Письма в ЭЧАЯ. А. 2011. Т. 8, № 9. С. 238–241

SEARCH FOR PARTICLE–ANTIPARTICLE BACK-TO-BACK CORRELATIONS IN $\sqrt{s_{NN}} = 200$ GeV Au + Au COLLISIONS

M. I. Nagy
for the PHENIX Collaboration
MTA KFKI RMKI, Budapest

A novel type of quantum mechanical correlations, hypothesized in the 1990s, the (squeezed) back-to-back correlations, was predicted to appear in heavy-ion collisions among particle–antiparticle (e.g., $\pi^+\pi^-$, K^+K^-, $p\bar{p}$) pairs, if their in-medium masses are different from the vacuum values. Observation of this correlation would provide new insight into the freeze-out dynamics of the created matter. The latest status of the PHENIX measurement, comprising the first measurement of this new effect, is presented.

PACS: 25.75.-q

1. INTRODUCTION AND PHYSICAL MOTIVATION

Since the discovery of the GGLP (or HBT) effect [1], measurements of quantum statistical correlations of identical bosons (mainly $\pi^{\pm}$s) became a powerful experimental tool to address the space-time structure of particle production and to investigate the phase transition from partonic to hadronic matter in relativistic heavy-ion reactions collisions. (For a review, see [4].) In the 1990s, a novel type of quantum optical correlation effect was postulated among back-to-back particle–antiparticle pairs [2, 3]. (For a detailed explanation of the theoretical background, and predictions, see [3–6]). This correlation would be present if a dense hadronic medium is formed, where the hadron masses are different from the vacumm (asymptotic) values. The reason is that the quantum field theoretical operators that create and annihilate particles with the modified masses are in a nontrivial relationship with their vacuum counterparts[1]. This relationship can be interpreted in the way that a quantum state of a mass-modified (in-medium) particle is a superposition of a free particle and an antiparticle of opposite momenta, with vacuum masses, thus a thermal distribution of in-medium particles leads to a correlation among particles and antiparticles with opposite momenta: the *squeezed back-to-back correlation*. This correlation is in principle *unlimited* from above. The mathe-

[1]The in-medium particle (antiparticle) creation and annihilation operators $\hat{b}^\dagger, \hat{b}$ ($\overline{\hat{b}}^\dagger, \overline{\hat{b}}$) are connected with vacuum ones ($\hat{a}^\dagger, \hat{a}, \overline{\hat{a}}^\dagger, \overline{\hat{a}}$) by a *Bogoliubov–Valatin transformation*:

$$\hat{b}^\dagger_{\mathbf{k}} = \cosh r_k \, \hat{a}^\dagger_{\mathbf{k}} - \sinh r_k \, \overline{\hat{a}}_{-\mathbf{k}}, \quad \overline{\hat{b}}^\dagger_{\mathbf{k}} = \cosh r_k \, \overline{\hat{a}}^\dagger_{\mathbf{k}} - \sinh r_k \, \hat{a}_{-\mathbf{k}}, \quad r_k = \frac{1}{2} \ln \omega_{\mathbf{k}}/\Omega_{\mathbf{k}}$$

in the bosonic case [3]. Here $\omega_{\mathbf{k}}$ and $\Omega_{\mathbf{k}}$ are the energy of the vacuum particle and the in-medium particle with three-momentum $\mathbf{k}$, respectively. We see that this transformation mixes the original creation and annihilation operators of opposite three-momenta.

matical formalism leading to these statements is more or less similar for particles of arbitrary spin[1], so the effect is expected to appear for other particle (and antiparticle) types as well.

Many theoretical models predict that in a dense hadronic medium the masses of the particles will be different from the vacuum ones. This new effect is very appealing to search for: it would be an effective tool to study the onset of mass modification[2], if such a medium is formed in heavy-ion collisions. In the following the recent status of the search for this new type of correlation, the first measurement ever aimed at squeezed back-to-back correlations is presented, as performed by the PHENIX experiment.

2. EXPERIMENT AND MEASUREMENT METHOD

The dataset recorded during the 2004 running period of RHIC was used, consisting of $\sim 900 \cdot 10^6$ available Au + Au collision events (passing necessary quality assurance cuts). For a detailed description of the PHENIX detectors, see [8]. This analysis relies on the charged particle tracking subsystems: the Drift Chamber and the Pad Chambers giving momentum measurement, track reconstruction, fake track and in-flight weak decay background rejection. The high-resolution Time-of-Flight detector, together with the Electromagnetic Calorimeter, yields time-of-flight information of hadrons so that (using their modelled track path length) their velocity can be determined: a cut on the observed m^2 spectrum of tracks around the nominal m^2 values of the desired particles enables reliable identification of pions (kaons, protons) in the $0.15\,(0.3, 0.4) < p_T\,(\mathrm{GeV}/c) < 1.2\,(1.0, 1.5)$ domains, respectively.

The experimental correlation function, C_{BB} is the normalized ratio of the phase-space distribution of particle pairs from collision events and the same kind of distribution of pairs from different events; its deviation from a constant 1 means the presence of the new effect. In the ideal case of infinite medium at rest, C_{BB} would be non-unity only in the identically back-to-back case ($\mathbf{k}_1 + \mathbf{k}_2 = 0$). For finite systems with radial flow, the region of $C_{BB} \neq 1$ is predicted to be wider, so $2K \equiv |\mathbf{k}_1 + \mathbf{k}_2|$ is an appropriate variable: we expect $C_{\mathrm{BB}}(2K) > 1$ around $2K = 0$. We will use the notation λ_{BB} for the correlation strength, i.e., the extrapolated intercept at $2K = 0$.

According to theory and simulation results [3, 6], λ_{BB} depends strongly on other parameters, such as the transverse momentum p_T (of either particle). Another such parameter is the particle emission time dependence: the signal is predicted to be suppressed by $\left|\tilde{F}(\omega_1 + \omega_2)\right|^2$, where ω are the energies of the particles, and $\tilde{F}(\omega) \equiv \int d\tau\, \mathrm{e}^{-i\omega\tau} F(\tau)$ is the Fourier transform of the freeze-out distribution $F(\tau)$. An exponential decay ($F(\tau) = \Theta(\tau)\, \mathrm{e}^{-\tau/\tau_0}$) yields a Lorentzian suppression, making the signal considerably weaker. If one assumes, e.g., a Levy

---

[1] In the fermionic case the only difference is in the form of the Bogoliubov–Valatin transformation [5]. The expectation is again a back-to-back correlation of fermion–antifermion pairs. (Note that in the HBT effect, identical fermion pairs show anticorrelation.)

[2] Let us mention a recent result on HBT correlation studies: a comprehensive analysis of two-pion HBT correlation strength data as a function of transverse momentum p_T (measured by the STAR and PHENIX experiments in $\sqrt{s_{NN}} = 200$ GeV Au + Au collisions) shows that the p_T spectrum of the η' meson breaks the expected m_T scaling, suggesting the in-medium mass modification of the η' meson. (This effect could be caused by the restoration of the chiral $U_A(1)$ symmetry of QCD.) It is thus not unreasonable to assume the formation of a thermalized hadronic medium in later stages of $\sqrt{s_{NN}} = 200$ GeV Au + Au collisions. (For details and experimental data, see [7], and references therein.)

distribution [9] or Gaussian for $F(\tau)$, then the Fourier transform gives a suppression stronger than exponential, and makes the effect almost completely vanish (i.e., decrease below the currently achievable experimental resolution); the only possible exception being very low momentum pions[1]. These suggest that one should explore every accessible particle (and antiparticle) type and momentum region differentially[2].

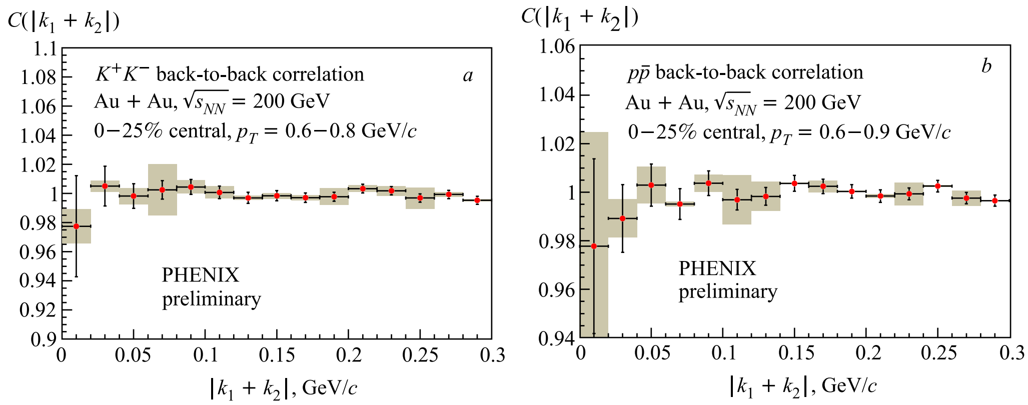

Fig. 1. Selected measurements for K^+K^- pairs (*a*) and for $p\bar{p}$ pairs (*b*), for typical p_T ranges. (Selection in p_T is for both particles.) Error bars represent statistical uncertainties, bands are for estimated systematic uncertainty. A $\gtrsim 1\%$ effect is not present on a significant level

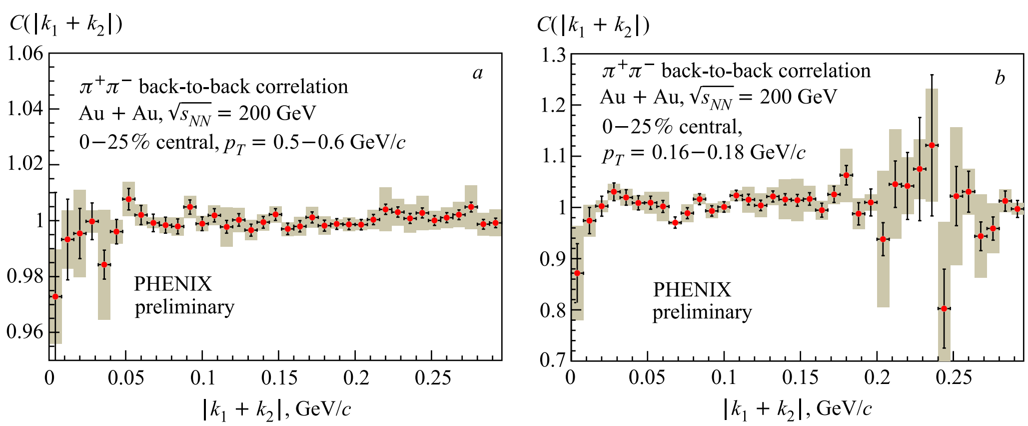

Fig. 2. Back-to-back correlations for $\pi^+\pi^-$ pairs at selected p_T ranges. Effect above the $\simeq 1$−2% resolution is not present on a significant level

[1]We cite some predictions for kaons based on [6]: with an instantaneous emission and no flow, $\lambda_{\rm BB}$ can reach ~ 1000 for $p_T \sim 1$ GeV/c, decreasing with decreasing p_T, while the presence of flow suppresses $\lambda_{\rm BB}$ by a factor of $\simeq 2$−3. Exponential freeze-out makes $\lambda_{\rm BB}$ reach only 2−3 at $p_T \sim 1$ GeV/c, and even less for lower p_T. For Gaussian, or Levy type emissions, $\lambda_{\rm BB}$ is in the order of $\sim 10^{-6}$−10^{-10}, depending on the emission time. In this latter case, $\lambda_{\rm BB}$ decreases with increasing particle energy.

[2]For verification of the measurement method, a cross-check, measuring identical particle pair back-to-back correlations (where no correlation effect is expected), was performed, showing no deviation from the expectation.

3. PRELIMINARY RESULTS

Figure 1 shows selected examples of measured correlation functions for K^+K^- and for $p\bar{p}$ pairs. The effect of a $\gtrsim 1{-}2\%$ back-to-back correlation would be visible with the current sensitivity. For the $\pi^+\pi^-$ case, two measurements at different p_T ranges are seen in Fig. 2.

4. CONCLUSIONS AND OUTLOOK

The results shown here seem to exclude the presence (with a strength of $\lambda_{\rm BB} \sim 2\%$ or greater) of the anticipated squeezed back-to-back correlation signal in $\sqrt{s_{NN}} = 200$ GeV Au + Au collisions for the presented momentum ranges and particle types. Interpretation of this preliminary result, however, requires care: even the absence of the effect (a conclusion not to be drawn from this measurement) can still be interpreted in two ways: either there is a mass modification of hadrons, but the suppression factor coming from the freeze-out distribution makes it practically unobservable (as discussed in Sec. 2), or there is really no mass modification. In this latter case, then would it contradict to the presence of a hadronic medium, which is a constraint on the phase transition from deconfined matter to hadrons. However, the possible mass modification of η' (see footnote 2 on p. 239) seems to support the presence of a hadronic medium.

Possible improvements of the theoretical description (estimation of the signal properties, understanding the causes of in-medium mass modification and the resonance decay contribution) as well as of the experimental technique (improved particle identification at lower and higher p_T values) or of the dataset volume (either at PHENIX, or at LHC experiments) would lead to measurements that either strengthen the upper limit on the squeezed particle–antiparticle back-to-back correlation or discover this new effect on a statistically significant level. In this way this effect can contribute to our understanding of the phase transition in high-energy heavy-ion collisions. Investigation of other colliding systems (other nuclei) or other collision energies (like as it will be possible in the upcoming RHIC low-energy scan programme) might be also interesting in the quest for this new type of quantum optical effect in heavy-ion collisions.

REFERENCES

1. *Goldhaber G. et al.* // Phys. Rev. 1960. V. 120. P. 300.;
   Brown Hanbury R., Twiss R. Q. // Nature. 1956. V. 178. P. 1046.
2. *Andreev I. V., Plümer M., Weiner R. M.* // Phys. Rev. Lett. 1991. V. 67. P. 3475.
3. *Asakawa M., Csörgő T., Gyulassy M.* // Phys. Rev. Lett. 1999. V. 83. P. 4013.
4. *Csörgő T., Padula S. S.* // Braz. J. Phys. 2007. V. 37. P. 949.
5. *Panda P. K. et al.* // Phys. Lett. B. 2001. V. 512. P. 49.
6. *Dudek D. M., Padula S. S.* // Phys. Rev. C. 2010. V. 82. P. 034905.
7. *Csörgő T., Vértesi R., Sziklai J.* // Phys. Rev. Lett. 2010. V. 105. P. 182301;
   Vértesi R., Csörgő T., Sziklai J. // Nucl. Phys. A. 2009. V. 830. P. 631.
8. *Adcox K. et al. (PHENIX Collab.)* // Nucl. Instr. Meth. A. 2003. V. 499. P. 469.
9. *Csörgő T., Hegyi S., Zajc W. A.* // Eur. Phys. J. C. 2004. V. 36. P. 67.