Squeezed spectra and elliptic flow of bosons and anti-bosons with different in-medium masses

Yong Zhang\(^1\), Shi-Yao Wang\(^2\), Peng Ru\(^3\), and Wei-Hua Wu\(^1\)

\(^1\)School of Mathematics and Physics, Jiangsu University of Technology, Changzhou, Jiangsu 213001, China
\(^2\)School of Physics, Dalian University of Technology, Dalian, Liaoning 116024, China
\(^3\)School of Materials and New Energy, South China Normal University, Shanwei 516600, China

We study the influence of the in-medium mass difference between boson and anti-boson on their spectra and elliptic flow. The in-medium mass difference may lead to a difference between the transverse momentum spectra of boson and anti-boson, and it also leads to the splitting between the elliptic flow of boson and anti-boson. This effect increases with the increasing in-medium mass difference between boson and anti-boson. With the increasing rapidity, the splitting effect of the transverse momentum spectra increases and the splitting effect of the elliptic flow decreases. These phenomena may provide a new sight to study the interactions between the bosons and source medium in high-energy heavy-ion collisions.

Keywords: Boson and anti-boson; in-medium mass difference; spectra; elliptic flow.

PACS numbers: 25.75.Dw, 21.65.jk

I. INTRODUCTION

The particle transverse momentum spectra and elliptic flow are important observables in high-energy heavy-ion collisions. The transverse momentum spectra can be utilized to investigate the thermalization and expansion of the systems produced in such collisions \([1, 14]\). In non-central nucleon-nucleon collisions, elliptic flow is one of the most widely studied observables and it reflects the source transverse anisotropic pressure property \([5–11]\).

In the particle-emitting source created in high-energy heavy-ion collisions, the in-medium mass modification of bosons caused by the interactions between the bosons and source medium may lead to a squeezing effect, and directly lead to a squeezed back-to-back correlation between boson and anti-boson \([12–15]\). This squeezing effect also affects the transverse momentum spectra and elliptic flow of bosons \([13, 14, 16, 17]\). The interactions of charged particles and their corresponding antiparticles in a medium are different, especially in a medium with a finite baryon chemical potential \([18–27]\). The in-medium energy difference between a particle and anti-particle leads to a mass splitting between the quasi-particles in a medium. The influence of the in-medium mass difference between a boson and an anti-boson on the particle spectra was investigated for spherical expanding Gaussian source. The in-medium mass difference leads to a difference between the transverse momentum spectra of boson and anti-boson \([17]\). This phenomenon may contribute to the investigation on the interactions between the bosons and source medium. The in-medium mass difference between a boson and an anti-boson may also lead to new effect on their elliptic flow. It is necessary to use a more realistic source model to study the influence of in-medium mass difference on spectra and elliptic flow of bosons and anti-bosons.

Relativistic hydrodynamics has been widely applied in high-energy heavy-ion collisions. As a first step to the study the influence of the in-medium mass difference between a boson and an anti-boson on the particle spectra and elliptic flow for a more realistic source model, we use the ideal relativistic hydrodynamics in 2 + 1 dimensions to describe the transverse expansion of sources with zero net baryon density and combine the Bjorken boost-invariant hypothesis \([20]\) for the source longitudinal evolution. These descriptions are suitable for the heavy-ion collisions at the RHIC top energy and the LHC energy \([27, 28]\).

In this paper, we present the formulas for calculating the spectra of the boson and anti-boson with different in-medium masses for hydrodynamic sources. The effect of in-medium mass difference on D meson and anti-D meson is investigated. Since D meson contain a charm quark, which is believed to be produced before the formation of the quark-gluon plasma (QGP) and experience the entire evolution of the QGP in high-energy heavy-ion collisions \([39, 40]\). Recently, D meson measurements have attracted great interest \([41–49]\).

This paper is organized as follows. In Sec.II, we present the formulas of the single-particle momentum distributions for boson and anti-boson with different in-medium masses. Then, the squeezed spectra and elliptic flow of boson and anti-boson are shown in Sec. III. Finally, summary and discussion of this paper are given in Sec. IV.

II. FORMULAS

Denote \(a_k(\mathbf{k})\) as the annihilation (creation) operator of the free boson with momentum \(\mathbf{k}\) and mass \(m_a\), and \(b_k(\mathbf{k})\) as the annihilation (creation) operator of the free anti-boson with momentum \(\mathbf{k}\) and mass \(m_b\). For a pair of free boson and anti-boson, \(m_a = m_b = m\), where \(m\) is the mass of boson or anti-boson in the vacuum. Denote \(a'_k(\mathbf{k})\) as the annihilation (creation) operator of the boson with momentum \(\mathbf{k}\) in medium, and \(b'_k(\mathbf{k})\) as the annihilation (creation) operator of the anti-boson in medium. The interactions of a boson and anti-boson with
a medium are different. Assuming the energy split between the boson and anti-boson in the medium is 2\(\delta\), the operators \(a_k, \tilde{a}_k^\dagger, b_k, \tilde{b}_k^\dagger\) for the free particles and \((a_k', \tilde{a}_k'^\dagger, b_k', \tilde{b}_k'^\dagger)\) for the quasiparticles were related by the Bogoliubov transformation [22]:

\[
a_k = c_k a_k' + s_{-k}^* b_{-k}'^\dagger, \quad b_k = \tilde{c}_k b_k' + s_{-k} \tilde{a}_{-k}'^\dagger,
\]

where

\[
c_k = 0, \quad s_{-k} = \tilde{c}_{-k}, \quad c_k = \tilde{c}_{-k}, \quad s_{-k} = \tilde{c}_{-k}, \quad r_k = \frac{1}{2} \ln (\omega_k/\Omega_k),
\]

\[
\omega_k = \sqrt{k^2 + m'^2}, \quad \Omega_k = \sqrt{k^2 + m'^2 + \delta^2},
\]

where \(m'\) is the in-medium mass of the boson or the anti-boson for \(\delta = 0\). The in-medium mass of the boson was considered momentum dependent [13]. In this paper, the in-medium masses of the boson or the anti-boson for \(\delta = 0\) is taken as:

\[
m' = m + \Delta m,
\]

\[
\Delta m = \Delta m_0 \exp[-k^2/\Lambda^2_s],
\]

where \(\Lambda_s\) is a parameter describing the momentum dependence of the in-medium mass-shift, and \(\Delta m_0\) is the in-medium mass-shift of the boson and anti-boson for \(k = 0\). The in-medium masses of the boson and the anti-boson are:

\[
m'_a = (\Omega_k + \delta)|_{k=0} = \sqrt{m'^2 + \delta^2 + \delta},
\]

\[
m'_b = (\Omega_k - \delta)|_{k=0} = \sqrt{m'^2 + \delta^2 - \delta},
\]

where the in-medium mass difference between boson and anti-boson is related to the parameter \(\delta\), the subscript \(a\) indicates the particle with larger mass and the subscript \(b\) represents the particle with smaller mass.

For hydrodynamic sources, the single particle momentum distributions of boson and anti-boson become [13, 17, 50]:

\[
N_a(k) = \int \frac{g_1}{(2\pi)^3} d^4\sigma_\mu(r) k^\mu \left\{ |c'_k|^2 n'_{a,k} + |s'_{-k}|^2 \left[ n'_{b,-k} + 1 \right] \right\},
\]

\[
N_b(k) = \int \frac{g_1}{(2\pi)^3} d^4\sigma_\mu(r) k^\mu \left\{ |c'_k|^2 n'_{b,k} + |s'_{-k}|^2 \left[ n'_{a,-k} + 1 \right] \right\},
\]

\[
c'_{\pm k'} = \cosh[f'_{k'}], \quad s'_{\pm k'} = \sinh[f'_{k'}],
\]

\[
f'_{k'} = \frac{1}{2} \log [\omega'_{k'}/\Omega'_k] = \frac{1}{2} \log [k^\mu u_\mu(r)/k'^\nu u_\nu(r)],
\]

\[
\Omega'_k(r) = \sqrt{k'^2(r) + m'^2 + \delta^2} = \sqrt{k^\mu u_\mu(r)^2 - m'^2 + \delta^2} = k'^\nu u_\nu(r),
\]

\[
n'_{a,k'} = \frac{1}{\exp[(\Omega'_k(r) + \delta)/T(r)] - 1},
\]

\[
n'_{b,k'} = \frac{1}{\exp[(\Omega'_k(r) - \delta)/T(r)] - 1}.
\]

The equation of state of s95p-PCE [36] is used in the hydrodynamic simulations. The initial energy density distribution in the transverse plane at \(\tau_0 = 0.6\) fm/c after the collision is taken as the Gaussian distribution:

\[
\epsilon = \epsilon_0 \exp\left[-x^2/(2R_x^2) - y^2/(2R_y^2)\right],
\]

where \(\epsilon_0\) and \(R_i\) \((i = x, y)\) are the parameters of the initial source energy density and radii [12].

### III. RESULTS

First, we consider the case that the energy split between the boson and anti-boson in the medium is 0 \(\delta = 0\). The transverse momentum spectrum of \(D\) meson with various \(\Lambda_s\) for \(\delta = 0\) are shown in Fig. 1. Here, the freeze-out temperature \(T_f\) of \(D\) meson is taken as 150 MeV [23] and the in-medium mass-shift parameter \(\Delta m_0\) is taken as \(-5\) MeV [23, 51, 52]. The \(\epsilon_0\) is taken as 9 and 45 GeV/fm\(^3\), and the initial radii \(R_x\) and \(R_y\) are taken at 3 fm [12]. Note \(\Lambda_s = 0\) indicates that the \(D\) meson is not affected by the medium. The in-medium mass-shift leads to an increase in the yield of \(D\) meson. This effect increases with the increasing \(\Lambda_s\).

In Fig. 2 we show the transverse momentum spectrum of \(D\) meson and anti-\(D\) meson for \(\delta = 40\) MeV. It can be seen that nonzero \(\delta\) leads to a difference between the transverse momentum spectra of \(D\) meson and anti-\(D\) meson. To quantitatively exhibit the effect of nonzero in-medium energy split on the transverse momentum spectrum of \(D\) meson and anti-\(D\) meson, we show the ratio \(N_a/N_b\) of \(D\) meson for \(\delta = 20\) and 40 MeV in Fig. 3.

For fixed \(\Lambda_s\), the ratio \(N_a/N_b\) decreases with the increasing in-medium energy split. In small transverse momentum region, the ratio \(N_a/N_b\) decreases with the increasing transverse momentum \(k_T\).

In Fig. 4, we show the dependence of the ratio \(N_a/N_b\) of \(D\) meson on the rapidity of the particle. The ratio
$N_a/N_b$ decreases with the increasing rapidity in the interval $0.4 \text{ GeV}/c \leq k_T \leq 0.5 \text{ GeV}/c$. For $\Lambda_s = 500 \text{ MeV}$, the ratio $N_a/N_b$ does not depend on the rapidity in the interval $1.1 \text{ GeV}/c \leq k_T \leq 1.2 \text{ GeV}/c$. The ratio $N_a/N_b$ decreases with the increasing rapidity in the interval $1.1 \text{ GeV}/c \leq k_T \leq 1.2 \text{ GeV}/c$ for $\Lambda_s = 1000 \text{ MeV}$ and $1500 \text{ MeV}$. The above results indicate that the in-medium energy split may lead to a difference between the transverse momentum spectra of $D$ meson and anti-$D$ meson. The difference increases with the increasing in-medium energy split and increases with the increasing rapidity of the particle.

$\Lambda_s$ represents the spectrum of the particle with a larger in-medium mass.

In non-central nucleon-nucleon collisions, elliptic flow is one of the most widely studied observables. To study the effect of nonzero in-medium energy split on the elliptic flow $v_2$, the initial source radii $R_x$ and $R_y$ are taken to be...
FIG. 7: (Color online) The ratio $v_{2a}/v_{2b}$ of $D$ meson for $\delta = 20$ and 40 MeV.

In Fig. 5 we show the elliptic flow $v_2$ of $D$ meson with various $\Lambda_s$ for $\delta = 0$. The in-medium mass-shift suppresses the elliptic flow and this effect increases with the increasing $\Lambda_s$. The elliptic flow $v_2$ of $D$ meson and anti-$D$ meson for $\delta = 40$ MeV are shown in Fig. 6. Here $v_{2a}$ represents the elliptic flow of the particle with larger in-medium mass. The in-medium energy split leads to a small difference between the elliptic flow of $D$ meson and anti-$D$ meson. In Fig. 7 we show the ratio $v_{2a}/v_{2b}$ of $D$ meson for $\delta = 20$ and 40 MeV. The ratio $v_{2a}/v_{2b}$ decreases with the increasing in-medium energy split $\delta$ and decreases with the increasing $\Lambda_s$. For fixed $\delta$ and $\Lambda_s$, the difference between $v_{2a}$ and $v_{2b}$ reduces with the increasing transverse momentum.

In Fig. 8 we show the dependence of the ratio $v_{2a}/v_{2b}$ of $D$ meson on the rapidity of the particle. The ratio $v_{2a}/v_{2b}$ increases with the increasing rapidity in the interval $0.4 \text{ GeV}/c \leq k_T \leq 0.5 \text{ GeV}/c$. For $\Lambda_s = 500$ MeV, the ratio $v_{2a}/v_{2b}$ does not depend on the rapidity in the interval $1.1 \text{ GeV}/c \leq k_T \leq 1.2 \text{ GeV}/c$. The ratio $v_{2a}/v_{2b}$ increases with the increasing rapidity in the interval $1.1 \text{ GeV}/c \leq k_T \leq 1.2 \text{ GeV}/c$ for $\Lambda_s = 1000$ MeV and 1500 MeV. The results in Fig. 8 indicate that the in-medium energy split may lead to a difference between the elliptic flow of $D$ meson and anti-$D$ meson. The difference increases with the increasing in-medium energy split and decreases with the increasing rapidity.

**IV. SUMMARY AND DISCUSSION**

In the particle-emitting source created in high-energy heavy-ion collisions, the in-medium mass modification of bosons caused by the interactions between the bosons and source medium may lead to a squeezing effect. The particle transverse momentum spectra and elliptic flow may be affected by this squeezing effect. The interactions of charged particles and their corresponding antiparticles in a medium are different. In this paper, we study the influence of in-medium mass difference on spectra and elliptic flow of bosons and anti-bosons. Our results indicate that the in-medium mass difference may lead to transverse momentum spectrum and elliptic flow splitting between bosons and anti-bosons. This effect increases with the increasing in-medium mass difference. At larger rapidity, the difference is larger in spectrum and smaller in elliptic flow $v_2$. These phenomena may provide a new sight to study the interactions between the bosons and source medium in high-energy heavy-ion collisions.

In the calculations, we introduce two parameters to describe the in-medium mass-shift. The $\Delta m$ represents the same part of the in-medium mass-shift of the boson and the anti-boson, and it is treated as momentum dependence. The $\delta$ represents the energy split between the boson and anti-boson in the medium, and it is treated as momentum independent. If the $\delta$ decreases with the increasing momentum, the splitting effect of the transverse momentum spectrum and the elliptic flow may be important for boson and anti-boson in small momentum regions.

With the increasing collision energy, the interactions between the bosons and source medium become more intense. The squeezed back-to-back correlation between boson and anti-boson is sensitive to the temporal distribution of the particle source $\frac{d^2 \sigma}{d^2 p_T}$, and it may be suppressed to no observed signal by the wide temporal distribution of the particle source. Thus, the splitting effect of the transverse momentum spectrum and the elliptic flow of bosons and anti-bosons may be significant for studying the interactions between the bosons and source.
medium for the sources with a wide temporal distribution.

Acknowledgments

This research was supported by the National Natural Science Foundation of China under Grant No. 11905085 and Changzhou Science and Technology Bureau under Grant No. CJ20210150.

[1] J. Adams et al. (STAR Collaboration), Phys. Rev. Lett. 92, 112301 (2004).
[2] S. S. Adler et al. (PHENIX Collaboration), Phys. Rev. C 69, 034909 (2004).
[3] B. Abelev et al. (ALICE Collaboration), Phys. Rev. Lett. 109, 252301 (2012).
[4] B. Abelev et al. (ALICE Collaboration), Phys. Rev. C 88, 044910 (2013).
[5] J. Adams et al. (STAR Collaboration), Phys. Rev. C 72, 014904 (2005).
[6] S. Afanasiev et al. (PHENIX Collaboration), Phys. Rev. C 80, 024909 (2009).
[7] B. B. Abelev et al. (ALICE Collaboration), JHEP 1506, 190 (2015).
[8] U. Heinz, Landolt-Bornstein 23, 240 (2010).
[9] J. Y. Ollitrault, Phys. Rev. D 46, 229 (1992).
[10] B. Schenke, J. Phys. G 38, 124009 (2011).
[11] R. Snellings, J. Phys. G 41, 124007 (2014).
[12] M. Asakawa and T. Csörgő, Heavy Ion Physics 4, 233 (1996). [hep-ph/9612331]
[13] M. Asakawa, T. Csörgő and M. Gyulassy, Phys. Rev. Lett. 83, 4013 (1999).
[14] S. S. Padula, G. Krein, T. Csörgő, Y. Hama, P. K. Panda, Phys. Rev. C 73, 044906 (2006).
[15] Y. Zhang, J. Yang, W. N. Zhang, Phys. Rev. C 92, 024906 (2015).
[16] Y. Zhang, J. Yang, Weihua Wu, Int. J. Mod. Phys. E 29, 2050047 (2020).
[17] Y. Zhang, Hui-Qiang Ding, Shi-Yao Wang, Int. J. Mod. Phys. E 30, 2150043 (2021).
[18] G. Q. Li, C. H. Lee, G. E. Brown, Nucl. Phys. A 625, 372 (1997).
[19] A. Sibirtsev, K. Tsushima, and A. W. Thomas, Eur. Phys. J. A 6, 351 (1999).
[20] C. M. Ko, J. Phys. G 27, 327 (2001).
[21] A. Mishra, E. L. Bratkovskaya, J. Schaffner-Bielich, S. Schramm, and H. Stöcker, Phys. Rev. C 69, 015202 (2004).
[22] A. Mishra, E. L. Bratkovskaya, J. Schaffner-Bielich, S. Schramm, and H. Stöcker, Phys. Rev. C 70, 044904 (2004).
[23] D. Blaschke, P. Costa, and Yu. L. Kalinovsky, Phys. Rev. D 85, 034005 (2012).
[24] A. Mishra, A. K. Singh, N. S. Rawat, P. Aman, Eur. Phys. J. A 55, 107 (2019).
[25] P. Z. Xu, W. N. Zhang, Y. Zhang, Phys. Rev. C 99, 011902(R) (2019).
[26] J. D. Bjorken, Phys. Rev. D 27, 140 (1983).
[27] D. H. Rischke, [arXiv:nucl-th/9809043].
[28] P. F. Kolb, U. Heinz. arXiv:nucl-th/0305084
[29] G. Baym, B. L. Friman, J. P. Blaizot, M. Soyeur, W. Czyż, Nucl. Phys. A 407, 397 (1983).
[30] M. Gyulassy, D. H. Rischke, B. Zhang, Nucl. Phys. A 613, 397 (1997).
[31] D. H. Rischke, S. Bernard, J. A. Maruhn, Nucl. Phys. A 595, 346 (1995); D. H. Rischke, M. Gyulassy, Nucl. Phys. A 608, 479 (1996).
[32] T. Csörgő, B. Lörstad, Phys. Rev. C 54, 1390 (1996).
[33] M. Csabád, T. Csörgő, B. Lörstad, A. Ster, J. Phys. G 30, S1079 (2004).
[34] P. F. Kolb, J. Sollfrank, and U. Heinz, Phys. Rev. C 62, 054909 (2000).
[35] P. F. Kolb and R. Rapp, Phys. Rev. C 67, 044903 (2003).
[36] C. Shen, U. Heinz, P. Huovinen, H. C. Song, Phys. Rev. C 82, 054904 (2010).
[37] M. J. Etaf, W. N. Zhang, M. Khaliliasr et al., High Energy Phys. Nucl. Phys. 29, 467 (2005).
[38] H. C. Song, Y. Zhou, K. Gajdosová, Nucl. Sci. Tech. 28, 99 (2017).
[39] J. Adam et al. (ALICE Collaboration), J. High Energy Phys. 03, 081 (2016).
[40] F. M. Liu, S. X. Liu, Phys. Rev. C 89, 034906 (2014).
[41] L. Adamczyk et al. (STAR Collaboration), Phys. Rev. Lett. 113, 142301 (2014).
[42] M. Lomnitz for STAR Collaboration, Nucl. Phys. A 956, 256 (2016).
[43] B. Abelev et al. (ALICE Collaboration), Phys. Rev. Lett. 111, 102301 (2013).
[44] B. Abelev et al. (ALICE Collaboration), Phys. Rev. C 90, 034904 (2014).
[45] S. Acharya et al. (ALICE Collaboration), Phys. Lett. B 790, 388 (2019).
[46] S. Acharya et al. (ALICE Collaboration), Eur. Phys. J. C 80, 979 (2020).
[47] S. Acharya et al. (ALICE Collaboration), Phys. Lett. B 813, 136054 (2021).
[48] S. Acharya et al. (ALICE Collaboration), J. High Energy Phys. 05, 220 (2021).
[49] F. Cooper and G. Frye, Phys. Rev. D 10, 186 (1974).
[50] C. Fuchs, B. V. Martemyanov, A. Faessler, and M. I. Krivoruchenko, Phys. Rev. C 73, 035204 (2006).
[51] A. G. Yang, Y. Zhang, L. Cheng, H. Sun, and W. N. Zhang, Chin. Phys. Lett. 35, 052501 (2018).
[52] Y. Zhang, W. N. Zhang, Eur. Phys. J. C 76, 419 (2016).