Kaon Interferometry at RHIC from AMPT Model

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Abstract. The two-kaon interferometry at RHIC is studied in a multi-phase transport model. Similar to the pion case, we find strong space-time correlation at freeze-out for the kaon emission source, which results in a large positive \( R_{out} - t \) term and tends to reduce the \( R_{out}/R_{side} \) ratio. Unlike the pion case, the source radii for kaons determined from the emission function are close to the radius parameters extracted from a Gaussian fit to the correlation function.

1. Introduction and Summary

Particle interferometry based on the Hanbury-Brown Twiss (HBT) effect has been used extensively in heavy ion collisions to extract the information on the emission source of particles \[1, 2, 3, 4\]. In particular, the long emission time as a result of the phase transition from the quark-gluon plasma to hadronic matter in relativistic heavy ion collisions may lead to an emission source which has a much larger radius in the direction of the total transverse momentum of detected two particles (\( R_{out} \)) than that perpendicular to both this direction and the beam direction (\( R_{side} \)) \[4, 5\]. Since the quark-gluon plasma is expected to be formed in heavy ion collisions at RHIC, it is surprising to find that the extracted ratio \( R_{out}/R_{side} \) from a Gaussian fit to the measured two-pion correlation function in Au+Au collisions at \( \sqrt{s} = 130A \) GeV is close to one \[6, 7, 8\], very different from predictions of hydrodynamical models \[4, 5\].

Since particle interferometry probes the phase-space distributions of particles at freeze-out, it is natural to apply transport models to HBT. The reason is that particle freeze-out is dynamically generated in transport models when the mean-free-path exceeds the system size at later stage of expansion, whereas freeze-out has to be imposed in hydrodynamical models. Using a multi-phase transport (AMPT) model, we have found that the small pion \( R_{out}/R_{side} \) ratio could be due to a large and positive space-time correlation in the emission source \[9\]. Furthermore, the pion source at freeze-out is highly non-Gaussian, leading to much larger pion source radii than the radius parameters from a Gaussian fit to the three-dimensional correlation function.

In this study, we extend the work of Ref.\[9\] by studying the kaon interferometry in central Au+Au collisions at RHIC energies. Using the AMPT model, we find that, unlike the pion case, the kaon source radii extracted directly from the emission function are close to the fitted radius parameters extracted from a Gaussian fit to the

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three-dimensional correlation function. Our results also show that the kaon emission source has a large and positive correlation between time and position along the out-
direction at freeze-out, similar to what we have found earlier for the pion emission 
source. We expect that the study of kaon interferometry, as well as other observables 
such as the strange hadron elliptic flow, will be useful in understanding the dynamics 
of strange quarks and hadrons in heavy ion collisions at RHIC.

2. A MultiPhase Transport Model - AMPT

The AMPT model is a hybrid model that uses the minijet partons from hard processes 
and excited strings from soft processes in the HIJING model \(10\) for the initial 
condition of relativistic heavy ion collisions. The time evolution of partons is then 
described by the ZPC \(11\) parton cascade model, and that of hadrons by an extended 
ART model \(12\). In the default AMPT model, only minijet partons are included 
in the parton cascade with a parton scattering cross section of \(\sigma_p = 3\) mb. After 
partons freeze out, they combine with their parent strings and then fragment to 
hadrons according to the Lund string fragmentation as implemented in PYTHIA \(13\). 
The default model has been quite reasonable in describing the measured rapidity 
distributions of charge particles \(14, 15\), particle to antiparticle ratios \(15\), and the 
spectra of low transverse momentum pions, kaons \(16\), multi-strange baryons \(17\) and 
\(\phi\) mesons \(18\) in heavy ion collisions at SPS and/or RHIC.

Since the initial energy density in Au+Au collisions at RHIC is expected to be 
much larger than the critical energy density at which the transition from hadronic 
matter to quark-gluon plasma would occur \(19, 20\), the AMPT model has been 
extended to allow the conversion of initial excited strings to partons at RHIC energies 
\(21, 9\). In this string melting scenario, hadrons that would have been produced 
from string fragmentation are converted instead to valence quarks and/or antiquarks. 
Interactions among these partons are again described by the ZPC parton cascade 
model. The transition from the partonic matter to hadronic matter at parton freeze-
out is achieved using a simple quark coalescence model by combining two nearest 
partons into mesons and three nearest partons into baryons (or anti-baryons) \(21\). 
With the energy in excited strings taking part in the early partonic interactions and 
using quark coalescence to model hadronization, the extended AMPT model with 
string melting \(21\) is able to describe the observed elliptic flow at RHIC \(22, 23\), 
which the default AMPT model failed to reproduce.

At present, the ZPC parton cascade \(11\) in the AMPT model includes only 
two-parton elastic scatterings. The in-medium differential cross section is given by 
\(d\sigma/d\hat{t} = 9\pi\alpha_s^2(1+\mu^2/\hat{s})/2/(1-\mu^2)^2\), where the effective screening mass \(\mu\) in principle 
depends on the temperature and density of the partonic matter \(11\). In this study, we 
take \(\mu\) as a parameter in order to study the effect of partonic scatterings. Also, for 
simplicity, we assume the same scattering cross section for partons of different flavors. 
We note, however, that comparisons of high-quality data on the elliptic flow of strange 
hadrons \(24, 25\) with theoretical predictions \(26, 27, 28, 29, 30\) is expected to provide 
very useful information on the interactions of strange quarks in dense matter.

3. Two Ways of Extracting Radius Parameters

To evaluate the two-kaon correlation function requires the knowledge of the single 
kaon emission function \(S(x, p)\). In the AMPT model, it is obtained from the kaon
space-time coordinate $x$ and momentum $p$ at kinetic freeze-out. The HBT correlation function for two identical hadrons of momenta $p_1$ and $p_2$ is then given by

$$C_2(Q, K) = 1 + \frac{\int d^4x_1d^4x_2S(x_1, K)S(x_2, K)\cos[Q \cdot (x_1 - x_2)]}{\int d^4x_1S(x_1, p_1)\int d^4x_2S(x_2, p_2)},$$

where $K = (p_1 + p_2)/2$ and $Q = (p_1 - p_2, E_1 - E_2)$. Expecting that the emission function is sufficiently smooth in momentum space, one can evaluate the correlation function by using $p_1$ and $p_2$ for $K$ in the numerator of above equation.

First, the size of the emission source can be extracted from the emission function via the curvature of the correlation function at $Q = 0$:

$$R_{ij}^2(K) = D_{x_i, x_j}(K) - D_{x_i, \beta_j t}(K) + D_{\beta_i t, x_j}(K) + D_{\beta_i t, \beta_j t}(K).$$

(2)

In the above, $\beta = K/K_0$ with $K_0$ denotes the average energy of the two kaons; $x_i(i = 1 - 3)$ are spatial coordinates of a kaon at freeze-out; and $D_{x,y} = \langle x \cdot y \rangle - \langle x \rangle \langle y \rangle$ with $\langle x \rangle$ denoting the average value of $x$. In this study we use the usual “out-side-long” (osl) coordinate system.

On the other hand, the measured correlation function $C_2(Q, K)$ is usually fitted by a Gaussian function in $Q$, i.e.,

$$C_2(Q, K) = 1 + \lambda \exp\left( -\sum_{i=1}^{3} R_{ii}^2(K)Q_i^2 \right),$$

(3)

We note that, for central heavy-ion collisions, the above fitted radius parameters would be identical to the source radii given by the curvature of the emission function at $Q = 0$ (i.e. Eq. (2)) only when the emission source is Gaussian in space and time.

4. AMPT Results at RHIC Energies

4.1. Two-kaon correlation function

![Figure 1](image-url)  
**Figure 1.** Correlation functions for $K_0^3$ ($-1 < y < 1, 200 < p_T < 400$ MeV/c).

Using the program Correlation After Burner, we have evaluated the correlation function $C_2(Q, K)$ of two kaons in their longitudinally comoving frame for central ($b = 0$ fm) Au+Au collisions at $\sqrt{s} = 130$ A GeV. In Figure 1, we show the invariant correlation function, i.e., the correlation function as a function of $Q_{inv} = \sqrt{-Q^2}$, and its projections onto one of the $Q_{out}, Q_{side}$ and $Q_{long}$ axes. In evaluating the projected correlation function, the other two $Q$-components have been integrated over the range $0 - 40$ MeV/c. The dash-dotted curves in Figure 1 represent results from the default AMPT model (no string melting), while the other curves are
from the extended AMPT model with string melting but using different values for $\sigma_p$. It is seen that the one-dimensional kaon correlation functions become narrower as $\sigma_p$ is increased in the extended AMPT model. Their dependence on $\sigma_p$ seems, however, to be much weaker than that of the pion correlation function [9].

4.2. Source radii versus fitted radius parameters

The source radii for kaons within $-1 < y < 1$ and $200 < p_T < 400 \text{ MeV}/c$ are shown in Figure 2 (a). The results are obtained from both the default AMPT model (shown at $\sigma_p = 0$) and the extended AMPT model with string melting. For the latter, we have used different parton cross sections of $\sigma_p = 3, 6, 10,$ and $15 \text{ mb}$. It is seen that these radii have values between 2 and 5 fm, and they are much smaller than the source radii for low $p_T$ pions (between 7 and 25 fm) [9]. The $R_{\text{out}}/R_{\text{side}}$ ratio (solid curves without symbols) from the kaon emission function is also shown in Figure 2 (a), and it increases appreciably with increasing parton scattering cross section.

![Figure 2](image)

Figure 2. (a) Source radii, (b) fitted radius parameters and $\lambda$ for $K^0_S$ as functions of $\sigma_p$ at 130A GeV. Points at $\sigma_p = 0$ correspond to the default AMPT.

The radius parameters obtained from fitting the three-dimensional correlation function $C_2(Q)$ by Eq. (3) are shown in Figure 2 (b). We find that they are close (mostly within 30%) to the source radii determined directly from the emission function. This is contrary to the pion case, where the pion source radii can be more than twice larger than the radius parameters from the Gaussian fit [9]. Note that kaons from $\phi$ meson decays have been included in the evaluation of the correlation function $C_2(Q)$ but not in the source radii (due to the long lifetime of $\phi$); however, pions from $\omega$ decays have been included in the source radii in Ref. [9]. Figure 2 (b) also shows that $R_{\text{out}}/R_{\text{side}}$ from fitted radius parameters changes little with parton cross section, in contrast to the significant increase seen in the source radii shown in Figure 2 (a).

Figure 3 (a) shows the extended AMPT results with $\sigma_p = 10 \text{ mb}$ for kaon source radii as functions of $m_T$ in the six $p_T$-bins, $0 - 200 - 400 - 600 - 800 - 1000 - 1500 \text{ GeV}/c$, for Au+Au collisions at $\sqrt{s} = 130\text{A GeV}$. We see that for all $m_T$ the source radii (solid) are close to the corresponding fitted radius parameters (filled squares). We note that, before making quantitative predictions on kaon correlations, abundances of strange resonances such as $K^*$ and $\phi$ need to be checked, and the effects of other resonances not yet included in the AMPT model also need to be investigated.
4.3. $x-t$ correlation and the $R_{out}/R_{side}$ ratio

Figure 3 (b) and (c) show the $x_{out} - x_{side}$ and $x_{out} - t$ distributions at freeze-out for $K^0_S$ with $200 < p_T < 400$ MeV/c and $-1 < y < 1$. The kaon emission source shows a positive shift in $x_{out}$ as in the pion case [9], consistent with a strong transverse flow. The emission source also appears to be highly non-Gaussian, which leads to different values of radius parameters extracted from the two methods in Section 3 [33, 9]. The solid curve with open diamonds in Figure 3 (c) gives the average value $\langle x_{out} \rangle$ as a function of freeze-out time $t$. The kaon emission source is seen to have a strong positive $x_{out} - t$ correlation as in the pion emission source [9].

Since $R_{side}^2 = D_{x_{side},x_{side}}$ but

$$R_{out}^2 = D_{x_{out},x_{out}} - 2 D_{x_{out},\beta_{\perp} t} + D_{\beta_{\perp} t,\beta_{\perp} t},$$  

the ratio $R_{out}/R_{side}$ contains information about the duration of emission (in the last term) and has been studied extensively [4, 34, 5, 35]. We note, however, that a direct relation between $R_{out}$ and the emission duration exists only if the $x_{out} - t$ correlation term $D_{x_{out},\beta_{\perp} t}$ is small, which is not the case according to our results from the extended AMPT. E.g., the above equation for the kaons is numerically written as $3.4^2 \approx 35 - 2 \times 22 + 20$ in units of fm$^2$. The $x_{out} - t$ correlation term $D_{x_{out},\beta_{\perp} t}$ is thus positive (+22 fm$^2$) and comparable to the magnitude of $D_{\beta_{\perp} t,\beta_{\perp} t}$ (20 fm$^2$), making it difficult to extract information about the duration of emission from $R_{out}/R_{side}$. The situation is similar for the pion emission source, e.g., for mid-rapidity pions with $125 < p_T < 225$ MeV/c, numerically the corresponding Eq. [32] is $17^2 \approx 185 - 2 \times 168 + 431$ in units of fm$^2$.

4.4. Energy dependence

Figure 4 shows the correlation functions for both neutral and charged kaons within $-1 < y < 1$ and $200 < p_T < 400$ MeV/c from AMPT model with string melting and $\sigma_{p} = 10$ mb for $\sqrt{s} = 130$A and 200A GeV. The effect due to Coulomb interactions is included for $K^-$ correlation functions using the program Correlation After Burner [32]. The kaon correlation functions are found to change only slightly from 130A to 200A GeV at RHIC.
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