativistic Heavy Ion Collider (RHIC) and the Large Hadron Collider (LHC) give a certain evidence of having formed the QGP matter in the experiments [6–13]. On the other hand, the weak interactions expected between the $\phi$ meson and the hadronic mediums makes it as a sensitive probe of the QGP properties [10–12, 14–20]. The investigations of $\phi$ elliptic flow in the heavy-ion collisions at the RHIC energies indicate that the flow reflects dominantly the anisotropy of the QGP matter and the effect of hadronic scattering is unimportant [10–12, 15–20]. However, the $\phi$ meson is also argued to be with a larger hadronic cross section than the estimations by current theories, based on the recent measurements of the elliptic flow of identified hadrons in the Pb-Pb collisions at $\sqrt{s_{NN}} = 2.76$ GeV at the LHC [21]. It is still an open issue to determine the interaction between $\phi$ and the hadronic medium.

In the particle-emitting sources formed in high-energy heavy-ion collisions, the interaction between the particle and source medium may lead to a modification of the particle mass, and thus give rise to a squeezed correlation of boson-antiboson [22, 23]. This squeezed correlation is the result of a quantum mechanical transformation relating in-medium quasiparticles to the two-mode squeezed states of their free observable counterparts, through a Bogoliubov transformation between the creation (annihilation) operators of the quasiparticles and the free observable particles [22, 23]. Because the correlation impels the boson and antiboson to move in opposite directions, it is known as back-to-back correlation (BBC) [22–24]. The measurements of the BBC of $\phi\phi$ pair may give a knowledge of the interaction between the $\phi$ meson and the source medium, and perhaps provide a new way to probe the thermal properties of the hadronic sources [22–26].

Recently, the BBC of $\phi\phi$ and $K^+K^-$ are calculated with ideal hydrodynamic sources [27]. The calculations indicate that the BBC of $\phi\phi$ may perhaps be observed in the peripheral heavy-ion collisions at the RHIC and LHC [27], because the temporal distribution of the source is narrower in the peripheral collisions. As the BBC is caused by the particle-mass modification in the medium, it is crucial to use suitable modified masses in examining the BBC. In this work, we analyze the mass modification of the $\phi$ in the source medium with the
experimental data measured by the STAR collaboration \cite{10}. The BBC of $\phi\phi$ in the Au+Au and d+Au collisions at the RHIC energies are investigated, using the viscous hydrodynamic model VISH2+1 \cite{28} and the modified masses extracted from the experimental data \cite{10}. The investigations indicate that the BBC of $\phi\phi$ may perhaps be observed in the collisions of d+Au and the peripheral collisions of Au+Au at the RHIC.

The BBC function of the two $\phi$ mesons with momenta $k_1$ and $k_2$ is defined as \cite{23, 24}

$$C(k_1, k_2) = 1 + \frac{|G_s(k_1, k_2)|^2}{G_c(k_1, k_1)G_c(k_2, k_2)},$$

(1)

where $G_c(k_1, k_2)$ and $G_s(k_1, k_2)$ are the chaotic and squeezed amplitudes, respectively. For evolution particle-emitting sources, they can be expressed as \cite{23, 26, 29}

$$G_c(k_1, k_2) = \int \frac{d^4\sigma_\mu(r)}{(2\pi)^3} K_{1,2}^\mu e^{i q_{1,2} \cdot r} \left\{ |c_{k_1, k_2}'|^2 n_{k_1, k_2}'^2 + |s_{-k_1, -k_2}'|^2 [n_{-k_1, -k_2}' + 1] \right\},$$

(2)

$$G_s(k_1, k_2) = \int \frac{d^4\sigma_\mu(r)}{(2\pi)^3} K_{1,2}^\mu e^{i q_{1,2} \cdot r} \left\{ s_{-k_1, k_2}' c_{-k_1, -k_2}'^* n_{-k_1, -k_2}' + c_{k_1, -k_2}' s_{-k_1, -k_2}'^* n_{k_1, -k_2}' + 1 \right\},$$

(3)

where $d^4\sigma_\mu(r)$ is the four-dimension element of freeze-out hypersurface, $q_{1,2}^\mu = k_1^\mu - k_2^\mu$, $K_{1,2}^\mu = (k_1^\mu + k_2^\mu)/2$, and $k_i'$ is the local-frame momentum corresponding to $k_i$ ($i = 1, 2$). In Eqs. (2) and (3), the quantities $c_{k_1, k_2}'$ and $s_{k_1, k_2}'$ are the coefficients of Bogoliubov transformation between the creation (annihilation) operators of the quasiparticles and the free particles, and $n_{k_1, k_2}'$ is the boson distribution associated with the particle pair \cite{22, 26}.

We use the VISH2+1 code \cite{28} to simulate the evolutions of the particle-emitting sources produced in the collisions of Au+Au and d+Au at the RHIC energies. The event-by-event initial conditions of MC-Glb \cite{30} are employed at $\tau_0 = 0.6$ fm/c in the simulations, and the ratio of the shear viscosity to entropy density of the QGP is taken to be 0.08 \cite{31, 32}. Figure \ref{fig}(a) and (b) show the transverse-momentum spectra of the $\phi$ meson calculated with the viscous hydrodynamic code at the freeze-out temperature $T_f = 140$ MeV for the collisions in different centrality ranges. The simulated events for each case is 1000. Here, the experimental data measured by the STAR collaboration \cite{10} are also plotted. One can see that the calculated spectra suit the experimental data well.

We plot in Fig.\ref{fig} the BBC functions $C(k, -k)$ in mass-momentum ($M_* k$) plane averaged over the 1000 simulated events of the Au+Au collisions at $\sqrt{s_{NN}} = 200$ GeV and in the centrality ranges 0–5% and 70–80%, respectively. After event average, the oscillations of the BBC functions with the momentum are smoothed \cite{26, 27}. The BBC function is sensitive
FIG. 1: Transverse momentum spectra of $\phi$ meson calculated with VISH2+1 for the Au+Au and d+Au collisions at the RHIC energies. The experimental data are from the STAR Collaboration measurements [10].

to the mass shift, $M_s - M_0$ ($M_0 = 1.02$ GeV/$c^2$). It is large for the peripheral collisions because the temporal distribution of the source for the peripheral collisions is narrow [27].

FIG. 2: BBC functions of $\phi\phi$ for the central and peripheral collisions of Au+Au at $\sqrt{s_{NN}} = 200$ GeV.

In order to estimate the BBC in the collisions, we need to determine the mass modification in the source medium. In Ref. [10], the $\phi$ mass and mass-width are investigated in the Au+Au and d+Au collisions at the RHIC, by measuring the decayed $K^+K^-$ pair. The results show that there are more differences between the experimental data and the Monte Carlo data in the low transverse momentum $p_T$ region [10]. We show in Fig. 3 the Gaussian-formula fits to the experimental data and the Monte Carlo data of the mass and mass-width [10] in
the Au+Au and d+Au approximately central collisions at the RHIC. The data of the three collisions have the similar variation with $p_T$. At low $p_T$, the similar mass and mass-width modifications for the large systems of the Au+Au collisions and the small system of the d+Au collision imply that the $\phi$ mesons may have sufficient interactions with the medium particles even for the small system, i.e., the $\phi$ mean free path is smaller as compared to the small system size. This is consistent with the estimations of the $\phi$ mean free path between 1 and 2.4 fm in the hadronic gas in the hidden local symmetry model [33]. Phenomenologically, a particle with lower momentum moves more circuitously in medium due to the collisions with the medium particles. The $\phi$ mesons with lower average transverse momentum, thus with lower average transverse velocity $\bar{v}_T$, have more possibility decaying inside the source medium and the possibility will be higher if the source with a transverse expanding velocity comparable to $\bar{v}_T$. The differences between the experimental data and the Monte Carlo data at low $p_T$ reflect the medium effects on the measurements of the mass and mass-width. On the other hand, the $\phi$ with higher momentum escapes the source more easily. The relativistic space shrink also makes the $\phi$ with high relative velocity to the medium go through the medium easily. In this case, the $\phi$ tends to decay outside of the source and the medium effects on the mass and mass-width approach to zero. However, the BBC of the $\phi\phi$ pairs can remain. In the reactions of 12 GeV p on Cu targets, KEK-PS E325 Collaboration also observed the mass modification of the $\phi$ in low velocity region [34], where the mediums are approximately rest for the lower energy collisions.
Assuming the measured invariant-mass distribution of $K^+K^-$ in the Au+Au and d+Au collisions [10] consists of the two parts, one from the contribution of the $\phi$ mesons decaying inside the source medium and another from the contribution of the $\phi$ mesons decaying outside of the source, we have the normalized density distribution of the mass as,

$$\rho_{\exp}(m; M_{\exp}, \Gamma_{\exp}) = \frac{\Gamma_{\exp}/2\pi}{(m - M_{\exp})^2 + (\Gamma_{\exp}/2)^2}$$

$$= f(p_T)\rho_0(m; M_0, \Gamma_0) + [1 - f(p_T)]\rho_*(m; M_*, \Gamma_*), \quad (4)$$

where $M_{\exp}$ and $\Gamma_{\exp}$ are the mass center and width measured in experiment, $M_0$ and $\Gamma_0$ are the mass center and width for the $\phi$ mesons decaying outside of the source, and $M_*$ and $\Gamma_*$ are the mass center and width for the $\phi$ mesons decaying inside the source medium. In Eq. (4), $f$ is the fraction of the $\phi$ meson decay outside of the source. With the experimental data of $(M_{\exp}, \Gamma_{\exp})$ [10] and with the corresponding Monte Carlo data [10] instead of $(M_0, \Gamma_0)$, we can obtain the distributions $\rho_{\exp}(m)$ and $\rho_0(m)$, and then determine $M_*$, $\Gamma_*$, and $f$ from Eq. (4).

In table I we present the results of $M_*$, $\Gamma_*$, and $f$ obtained by fitting the distributions $\rho_{\exp}(m)$ with the formula (4), where $\rho_{\exp}(m)$ and $\rho_0(m)$ are calculated with the three experimental data and the Monte Carlo data of the mass and mass-width shown in Fig. 3. For the Fit 1 in the table, we first perform the fit in the lowest transverse momentum region with the average 0.5 GeV/c and get the fitted results $M_* = 1.0157$ GeV/$c^2$ and $\Gamma_* = 9.785$ MeV/$c^2$. Because the distribution $\rho_{\exp}(m)$ is calculated with the data of $(M_{\exp}, \Gamma_{\exp})$ which have large differences to the date of $(M_0, \Gamma_0)$ in the momentum region, the fitted result of $f$ is zero. When the interaction between the medium particles and the $\phi$ is sufficient, the effect of the source medium on the $\phi$ mass may reach a saturation. In this case, if we assume that the values of $M_*$ and $\Gamma_*$ are momentum-independent, we can obtain the values of $f$ in the higher $p_T$ regions as shown in the Fit 1 of table II by performing the fits with the fixed $M_*$ and $\Gamma_*$ values. The fitted results of $f$ increase with $p_T$ when the differences between the experimental data of $(M_{\exp}, \Gamma_{\exp})$ and the Monte Carlo data of $(M_0, \Gamma_0)$ decrease with $p_T$.

In the fit with Eq. (4), the fitted results of $\Gamma_*$ and $f$ are highly correlated when $f$ is not zero. In this case it is hard to get the appropriate results of them meanwhile in the fit. If we assume that only 60 percent and even 20 percent of the $\phi$ mesons in the lowest transverse momentum region decay inside the source medium, we can obtain the fitted results $(M_* = 1.0148$ GeV/$c^2$, $\Gamma_* = 12.069$ MeV/$c^2$) presented in the Fit 2 of table II by
TABLE I: Results of fitting $\rho_{\text{exp}}(m)$ with Eq. (4).

| $p_T$(GeV/c) | $M_*(\text{GeV}/c^2)$ | $\Gamma_*(\text{MeV}/c^2)$ | $f$ | $\chi^2$/NBF |
|--------------|------------------------|---------------------------|-----|--------------|
| 0.5          | 1.0157 ± 0.0003        | 9.785 ± 0.373             | 0.000 ± 0.008 | 0.04/30 |
| Fit 1        | 0.7 1.0157(fixed)      | 9.785(fixed)              | 0.481 ± 0.031 | 65.05/30 |
|              | 1.0 1.0157(fixed)      | 9.785(fixed)              | 0.753 ± 0.014 | 68.43/30 |
| 0.5          | 1.0148 ± 0.0005        | 12.069 ± 0.921            | 0.40(fixed)  | 0.56/30 |
| Fit 2        | 0.7 1.0148(fixed)      | 12.069(fixed)             | 0.640 ± 0.021 | 51.98/30 |
|              | 1.0 1.0148(fixed)      | 12.069(fixed)             | 0.829 ± 0.009 | 65.82/30 |
| 0.5          | 1.0107 ± 0.0016        | 20.197 ± 5.773            | 0.80(fixed)  | 5.95/30 |
| Fit 3        | 0.7 1.0107(fixed)      | 20.197(fixed)             | 0.846 ± 0.009 | 71.80/30 |
|              | 1.0 1.0107(fixed)      | 20.197(fixed)             | 0.926 ± 0.004 | 111.79/30 |

fixing $f = 0.4$ and the fitted results ($M_* = 1.0107 \text{ GeV}/c^2$, $\Gamma_* = 20.197 \text{ MeV}/c^2$) presented in the Fit 3 of table I by fixing $f = 0.8$, respectively. With the same way, we can also obtain the fitted results of $f$ in the momentum regions of higher $p_T$. The fitted results of $f$ in the Fit 2 and Fit 3 of table I are larger than those in the Fit 1 of table I. In the fits, the increase of $f$ with increasing $p_T$ implies more and more the $\phi$ mesons decaying outside of the source medium with increasing $p_T$. Considering that not all the $\phi$ mesons in the transverse momentum region of $p_T = 0.5 \text{ GeV}/c$ decay inside the source medium, the values of $M_*$ and $\Gamma_*$ will have larger differences to the values of $M_0$ and $\Gamma_0$, respectively, compared to those for the Fit 1 of table I. This will lead to stronger BBC.

FIG. 4: Mass distributions $\rho_*$ and $\rho_0$ for the Au+Au collisions at $\sqrt{s_{NN}} = 200 \text{ GeV}$.
Once obtaining the values of $M_*$ and $\Gamma_*$, we can calculate the BBC functions with the hydrodynamic code for the heavy-ion collisions. As shown in Fig. 4 for the Au+Au collisions at \( \sqrt{s_{NN}} = 200 \text{ GeV} \) for instance, the mass $m_L(m_R)$ in Fig. 4(a), which is at the left(right) of the peak, is taken with relative probability $\frac{1}{2}0.8$ in the calculations for the mass in the source medium, and the corresponding mass out of the source is $m'_L(m'_R)$ shown in Fig. 4(b). Here, the values of $M_*$ and $\Gamma_*$ are taken as in the Fit 1 in table I, $M_0$ is taken to be the Gaussian-formula fit result for the corresponding Monte Carlo data, and $\Gamma_0$ is taken to be $6.09 \text{ MeV}/c^2$ (see Fig. 3).

We show in Fig. 5 the BBC functions $C(\Delta \phi)$ for the collisions of Au+Au and d+Au at the RHIC energies. Here, $\Delta \phi$ is the angle between the transverse momenta $k_{T1}$ and $k_{T2}$ of the two $\phi$ mesons, and the results for the marks of $k_{T1}$ and $k_{T2}$ are calculated in the higher and lower momentum regions $0.4 < |k_{Tr}| < 0.5 \text{ GeV}/c$ and $0.8 < |k_{Tr}| < 0.9 \text{ GeV}/c$, respectively. We take 1000 events for each of the collisions. The masses of the $\phi$ mesons in and out the source medium are taken with the distributions $\rho_*(m)$ and $\rho_0(m)$ as explained with Fig. 4. In Figs. 5(a1)–(c1), label “M*1” means that the values of $M_*$ and $\Gamma_*$ for calculating $\rho_*(m)$ are taken as the fit results in the Fit 1 of table I. One can see that the $C(\Delta \phi)$ results for the peripheral Au+Au collisions are larger than those for the central collisions, because the peripheral collisions have narrower source temporal distributions [27].
For the same reason, the results for d+Au collisions are large. For the asymmetric collisions of d+Au, the BBC function $C(\Delta \phi)$ for 0–100% centrality is slight narrower than that for 0–20% centrality. The main reason is that the more event-by-event fluctuations of the BBC function [26] in the collisions of a wider centrality range lead to smaller averaged results [27]. In Figs. 5(a2)–(c2), the in-medium mass distributions $\rho_*(m)$ are calculated with the $M_*$ and $\Gamma_*$ which are taken as the fit results in the Fit 2 of table II (labeled $M_2$) and in the Fit 3 of table II (labeled $M_3$), respectively. In these cases, the BBC functions are larger than those in the $M_1$ case, which are the lower limits. In Figs. 5(a3)–(c3), the results labeled “left” are calculated with only the $\phi$ mesons which with the masses smaller than the maximum (at left of the peak). The interactions in medium lead to the decrease of $M_*$ to $M_0$ and the increase of $\Gamma_*$ to $\Gamma_0$. This makes the “left” particles have larger mass shifts (see Fig. 4), and thus have stronger BBC.

In summary, we have presented an analysis of the medium effect on the $\phi$ mass in the Au+Au and d+Au collisions at the RHIC and investigated the BBC of $\phi\phi$ pairs in the collisions. We find that the invariant mass and mass-width of $K^+K^-$ measured in the collisions are consistent with a picture in which the $\phi$ with low transverse momentum has more possibility decaying inside the source medium than the $\phi$ with high transverse momentum. The investigations indicate that the BBC may perhaps be observed in the collisions of d+Au and the peripheral collisions of Au+Au at the RHIC. We suggest to measure the BBC experimentally for understanding the mass modifications of the $\phi$ meson in the collisions.

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