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# Kaon versus pion interferometry signatures of quark-gluon plasma formation

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The advantages of kaon versus pion interferometry as a probe of quark-gluon plasma formation in high energy nuclear collisions are studied by comparing predictions of Lund resonance gas and plasma hydrodynamic models.

One of the striking signatures of the formation of a quark-gluon plasma in nuclear collisions is predicted to be an unusually long decoupling time of pions.[1,2] This prediction follows simply from the second law of thermodynamics together with the expected large ratio of entropy densities in the plasma and hadronic states. Detailed hydrodynamic calculations[2] for O+Au led to the prediction that the decoupling proper time and transverse radius would be $\tau \approx 9$ fm/c and $R_T \approx 3.3$ fm if a plasma were formed in that reaction. In Ref. 3 we showed that the above freeze-out geometry is in fact consistent with the recent pion interferometry data of NA35.[4] However, we showed at the same time that the freeze-out geometry of the Lund resonance gas model,[5] with $\tau \approx 4$ fm/c and $R_T \approx 4$ fm, was also consistent with the data within experimental uncertainties. This accidental numerical coincidence of these two models can be traced to the effect of long lived resonances. Even though the resonances freeze-out at a significantly earlier time in the Lund model, they propagate an additional time before they decay into the final pions. Since the Bose-Einstein interference pattern is only sensitive to the final pion interaction coordinates,[6] the effective pion freeze-out geometry is significantly bigger than the resonance one if a large fraction of the final pion multiplicity arises from the decay of long lived resonances. The Lund model predicts, in fact, that a significant fraction of the negative pion multiplicity comes from the decay of long lived $\omega$ ($f_\omega \approx 0.16$) and $K^*$ ($f_{K^*} \approx 0.09$). Numerically, this fraction just happens to lead to approximately the same negative pion correlation function as does the plasma model for the kinematic cuts of the NA35 data.

An enhanced sensitivity to differences between the two dynamical models could be achieved via much higher statistics experiments: (i) by detailed multidimensional analysis[3] of the correlation function $C(q_T,q_L)$ in transverse and longitudinal momentum difference with $\sim$10–20 MeV/$c$ resolution in both variables; (ii) by comparison of outward versus sideward projected transverse momentum correlation functions;[1,2,7] and (iii) by comparing the systematic trends of the deduced freeze-out geometry as a function of atomic number, transverse energy, or multiplicity triggers that constrain the initial reaction geometry. For example, one could look for the onset of plasma formation in going from peripheral collisions to central collisions, which are expected to generate much higher energy densities.

In addition, the distinction between different dynamical models could also be enhanced by complementary studies of the constructive interference pattern of bosons other than pions and the destructive interference pattern of protons. In this paper we explore the sensitivity of kaon versus pion interferometry in the search for signatures of quark-gluon plasma formation. The main motivation is that an entirely different set of hadronic resonances decay to kaons than to pions. In particular, long lived $\omega$, $\eta$, and $\eta'$ do not contribute to the kaon multiplicity. The Lund model predicts that roughly one half of the kaons are produced directly from string decay and the other half from the decay of $K^*$. Therefore, the freeze-out geometry of kaons is expected to be quite different than that of pions for the same resonance freeze-out geometry. In particular, the kaon proper freeze-out time should be significantly shorter than the pion one if resonance dynamics is taken into account. On the other hand, in the plasma model of Ref. 2 the freeze-out geometry of all hadrons is expected to be about the same and controlled mainly by the slowness of the plasma deflagration process.

For our numerical comparison, we employ the same freeze-out phase space distribution as in Ref. 3:

$$D(x,p) \propto \tau e^{-\tau^2/\tau_f^2} e^{-(\eta-y)^2/2\Delta\eta^2} e^{-(y-y^*)^2/2Y_c^2} e^{-r_T^2/R_T^2}, \tag{1}$$

where $\tau_f$ specifies the width and mean value of the freeze-out proper time, $\tau=(t^2-z^2)^{1/2}$ distribution, $\Delta\eta$ specifies the rms fluctuations of $\eta=\frac{1}{2}\ln[(t+z)/(t-z)]$ around $y=\frac{1}{2}\ln[(E+p_z)/(E-p_z)]$, $Y_c$ is the width of the rapidity distribution centered at $y^*$, and $R_T$ is the rms transverse radius at freeze-out. We also take the same freeze-out parameters estimated using the ATTILA version of the Lund Fritiof multistring model[5] and a string tension $\kappa=1$ GeV/fm to map momentum space into coordinate space. For O+Au at 200$A$ GeV, we found that the formation distribution of resonances could be characterized by $Y_c \approx 1.4$, $y^*=2.5$, $\Delta\eta \approx 0.8$, $\tau_f \approx 3$ fm/c, and $R_T \approx 3$ fm. Due to final-state cascading, however, the resonance freeze-out geometry was slightly bigger with $\tau_f \approx 4$ fm/c and $R_T \approx 4$ fm.

In the current ensemble formalism utilized in Ref. 3, the two-particle correlation function can be written as

$$C(k_1,k_2)=1+\chi(q)\frac{|G(k_1,k_2)|^2}{G(k_1,k_1)G(k_2,k_2)}, \tag{2}$$

 

where

$$\chi(q) = \xi/(e^{\xi}-1), \quad \xi = 2\pi am/q, \quad q = [-(k_1-k_2)^2]^{1/2} \tag{3}$$

is the Gamow factor that takes into account Coulomb final-state interaction. The two-particle amplitude $G(k_1, k_2)$ for a semiclassical hadron resonance gas is given by

$$G(k_1,k_2) \approx \left\langle \sum_r f_r (1 - iqu_r/\Gamma_r)^{-1} \exp(iqx_r - Ku_r/T_r) \right\rangle , \tag{4}$$

where $K = \frac{1}{2}(k_1+k_2)$ is the average momentum of the pair. The ensemble average is over the resonance freeze-out coordinates $(x_r^\mu, u_r^\mu)$ distributed according to Eq. (1). The $f_r$ are the fractions of the final pion or kaon multiplicity arising from the decay of resonance type $r$, which has a width $\Gamma_r$ and a four-velocity $u_r^\mu$; $T_r$ characterizes the decay distribution of the resonance and is set to $T_r \approx 0.17$ GeV. (Note that the values of $T_r$ and $\Delta\eta$ were misprinted in Ref. 3) For negative pions, we found[3] that $f_\pi = 0.19$, $f_\rho = 0.40$, $f_\omega = 0.16$, and $f_{K^*} = 0.09$. The contribution from longer lived $(\eta, \eta')$ resonances was set to be zero. For kaons, the Lund model predicts $f_K \approx f_{K^*} \approx \frac{1}{2}$.

The resulting transverse momentum projected correlation functions for the central rapidity region with $|y_{\mathrm{c.m.}}| < \frac{1}{2}$ are shown in Fig. 1. In all cases a finite cut on the longitudinal momentum $q_L \leq 0.1$ GeV was taken. The solid (dashed) curves indicate the correlation functions without (with) the Coulomb-Gamow corrections. Figures 1(a) and 1(c) compare pion and kaon interferometry, respectively, in the Lund resonance gas model. Figures 1(b) and 1(d) compare the corresponding correlations based on the quark-gluon plasma hydrodynamic model.[2] Without resonance and Coulomb corrections, the pion and kaon correlation functions turn to be quite similar for the kinematic cuts considered. We note that a substantial difference occurs if the rapidities of the particles is set to be the same, however. As we first pointed out in Ref. 3, Figs. 1(a) and 1(b) reveal that, for this reaction and kinematical cuts, both the resonance and plasma models can account for the observed NA35 correlations. However, Figs. 1(c) and 1(d) show that in this case a much more significant difference between the two models is expected for kaon interferometry. Note that the Coulomb corrections at small $q_T$ are much larger for kaons than for pions due to their increased mass, but since those corrections are well understood, the data can be readily corrected for Coulomb distortions as in Ref. 4. We therefore conclude that kaon interferometry can serve as a valuable complementary probe of the space-time geometry of nuclear collisions. Being less sensitive to the effects of long lived resonances than pions, a clearer distinction between the formation of long lived quark-gluon plasma droplets and more conventional resonance dynamics is possible to achieve.

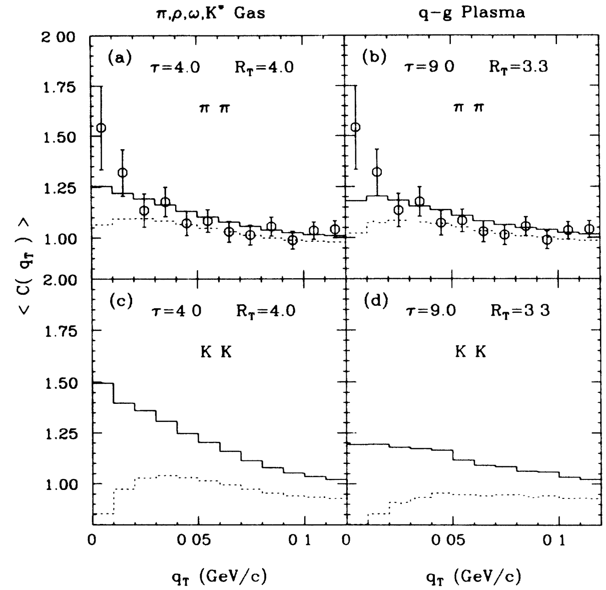


FIG. 1. (a),(b) Pion and (c),(d) kaon projected correlation functions vs transverse momentum difference $q_T$ in the central rapidity region with $q_L \leq 0.1$ GeV. Solid (dashed) lines indicate correlations without (with) Coulomb distortions. (a),(c) and (b),(d) correspond to predictions based on the Lund model (Ref. 5) and the plasma hydrodynamical model (Ref. 2), respectively. The pion data are from Ref. 4.

The disadvantage of kaon interferometry is of course the need for vastly higher statics $[(\pi/K)^2 \sim 100]$. With such statistics the multidimensional analysis of pion interferometry becomes possible and the enhanced sensitivity to dynamical differences may be competitive with those of transverse projected kaon correlations. However, kaon interferometry is cleaner in the sense that only $K^*$'s distort their freeze-out geometry. Direct measurements of $K^*$ production via $\pi K$ correlation studies could therefore remove most of the theoretical uncertainty in that regard. It may be much more difficult to measure all the resonance abundance contributing to the pion channel.

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