Bombarding Energy Dependence of π^- Interferometry at the Brookhaven AGS

M. A. Lisa,[1] N. N. Ajitanand,[2] J. M. Alexander,[2] M. Anderson,[3] D. Best,[4] F. P. Brady,[3] T. Case,[4] W. Caskey,[3] D. Cebra,[3] J. L. Chance,[3] P. Chung,[2] B. Cole,[5] K. Crowe,[4] A. C. Das,[1] J. E. Draper,[3] M. L. Gilkes,[2] S. Gushue,[6,2] M. Heffner,[3] A. S. Hirsch,[7] E. L. Hjort,[7] L. Huo,[8] M. Justice,[9] M. Kaplan,[10] D. Keane,[9] J. C. Kintner,[11] J. Klay,[3] D. Krofcheck,[12] R. A. Lacey,[2] J. Lauret,[2] H. Liu,[9] Y. M. Liu,[8] R. McGrath,[2] Z. Milosevich,[10] G. Odyniec,[4] D. L. Olson,[4] S. Y. Panitkin,[9] C. Pinkenburg,[2] N. T. Porile,[7] G. Rai,[4] H. G. Ritter,[4] J. L. Romero,[3] R. Scharenberg,[7] L. Schroeder,[4] B. Srivastava,[7] N. T. B. Stone,[4] T. J. M. Symons,[4] R. Wells,[1] J. Whitfield,[10] T. Wienold,[4] R. Witt,[9] L. Wood,[3] and W. N. Zhang[8]

(E895 Collaboration)

[1]*The Ohio State University, Columbus, Ohio 43210*
[2]*Departments of Chemistry and Physics, SUNY, Stony Brook, New York 11794-3400*
[3]*University of California, Davis, California, 95616*
[4]*Lawrence Berkeley National Laboratory, Berkeley, California 94720*
[5]*Columbia University, New York, New York 10027*
[6]*Brookhaven National Laboratory, Upton, New York 11973*
[7]*Purdue University, West Lafayette, Indiana 47907-1396*
[8]*Harbin Institute of Technology, Harbin, 150001 People's Republic of China*
[9]*Kent State University, Kent, Ohio 44242*
[10]*Carnegie Mellon University, Pittsburgh, Pennsylvania 15213*
[11]*St. Mary's College, Moraga, California 94575*
[12]*University of Auckland, Auckland, New Zealand*

(Received 6 December 1999)

We present the first excitation function of π^- intensity interferometry at Alternating Gradient Synchrotron (AGS) energies (2–8 A GeV). The sensitivity of the multidimensional correlation functions to the geometry and dynamics of the pion-emitting system provides a stringent test of transport models of heavy ion collisions. Detailed comparisons with a realistic transport model, both with and without an explicit nuclear mean field, suggest that the beam energy evolution in the reaction dynamics is different in the model than in the data. A significantly increased π^- emission time scale, which has been suggested as a signal of the onset of the transition to quark-gluon plasma, is not observed.

PACS numbers: 25.75.Gz, 25.75.Ld

Intensity interferometry (aka HBT) techniques have been used extensively to probe the space-time structure of heavy ion collisions (see, e.g., [1]). Multidimensional analysis of two-pion correlation functions has been shown to be sensitive to the geometry of the pion-emitting source [1], the duration of pion emission [2–5], and the details of resonance decay contributions [4,6–8]. The dependence of the correlations on kinematic variables displays sensitivity to the dynamics of the collision, including collective flow [4,9,10]. Further, the interplay among these physical effects evolves with collision energy. Therefore, correlation functions—and especially HBT excitation functions—are a powerful tool to stringently test the dynamics in microscopic transport models [7,11].

In this Letter, we compare the data to the relativistic quantum molecular dynamics (RQMD) model (v2.3) [12], which incorporates known and calculated hadronic cross sections and resonances, relativistic kinematics, rescattering effects, and a parametrized nuclear mean field. The predictions of such models represent the current knowledge of effects arising from "normal" hadronic physics in a heavy ion collision. As such, one would like to use these models at higher collision energies, e.g., at Brookhaven's Relativistic Heavy Ion Collider (RHIC), to describe a normal collision and attribute (perhaps subtle) discrepancies with the data to "new" physics. Confidence in such an interpretation would be greatly enhanced if the model reproduces the evolution of the measured systematics over a large range of lower collision energies.

The most intriguing new physics sought in heavy ion collisions is the phase transition from hadronic matter to a quark gluon plasma (QGP), in which partons are deconfined. If such a transition takes place, the time scale for pion emission is expected to increase significantly, perhaps to tens of fm/c, detectable via two-particle interferometry as an apparent source geometry extended in the direction of the pion momentum [4]. The exact magnitude of the lifetime signal in case of QGP formation is model dependent [13] and requires a more complete understanding of the phase transition. Heavy ion reaction studies at Brookhaven's Alternating Gradient Synchrotron (AGS) probe nuclear matter at very high baryon density ($\rho \sim 6$–$8\rho_0$) [14,15]. Some models [14–18] and equilibrium-based metaanalyses of data [19] suggest that sufficient energy density may be generated in collisions below maximum AGS energies to trigger QGP formation. Hydrodynamic calculations suggest an HBT excitation function as an excellent method to detect the transition to QGP through a sudden increase of emission time scale [13].

The E895 Collaboration has measured about 0.75 million Au + Au collisions at $E_{\mathrm{beam}} = 2$, 4, 6, and 8 A GeV at the Brookhaven AGS using the EOS Time Projection Chamber (TPC) [20]. The TPC, located in a magnet operated at 0.75 or 1.0 T, provides nearly full acceptance for pions with rapidity $y_{\mathrm{lab}} \geq 0.5$ with no lower threshold in transverse momentum (p_T).

Particle identification was achieved by correlating the magnetic rigidity of a track with its specific ionization (dE/dx) in the P10 gas. While $\bar{p}$ and K^- production are negligible compared to π^- at these energies, the electron and π^- bands overlap somewhat in the dE/dx rigidity space. After track-quality cuts, we estimate the level of e^- contamination at $\lesssim 5\%$, with less contamination at the lower beam energies and higher p_T.

Correlation functions are generated from the off-line event reconstruction after a series of quality cuts. Requiring that a track projects back to the interaction vertex eliminates "ghost" tracks originating from unused hit combinatorics. This cut also eliminates many π^- from decays of long-lived particles (e.g., Λ, η, K^0). However, detailed simulations with the RQMD model reveal that roughly 10% (5%) of the π^- from the 8 A GeV (2 A GeV) collisions that pass this cut originate from long-lived particles; these pions are typically at low p_T and their effect is to lower the strength of the correlation at zero relative momentum [quantified by the λ fit parameter (see below)]. As in the data, these pions are included when generating correlation functions for the model.

The correlation function is constructed by dividing the two-particle yield as a function of relative momentum vector, q, by a "background" generated by mixing pions of the current event with those of the previous ten events, following the standard event-mixing technique [21]. The large acceptance of the TPC eliminates several complications associated with correlation measurements with "keyhole" spectrometers [22]. First, the measured pion multiplicity in each event is much greater than unity, eliminating possible ambiguities about differing classes of events used in the correlated distribution and the background. Second, the effect of residual correlations in the background are greatly reduced. Finally, an unrestricted acceptance in q provides greater sensitivity to the shape of the effective pion source in coordinate space.

To eliminate track-merging effects in the TPC, which suppress the correlation function at low q, we require the tracks in a pair to be well separated (by at least 4.5 cm over a distance of 18 cm in the beam direction). In applying this cut to the mixed event background, we account for event-to-event variation in primary vertex position. This cut also removes false "pairs" from split tracks.

The Coulomb correction applied to the raw correlation functions is obtained by averaging the square of the Coulomb wave function [4,23] over a spherical Gaussian source of 5 fm radius. Changing this radius by ± 1 fm has a negligible effect on the fit parameters. Our correction is the same as that used by several groups [24,25]. Identical Coulomb corrections were applied to the data and to RQMD model predictions.

The momentum resolution of the TPC ($\delta p/p \sim (1.5-3)\%$, including multiple Coulomb scattering and straggling effects) artificially broadens the experimental correlation functions. Using detailed studies of our resolution, we correct the correlation functions with an iterative technique similar to that used by the NA44 Collaboration [26]. This correction typically increases the λ and radii fit parameters by 15% and 5%, respectively. We compare corrected data to model correlations and do not smear the model results by the momentum resolution.

Multidimensional correlation functions were generated [27] by decomposing q in the Au + Au c.m. frame using the Bertsch-Pratt (BP) parametrization [3,4]. Here, q_{long} is the component of the relative momentum parallel to the beam, q_{side} is perpendicular to the beam and to the total momentum of the pair, and q_{out} is perpendicular to q_{long} and q_{side}. The correlation functions were constructed from midrapidity ($y = y_{\mathrm{c.m.}} \pm 0.35$) pions with $p_T = 0.1-0.3$ GeV/c from central (11% σ_T as determined by event multiplicity) Au + Au collisions. This lower p_T cut was selected to reduce the effects of e^- contamination [28] and to allow comparison with correlation measurements at midrapidity by the E866 Collaboration at 10.6 A GeV [29]. For this narrow p_T cut, the phasespace distortions due to the two-track cut are minimal, and the average p_T of pions in low-q pairs varies little: from 157 MeV/c at 2 A GeV to 165 MeV/c at 8 A GeV.

We performed maximum log-likelihood fits to the three-dimensional correlation functions with the form

$$C(q_{\mathrm{out}}, q_{\mathrm{side}}, q_{\mathrm{long}}) = 1 + \lambda e^{-R_{\mathrm{out}}^2 q_{\mathrm{out}}^2 - R_{\mathrm{side}}^2 q_{\mathrm{side}}^2 - R_{\mathrm{long}}^2 q_{\mathrm{long}}^2 - 2R_{\mathrm{ol}}^2 q_{\mathrm{out}} q_{\mathrm{long}}}. \quad (1)$$

The cross term [30] R_{ol}^2 (which may be negative) was included in all fits, but always came out consistent with zero with very large uncertainty. At midrapidity, this term is expected to vanish identically [30]. It was verified for all energies that fixing $R_{\mathrm{ol}}^2 = 0$ in the fits of the midrapidity correlation functions has a negligible effect on the other parameters. The correlation functions are well described by this Gaussian form [27] even down to very small relative momentum; hence the fit parameters may be used to summarize the correlations [4].

The excitation function of the BP fit parameters is shown in the left panels in Fig. 1. The λ parameter falls sharply

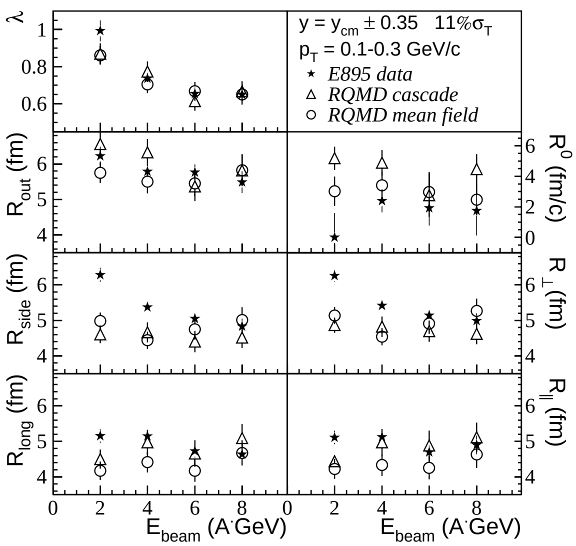

FIG. 1. Fit parameters for the measured correlation functions decomposed with the BP (left panels) and YKP (right panels) decompositions are shown as stars. Triangles and circles represent the results of fits to correlation functions from RQMD in cascade and mean field modes, respectively.

with beam energy, due mostly to increased production of long-lived π^--emitting particles at the higher energies [7]. Values of $\lambda \approx 1$ have been reported by some (e.g., [28]) but not all [22] groups measuring correlation functions at similar energies at the Bevalac. (The small e^- contamination is estimated to reduce λ by up to 10% for the highest beam energy [31]. Purposely increasing the e^- contamination by relaxing particle cuts affects only λ, not the extracted radii, consistent with observations from higher energies [25].)

Perhaps surprisingly, R_{side}, which is most directly related to source size transverse to the beam direction, and R_{out}, which is sensitive to temporal as well as spatial extent [3,4], are also seen to decrease with increasing bombarding energy, while R_{long} remains almost constant.

Also shown in Fig. 1 are results of fits to correlation functions from the RQMD transport model. At each energy, sets of events with impact parameter $b = 0\text{–}5$ fm (geometrically weighted) were generated with and without mean field effects included in the calculation. Correlation functions were built by correlating π^- from the RQMD freeze-out phase space (including π^- from long-lived particle decay) with the correlator code of Pratt [11].

Good agreement in the λ fit parameter is observed between the data and the model. This suggests that the *fraction* of π^- originating from long-lived particle decays is well reproduced in the model, independent of mean field. R_{out} and R_{long} from the model fits agree reasonably well with the data and exhibit some sensitivity to the action of the mean field during the collision. However, the model predicts a flat beam energy dependence of R_{side}, with or without the mean field, in strong disagreement with the data. R_{side} is underpredicted by $\sim$1.5 fm for 2 A GeV collisions; agreement between data and model improves with increasing beam energy.

These discrepancies suggest that the effective source generated by the model is too small, and with too large a lifetime. Such an interpretation is more clearly illustrated by constructing the correlation functions using the Yano-Koonin-Podgoretsky (YKP) decomposition [32] of relative momentum, in which the effective lifetime is fit more directly. In this parametrization, one fits the correlation function to the form

$$C(q^0, q_\perp, q_\parallel) = 1 + \lambda e^{-R_\perp^2 q_\perp^2 - R_\parallel^2[q_\parallel^2 - (q^0)^2] - [(R^0)^2 + R_\parallel^2](qU)^2}, \quad (2)$$

where $U = \gamma(1, 0, 0, v)$ and v is the actual source velocity in the beam direction, relative to the analysis frame; $\gamma = (1 - v^2)^{-1/2}$. For all energies, v was found to be consistent with zero, which is expected since the analysis is performed in the system c.m. frame, with midrapidity pions. Fixing $v \equiv 0$ in the fits has no significant effect on the other parameters [33]. The λ parameter in the YKP and BP parametrizations are identical within errors.

R^0 measures the effective lifetime of the π^--emitting source, and $R_\perp$ and $R_\parallel$ the effective size perpendicular to and parallel to the beam axis. As shown in Fig. 1, the effective π^- source consistent with the data has a lifetime $\lesssim$2 fm/c, and a transverse radius that evolves from 6.3 to 5.0 fm, while the RQMD indeed produces an effective source that is longer lived and smaller at the lower collision energy.

Given the observed energy dependence of the discrepancy between RQMD and the data at AGS energies, it is interesting to note that for Pb + Pb collisions at the CERN Super Proton Synchrotron (158 A GeV), the effective π^- source from RQMD is significantly *larger* than the measured size [34].

Further detail is obtained by examining the dependence of the correlations on $m_T = \sqrt{p_T^2 + m^2}$. Collective flow effects that induce position-momentum correlations [10,34], as well as source expansion coupled with a finite emission time scale [4], both tend to decrease the effective source size at higher m_T.

As is clear from Fig. 2, the magnitude of these effects evolves with beam energy in nature. While R_{long} has similar values and decreases similarly with m_T at all energies, the transverse radius R_{side} (and $R_{\mathrm{out}} \approx R_{\mathrm{side}}$, not shown) exhibits two trends. The first is a decrease in the overall scale of R_{side} as the beam energy increases. Second, the reduction of R_{side} with increasing m_T, familiar in HBT studies at higher beam energies [34–36], appears weaker at 2 A GeV. Inconsistent reports exist on the presence [37] or absence [38] of a momentum dependence of transverse radii in HBT analyses for heavy systems at the Bevalac at slightly lower energy.

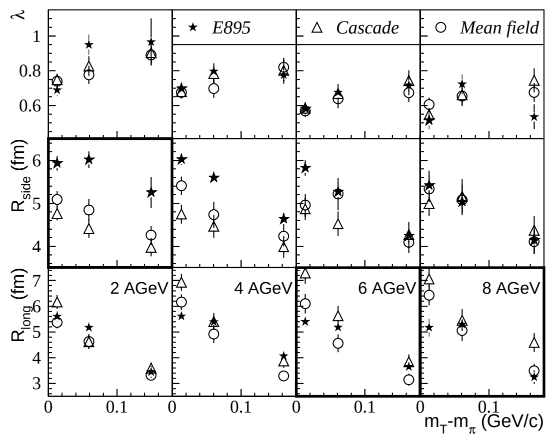

FIG. 2. Filled stars indicate the m_T dependence of the measured BP parameters for midrapidity ($y = y_{\mathrm{c.m.}} \pm 0.5$) π^- for central (11% σ_T) collisions at four beam energies. Open symbols show the parameters from fits to correlation functions from RQMD calculations.

In contrast, the overall scale and m_T dependence of R_{side} predicted by the RQMD model is almost independent of collision energy. While the model reproduces the measurements at 8 A GeV, at lower energy R_{side} is underpredicted at low m_T. This discrepancy worsens as E_{beam} decreases until, at 2 A GeV, R_{side} is underpredicted for all m_T bins.

As expected due to the increasing fraction of π^- from particle decay at low p_T, λ increases with m_T; similar trends are seen at higher energy [34]. Since the model reproduces the trends of λ reasonably well (cf. Figs. 1 and 2), it is unlikely that the details of resonance production dominate the discrepancy in m_T systematics [6].

Because flow and source evolution effects both influence the overall scale and m_T dependence of R_{side} similarly, it is difficult to isolate the physical origin of the difference between the model and data. Nevertheless, the discrepancy appears to be slightly worse when the mean field is switched off. Overall, collective flow at these energies is indeed better described when the mean field is included in the model [39–41]. However, the *details* of flow are not reproduced by the model [41], and interferometry's sensitivity to space-momentum correlations provides another tool to study these dynamics.

In summary, we have presented the first excitation function of pion interferometry at the AGS. The correlations at midrapidity for central collisions show no sharp increase in emission time scale that would signal QGP formation. A detailed comparison of measured multidimensional correlation functions to those from the popular transport model RQMD revealed systematic discrepancies. In particular, the effective pion sources generated by the model are too small in size and too large in temporal extent for the lower bombarding energies. The discrepancy diminishes with increasing energy, finally reversing at CERN energies, where the predicted source is too large. The m_T dependence of the correlations reveals an evolution in the strength of dynamical and/or lifetime effects at AGS energies; this evolution with collision energy appears to be absent in the model. It is important to understand energy-dependent discrepancies in more detail before extrapolating transport models to the still higher energies of RHIC.

For enlightening discussions, M. A. L. thanks Dr. D. Hardtke, Dr. U. Heinz, Dr. T. Humanic, Dr. S. Pratt, Dr. R. Soltz, Dr. H. Sorge, and Dr. J. Sullivan. We thank Dr. S. Pratt and Dr. H. Sorge for the use of their codes. We acknowledge the U.S. DOE, NSF, and other funding agencies as detailed in Refs. [40,41].

[1] W. Bauer *et al.*, Annu. Rev. Nucl. Part. Sci. **42**, 77 (1992).
[2] S. Pratt, Phys. Rev. C **49**, 2722 (1994).
[3] G. Bertsch *et al.*, Phys. Rev. C **37**, 1896 (1988).
[4] S. Pratt *et al.*, Phys. Rev. C **42**, 2646 (1990).
[5] S. Pratt, Phys. Rev. D **33**, 72 (1986).
[6] B. R. Schlei and N. Xu, Phys. Rev. C **54**, R2155 (1996).
[7] J. P. Sullivan *et al.*, Nucl. Phys. **A566**, 531c (1994).
[8] M. Gyulassy and S. S. Padula, Phys. Rev. C **41**, R21 (1990).
[9] S. Pratt, Phys. Rev. Lett. **53**, 1219 (1984).
[10] A. N. Makhlin and Y. M. Sinyukov, Z. Phys. C **39**, 69 (1988).
[11] S. Pratt, Nucl. Phys. **A566**, 103c (1993).
[12] H. Sorge, Phys. Rev. C **52**, 3291 (1995).
[13] D. H. Rischke, Nucl. Phys. **A610**, 88c (1996).
[14] B. A. Li and C. M. Ko, Nucl. Phys. **A601**, 457 (1996).
[15] P. Danielewicz *et al.*, Phys. Rev. Lett. **81**, 2438 (1998).
[16] J. I. Kapusta *et al.*, Phys. Rev. C **51**, 901 (1995).
[17] D. Rischke *et al.*, J. Phys. G **14**, 191 (1988); Phys. Rev. D **41**, 111 (1990).
[18] N. K. Glendenning, Nucl. Phys. **A512**, 737 (1990).
[19] P. Braun-Munzinger and J. Stachel, Nucl. Phys. **A606**, 320 (1996).
[20] G. Rai *et al.*, IEEE Trans. Nucl. Sci. **37**, 56 (1990).
[21] G. I. Kopylov, Phys. Lett. **50B**, 472 (1974).
[22] W. A. Zajc *et al.*, Phys. Rev. C **29**, 2173 (1984).
[23] A. Messiah, *Quantum Mechanics* (North-Holland, Amsterdam, 1961).
[24] E877 Collaboration, J. Barrette *et al.*, Nucl. Phys. **A610**, 227c (1996); J. Barrette *et al.*, Phys. Rev. Lett. **78**, 2916 (1997).
[25] NA49 Collaboration, K. Kadija *et al.*, Nucl. Phys. **A610**, 248c (1996).
[26] NA44 Collaboration, H. Bøggild *et al.*, Phys. Lett. B **302**, 510 (1993).
[27] E895 Collaboration, M. A. Lisa *et al.*, in Proceedings of Quark Matter '99 [Nucl. Phys. **A661**, 444c (1999)].
[28] D. Beavis *et al.*, Phys. Rev. C **27**, R910 (1983).
[29] E866 Collaboration, M. D. Baker *et al.*, Nucl. Phys. **A610**, 213c (1996).
[30] S. Chapman *et al.*, Phys. Rev. Lett. **74**, 4400 (1995).
[31] T. Csörgő *et al.*, Z. Phys. C **71**, 491 (1996).
[32] U. Heinz, Nucl. Phys. **A610**, 264c (1996).
[33] U. Heinz *et al.* [Phys. Lett. B **382**, 181 (1996)] provide consistency relations between the YKP and BP fit

parameters. The consistency of the fit parameters for all correlation functions in this work has been verified.
[34] NA44 Collaboration, I. G. Bearden *et al.*, Phys. Rev. C **58**, 1656 (1998).
[35] S. Pratt, Nucl. Phys. **A638**, 125c (1998).
[36] NA35 Collaboration, G. Roland *et al.*, Nucl. Phys. **A566**, 527c (1994).
[37] W. B. Christie *et al.*, Phys. Rev. C **47**, 779 (1993).
[38] A. D. Chacon *et al.*, Phys. Rev. C **43**, 2670 (1991).
[39] H. Sorge, Phys. Rev. Lett. **78**, 2309 (1997).
[40] E895 Collaboration, C. Pinkenburg *et al.*, Phys. Rev. Lett. **83**, 1295 (1999).
[41] E895 Collaboration, H. Liu *et al.* (to be published).