The RHIC HBT puzzle, chiral symmetry restoration, and pion opacity

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We present a relativistic quantum wave-mechanical optical model treatment of the opacity and refractive effects of pions emerging from a hot dense expanding source. The Klein-Gordon equation with Bjorken-cylinder geometry is solved for distorted waves representing the emerging pions. These waves are combined with a hydro-inspired pion source function to predict HBT radii and pion spectra. The model, when using a very deep potential well, has produced excellent HBT radii and spectrum fits to RHIC $\sqrt{s_{NN}} = 200$ GeV Au+Au data from STAR, reproducing the observed small source sizes, $R_O/R_S \approx 1$, the low-momentum behavior of the radii, and the pion spectrum in shape and magnitude. The calculations represent a new tool for investigating the presence and characteristics of chiral symmetry restoration in heavy ion collisions.

1. Introduction

Many of the "signals" from analysis of Au+Au collisions at RHIC suggest that a quark gluon plasma (QGP) has been created in the initial stages of the collision. A major problem with such an interpretation has been that a QGP scenario would require a large source that has expanded for a long time before freeze out and has a long duration for emission of pions. On the other hand, analysis of RHIC data using HBT interferometry has been interpreted as indicating a relatively small unexpanded source with a very short pion emission duration. In the literature, this conundrum has been called the "RHIC HBT Puzzle".

In an effort to understand the origins of this problem, we have undertaken a new approach to RHIC physics that required the application of quantum wave mechanics and the nuclear optical model to the medium produced by the colliding systems. We formulated a new relativistic quantum mechanical description of the collision medium that included collective flow as well as absorption and refraction in a complex potential. We solved the Klein-Gordon wave equations for pions in the medium and calculated overlap integrals with these wave functions to obtain predictions of pion spectra and HBT radii.

2. Formalism

Extensive details of the formalism used in our model have been presented in a long paper recently submitted to Physical Review C[1], and the formal approach will only be summarized here. Briefly, we treat the dynamics of the observed pions from their point of initial emission (not from freezeout). We separate the emitted particles into "channels", and explicitly threat only the channel including pions that participate in Bose-Einstein symmetrization leading to the observed HBT correlation "bump".

We apply the nuclear optical model to the pions in that channel as they traverse the hot dense medium of the collision fireball and emerge into the vacuum. We deal with other channels of the problem (e.g., halo pions, pions from long-lived resonances, reaction-channel absorption of pions, ...) through the use of an imaginary potential that removes pions from the channel of interest. We solve the Klein-Gordon wave equation in a partial-wave expansion and numerically calculate the wave functions of the pions in the channel of interest. We do not explicitly use a freezeout hypersurface, but rather allow the optical potential to describe the interactions of the emitted pions with the medium.

We employ a "hydro-inspired" multi-dimensional Gaussian emission function $S_0(\vec{x},\vec{p})$ to describe the probability of pion emission as a function of position and momentum in the medium. We then combine this with optical model wave functions to obtain $S(\vec{x},\vec{p})$, a distorted-wave emission function (DWEF) that is used to calculate the pion correlation function and spectrum. The optical potential used is not explicitly time dependent, but it acts only over a relatively short time interval limited by the emission function.

3. Application

Numerical calculations applying this formalism were placed under the control of a Marquardt-Levenberg chi-squared minimization program that varied up to 12 model parameters to obtain the best fit to STAR $\sqrt{s_{NN}}$=200 GeV Au+Au pion spectrum[3] and HBT radii[4]. We note that we calculate the HBT radii by explicitly evaluating the correlation function near its half-maximum point and calculating the Gaussian radius that would give this value. We find that this method gives stable results even in the region of low average momentum K, while the widely-used second-moment method is unreliable in that region.

Because the pion channel that is calculated does includes only those pions that participate in producing the correlation "bump", we must correct the measured spectrum data by multiplying by values from a linear fit to the experimental values of $\sqrt{\lambda}$, where λ is the HBT "dilution" parameter. We use these corrected spectrum values in the fits, and then correct the predicted spectrum by multiplication by $1/\sqrt{\lambda}$. The dotted line in Fig. 2 shows the "raw" uncorrected prediction.

Our initial expectation was that the imaginary part of the optical potential would be important for simulating pion absorption, while the real potential with its refractive effects was included mainly for formal reasons. To our surprise, when the fitting began the real potential grew deeper and deeper as the fit improved, until it was essentially as deep as the pion mass. This result suggested to us that the pion must be losing mass in the hot dense medium of the collision because chiral symmetry had been partially restored in the medium. Therefore, we gave the optical potential the momentum dependence that is consistent with chiral symmetry restoration. The result of this inclusion was impressive. Good fits to the STAR data, giving a chi-squared of about 3.7 per data point and 5.6 per degree of freedom, were obtained. These results have been published in Physical Review Letters[2]. Some of these fits are shown in Figs. 1 and 2.

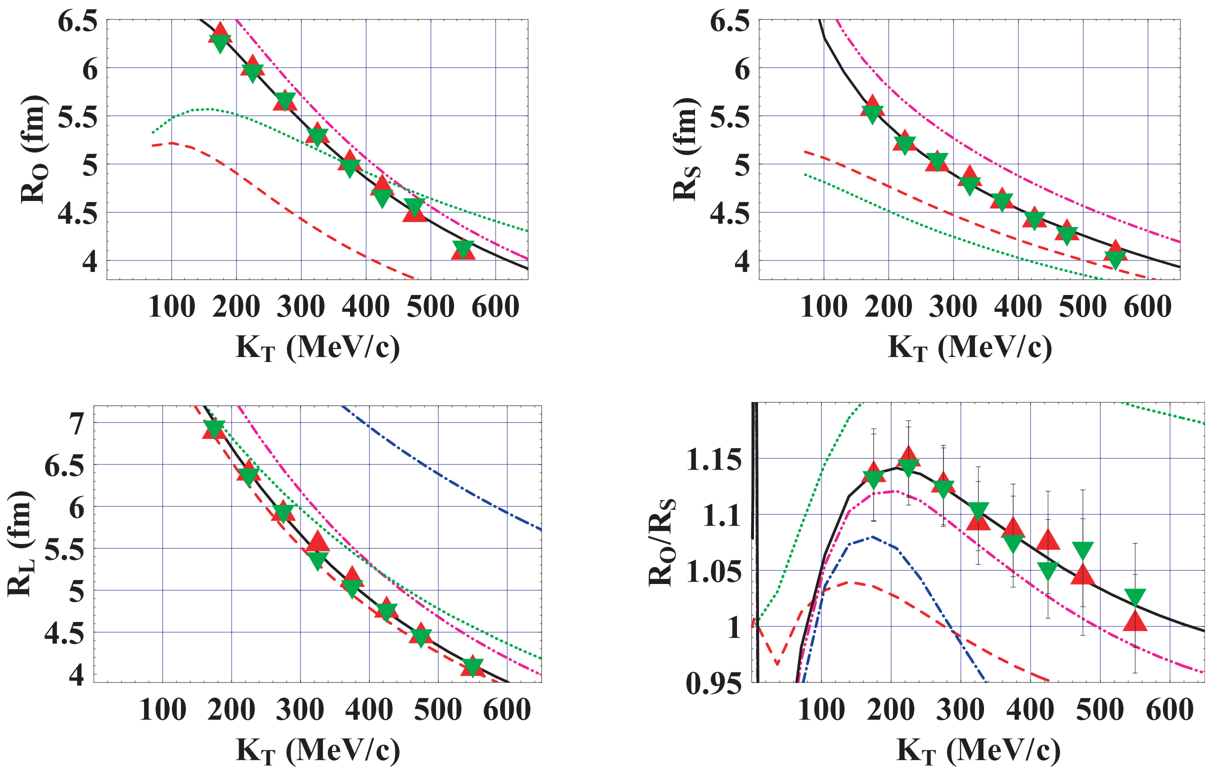

Figure 1. HBT Radii $R_s, R_o,$, R_l and the ratio R_o/R_s; Data: $\nabla \Rightarrow \pi^+\pi^+$; $\triangle \Rightarrow \pi^-\pi^-$. Curves: solid $\Rightarrow$ full calculation; dotted $\Rightarrow \eta_f = 0$ (no flow); dashed $\Rightarrow$ Re[U]=0 (no refraction); dot-dashed) $\Rightarrow U$=0 (no optical potential), double-dot-dashed $\Rightarrow$ substituting Boltzmann for Bose-Einstein thermal distribution.

4. Conclusion

These results indicate that roughly half of the pions are absorbed, with those surviving emitted primarily from a localized "bright ring" near the outer surface of the medium. Moreover, the emerging pions must regain their mass by expending a sizable fraction of their kinetic energy in climbing out of the very deep well made by the real potential. When these effect are properly taken into account, the pion source size and emission duration are consistent with a QGP scenario. Further, in most lattice gauge studies of heated and compressed nuclear matter the chiral phase transition and the transition to a quark-gluon plasma occur under about the same conditions. Our inferred observation of a chiral phase transition at RHIC is therefore consistent with the presence of a quark-gluon plasma transition in RHIC collisions.

In closing, we note that this work may represent the first direct observation of a chiral phase transition in a multiparticle system. Other experimental support of chiral symmetry restoration comes from the structure of highly excited states of the nucleon. Therefore,

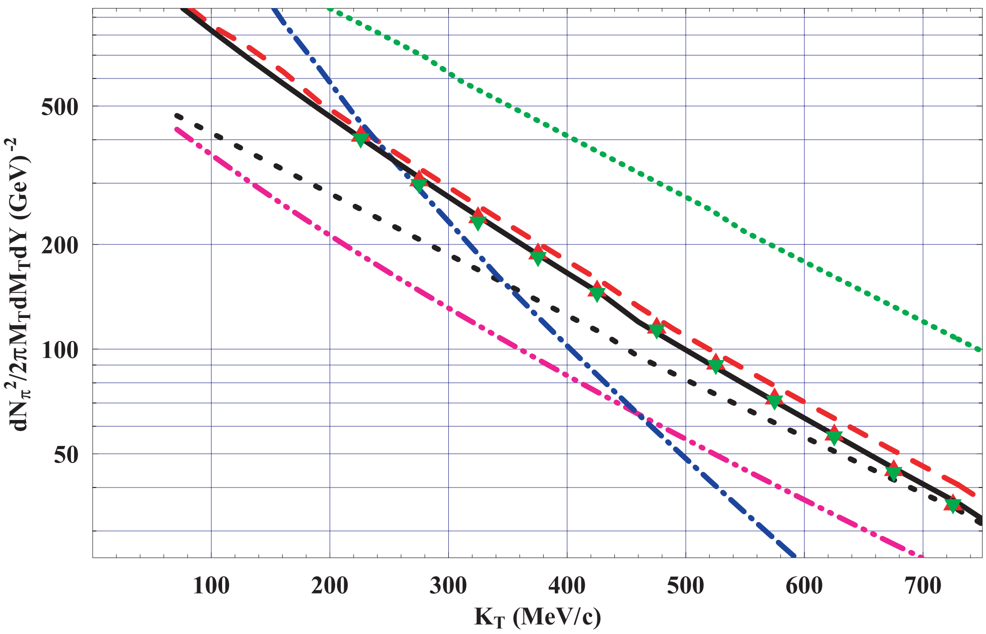

Figure 2. Pion transverse momentum spectrum. Data: $\nabla \Rightarrow \pi^+$; $\triangle \Rightarrow \pi^-$. Curves: solid $\Rightarrow$ full calculation; dotted $\Rightarrow \eta_f = 0$ (no flow); dashed $\Rightarrow$ Re[U]=0 (no refraction); dot-dashed) $\Rightarrow U$=0 (no optical potential), double-dot-dashed $\Rightarrow$ substituting Boltzmann for Bose-Einstein thermal distribution. The short dashed line shows the "raw" uncorrected spectrum prediction.

we have developed a new tool for relativistic heavy ion physics, which we plan to use for investigating the onset and properties of chiral symmetry restoration as a function of energy and centrality in relativistic heavy ion collisions, using data at the very wide range of energies and systems that has already been provided by experiments at the AGS, SPS, and RHIC.

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