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Charged and neutral kaon correlations in Au–Au collisions at $\sqrt{s_{NN}} = 200$ GeV using the solenoidal tracker at RHIC (STAR)

Selemon Bekele (for the STAR Collaboration)

The Ohio State University, 174 W 18th Ave., Columbus, OH 43210, USA

E-mail: bekele@pacific.mps.ohio-state.edu

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Abstract
Two boson intensity interferometry (also known as Hanbury-Brown–Twiss, or HBT (Brown R Hanbury and Twiss R Q 1956 *Nature* **178** 1046)) offers information on the spacetime structure of the particle-emitting source created in heavy-ion collisions. Kaon HBT has been suggested as a promising probe of quark–gluon plasma and reveals strangeness dynamics. Small contributions from resonance decays make kaon HBT an ideal tool for correlation studies. In conjunction with pion correlation measurements, they can also reveal properties of collective dynamics in heavy-ion collisions. We present preliminary results on neutral and charged kaon correlations in $\sqrt{s_{NN}} = 200$ GeV Au–Au collisions measured by the STAR Collaboration at the relativistic heavy ion collider.

1. Introduction

In the collision of nuclei at extremely high energies, a new state of nuclear matter is expected to be formed. This new state of matter is believed to have as its degrees of freedom the fundamental particles of QCD, quarks and gluons and is often referred to as the quark–gluon plasma (QGP) [2]. The fundamental problem of high energy heavy-ion collision experiments is to identify and study observables which are believed to be signatures for the formation of the QGP, which lives only for a fleeting moment before undergoing a phase transition to normal nuclear matter consisting of hadrons which are eventually measured. Thus, the challenge facing experimental high energy and nuclear physicists is to characterize the earliest moments of the hot reaction zone by extrapolating back from the measured hadronic observables.

Measuring the size of the particle-emitting source has been an important goal in the study of high energy e^+e^-, p–p and nuclear collisions for several decades [3]. HBT interferometry has been used to study the spacetime structure of the reaction zone from an analysis of two-particle correlation functions [3, 4]. HBT measures the so-called homogeneity length, which is the size of a particular region within the source emitting particles with identical momenta [5]. A phase transition from a QGP to normal hadronic matter is expected to delay the expansion of the system due to a softening of the equation of state. If this is so, a long duration of particle emission is expected, leading to a large source size in the direction of the pair's total transverse momentum as compared to that in the direction perpendicular to it in the plane normal to the beam [2, 6, 7].

Experimentally, the correlation function is defined as

$$C_2(q) = \frac{A(q)}{B(q)} \tag{1}$$

where $A(q)$ represents the distribution of 4-momentum difference $q = p_1 - p_2$ for a pair of particles from the same event. $B(q)$ is the reference distribution constructed by mixing particles from different events. The mixed pairs are also required to satisfy the same pairwise cuts applied to pairs from the same event.

We present here preliminary charged and neutral kaon correlation measurements as a function of transverse mass $\left(M_{\rm t} = \sqrt{k_{\rm t}^2 + m^2}, k_{\rm t} = \frac{1}{2}\sqrt{p_{1\rm t}^2 + p_{1\rm t}^2}\right)$ in Au–Au collisions at $\sqrt{s_{NN}} = 200$ GeV carried out by the STAR experiment at the relativistic heavy ion collider (RHIC).

2. The STAR experiment

The main tracking device for STAR is a large cylindrical time projection chamber (TPC) that provides momentum information and particle identification for charged particles [9]. Charged particles are identified through a measurement of their specific energy loss $\mathrm{d}E/\mathrm{d}x$ in the gas of the TPC as a function of momentum. Two zero degree calorimeters (ZDC) measuring spectator neutrons in coincidence are used to define a minimum bias trigger. A central trigger barrel (CTB) made up of scintillator paddles around the TPC is used to select central events with high multiplicity. More details of the experimental set-up can be found in [10]. Data from Au–Au collisions at $\sqrt{s_{NN}} = 200$ GeV were used for the results presented here.

3. Charged kaon correlations

Charged kaons could provide a cleaner signal for correlation studies than pions since the former are less affected by resonance decays [4, 11]. Also, the difference in the nuclear cross sections of the K^+ and K^- may lead to differences in the HBT radii obtained from correlation measurements. Similar radius values imply a nucleon-free environment through which the particles propagated before freeze-out.

Central events (0–10% of the total hadronic cross section) with vertex position within ±25 cm from the centre of the TPC were selected for this analysis. The effects of track splitting (one track erroneously reconstructed as two tracks) and track merging (two tracks with similar momenta mistakenly reconstructed as one) were eliminated as described in [13]. Tracks were required to have a distance of closest approach less than 3 cm from the primary vertex and have at least ten hit points on them. The transverse momentum of the pair, $k_{\rm t}$, was divided into two bins, the lowest bin ranging from 150 MeV/c to 350 MeV/c and the highest bin from 350 MeV/c to 550 MeV/c. For the reference distribution, those events with similar vertex z position were mixed.

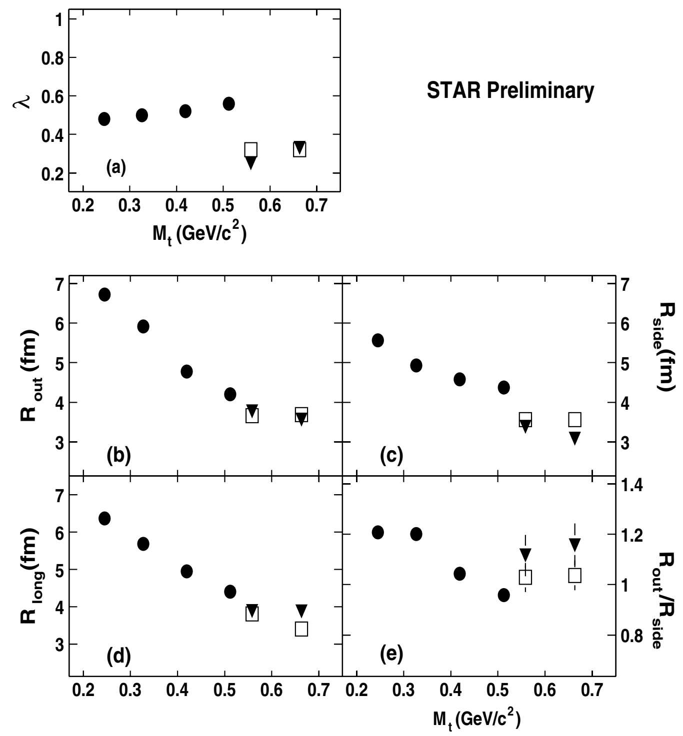

Figure 1. The HBT radii and λ as a function of transverse mass M_t. Circles are for $\pi^-\pi^-$, triangles for K^-K^- and open squares for K^+K^+. The kaons are not corrected for purity and momentum resolution. The errors shown are only statistical.

The three-dimensional correlations were fit to a function [12]

$$\frac{A(q)}{B(q)} = N[1 + \lambda(K_{\mathrm{Coul}}(q)\{1 + G(q)\} - 1)] \tag{2}$$

where $G(q) = \exp\sqrt{-\left(R_{\mathrm{out}}^2 q_{\mathrm{out}}^2 + R_{\mathrm{side}}^2 q_{\mathrm{side}}^2 + R_{\mathrm{long}}^2 q_{\mathrm{long}}^2\right)}$, and the $K_{\mathrm{Coul}}(q)$ is a distribution of Coulomb weights calculated via a five-dimensional Monte Carlo integration of Coulomb wavefunctions over a uniform spherical source of particles. The Coulomb effect is included only for those pairs that contribute to the Bose–Einstein (BE) enhancement [12]. N is a normalization constant and λ is the chaoticity parameter. For this analysis we used the Pratt–Bertsch components q_{long} along the beam axis, q_{out} along the sum of the momentum components of the pair transverse to the beam and q_{side} which is perpendicular to both q_{out} and q_{long}. R_{out}, R_{side}, R_{long} denote the corresponding size parameters.

A plot of λ and the radius parameters as a function of the pair transverse mass M_t is shown in figure 1. The pion (circles) points correspond to the same data presented at the Quark Matter 2002 meeting [14] but fitted with equation (2). The value of λ seems to be slightly increasing with M_t while the radii appear to decrease with M_t. As resonance contribution is supposed to be small, the M_t dependence of the radii seems to be a consequence of collective flow [15]. We note that there is no dramatic increase in the ratio $R_{\mathrm{out}}/R_{\mathrm{side}}$ which has been suggested by many authors as a clear sign of a deconfinement phase transition in heavy-ion collisions [8, 16]. The radius parameters are comparable to those measured at SPS in Pb+Pb collisions at 158 GeV/c while λ is smaller by about a factor of 2.5.

4. Neutral kaon correlations

Neutral kaons, which are eigenstates of the strong interaction that conserve strangeness, are in general not detected as such but rather as the short-lived K_s^0 and the long-lived K_l^0 which are mixtures of K^0 and $\overline{K^0}$ [17]. The $K_s^0 K_s^0$ system is a linear combination of $K^0 K^0$, $\overline{K^0}\,\overline{K^0}$ and $K^0\overline{K^0}$. If a $K_s^0 K_s^0$ pair comes from $K^0 K^0(\overline{K^0}\,\overline{K^0})$, it is subject to BE enhancement as it originates from an identical boson pair. On the other hand, a $K^0\overline{K^0}(\overline{K^0}K^0)$ system gives a $K_s^0 K_s^0$ pair which is not necessarily subject to BE symmetrization. In general, the wavefunction of the $|K^0\overline{K^0}\rangle$ state is made up of $C = +1$ and $C = -1$ eigenstates of the charge conjugation operator [18]:

$$|K^0\overline{K^0}\rangle_{C=\pm 1} = \frac{1}{\sqrt{2}}(|K^0(p)\overline{K^0}(-p)\rangle \pm |\overline{K^0}(p)K^0(-p)\rangle) \tag{3}$$

where p is the 3-momentum vector of one of the pairs in their centre of mass frame. One can see that the probability amplitude for the $C = -1$ state disappears in the limit of vanishing momentum while it goes to unity for the $C = +1$ state. A measurement of only $K_s^0 K_s^0$ thus leads to a BE-like enhancement in the low Q region. This brings into question whether the correlation function of the neutral kaons comes from the decay of the $f^0(980)$ into a $K^0\overline{K}^0$ system. The answer lies in what the yield of the $f^0(980)$ is at the temperatures present in the collisions at chemical freeze-out.

The STAR experiment has carried out the first significant measurement of $K_s^0 K_s^0$ correlation in heavy-ion experiments. This particle has a decay length of 2.7 cm and decays via the weak interaction into π^+ and π^-. Unlike the charged kaons, these neutral particles are identified through their decay topology. Experimentally, one looks for pairs of oppositely charged tracks that extrapolate to a common point which is as far away as possible from the primary vertex. This analysis included all those candidates in the mass range from 0.48 GeV/c to 0.51 GeV/c, transverse momentum from 0.1 GeV/c to 3.5 GeV/c and rapidity between -1.5 and 1.5. The distance of closest approach of the parent particle to the primary vertex was kept below 6 cm and the decay length was set to be greater than 4 cm. The possibility of a single neutral kaon being correlated with itself was eliminated by requiring that a pair of K_s^0 have unique daughters, and that their decay positions were spatially well separated.

We reconstructed about 3.8 K_s^0 candidates per event. The mean transverse pair momentum is about 800 MeV/c. Figure 2(a) shows the invariant mass distribution of the K_s^0 which is not background subtracted. One can see a clear signal relative to the background. The correlation function is displayed in figure 2(b). The line is a fit to the functional form

$$C(q) = N\left(1 + \lambda \mathrm{e}^{-R_{\mathrm{inv}}^2 q_{\mathrm{inv}}^2}\right) \tag{4}$$

where q_{inv} is the invariant 4-momentum and R_{inv} is the corresponding size parameter. Figures 2(c) and (d) show the M_{t} systematics of R_{inv} and λ. The pion (circles) and charged kaon (open symbols) points were obtained through a fit to the one-dimensional version of equation (2). The value of λ is not close to unity which is the value expected for a system with little contamination from decaying resonances, while R_{inv} is large considering the large mean transverse momentum of the pair. As can be seen from figure 2(d), this seems to violate the M_{t} scaling that hydrodynamics predicts [15]. The value of λ is similar to results from the DELPHI [19] experiment while it is almost half of the values that the experiments OPAL [20] and ALEPH [21] report for correlations of neutral kaons from hadronic decays of Z^0 in e^+e^- collisions at LEP.

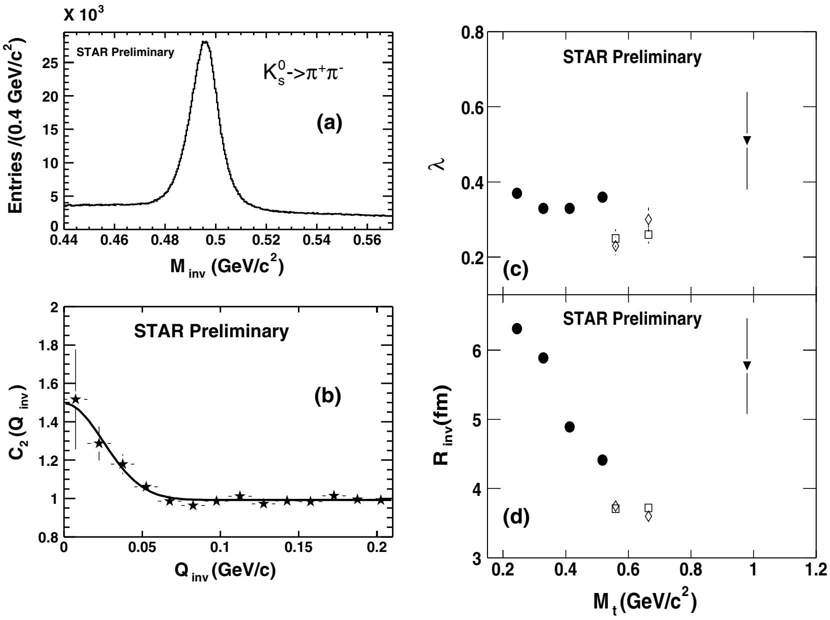

Figure 2. (a) K_s^0 invariant mass distribution and (b) $K_s^0K_s^0$ correlation function. (c) λ as a function of M_t. (d) R_inv as a function of M_t. Solid circles are for $\pi^-\pi^-$, open squares for K^+K^+ and diamonds for K^-K^-. Only statistical errors are shown.

5. Conclusions

We have presented preliminary results on kaon correlations in Au+Au collisions at RHIC. The radius parameters for the charged kaons seem to follow the M_t scaling predicted by hydrodynamical calculations. We have presented the first measurement on neutral kaon correlations in heavy-ion collisions. The value of the radius parameter seems to indicate a violation of the M_t systematics that the charged particles appear to obey. The value of λ is not close to unity as for a system where the effect of resonance decays is supposed to be small. We expect that λ would go up when the data are corrected for purity and momentum resolution effects.

Acknowledgments

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