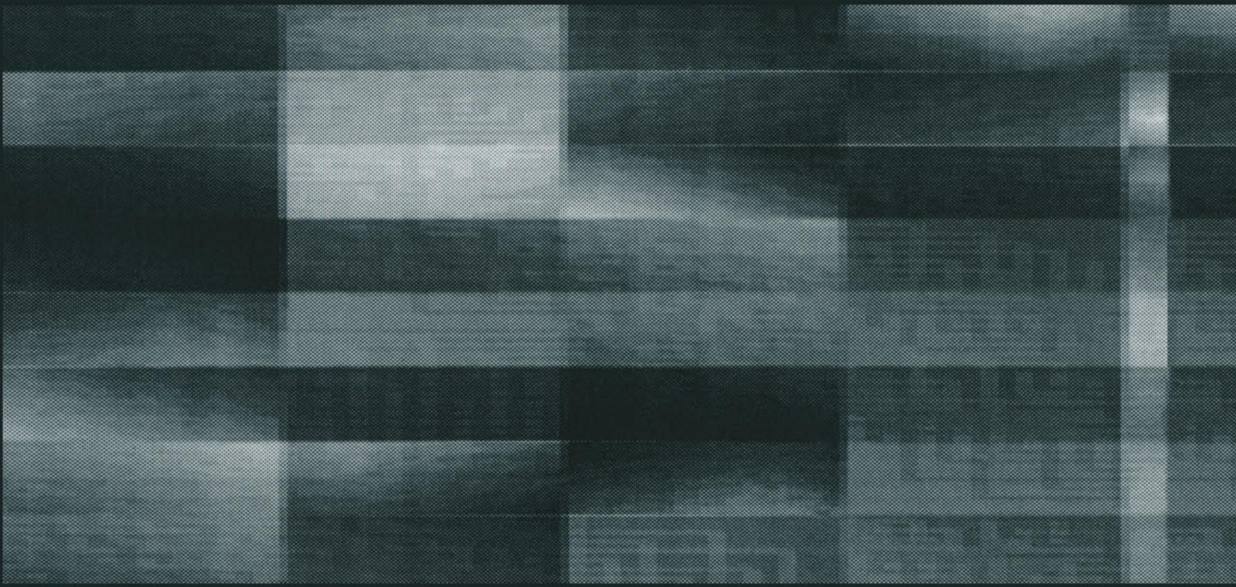
Advances in Nuclear Dynamics
2



Edited by
Wolfgang Bauer and
Gary D. Westfall

Advances in
Nuclear Dynamics 2

Advances in Nuclear Dynamics 2

Edited by

Wolfgang Bauer and
Gary D. Westfall
Michigan State University
East Lansing, Michigan

Springer Science+Business Media, LLC

Library of Congress Cataloging-in-Publication Data

Advances in nuclear dynamics 2 / edited by Wolfgang Bauer and Gary D. Westfall
p. cm.
"Proceedings of the 12th Winter Workshop on Nuclear Dynamics, held February 3-10, 1996, in Snowbird, Utah"--CIP verso t.p.
Includes bibliographical references and index.
ISBN 978-1-4757-9088-7 ISBN 978-1-4757-9086-3 (eBook)
DOI 10.1007/978-1-4757-9086-3
1. Nuclear structure--Congresses. 2. Heavy ion collisions--Congresses. I. Bauer, W. (Wolfgang), 1959- . II. Westfall, Gary D. III. Winter Workshop on Nuclear Dynamics (12th : 1996 : Snowbird, Utah)
QC794.8.H4A39 1996
539.7'232--dc20 96-28266
CIP

Reader's Note: This volume was prepared by the authors using $\mathrm{T_EX}$. In a number of chapters the first equation number is "2."

Proceedings of the 12th Winter Workshop on Nuclear Dynamics,
held February 3 – 10, 1996, in Snowbird, Utah

ISBN 978-1-4757-9088-7

Originally published by Plenum Press, New York in 1996
Softcover reprint of the hardcover 1st edition 1996

10 9 8 7 6 5 4 3 2 1

PREFACE

The 12^{th} Winter Workshop on Nuclear Dynamics carried on the tradition, started in 1978, of bringing together scientists working in all regimes of nuclear dynamics. This broad range of related topics allows the researcher attending the Workshop to be exposed to work that normally would be considered outside his/her field, but could potentially add a new dimension to the understanding of his/her work. At Snowbird, we brought together experimentalists working with heavy ion beams from 10 MeV/nucleon up to 200 GeV/nucleon and theoretical physicists working in diverse areas ranging from antisymmetrized fermionic dynamics to perturbative quantum chromodynamics. Future work at RHIC was discussed also, with presentations from several of the experimental groups. In addition, several talks addressed issues of cross-disciplinary relevance, from the study of water-drop-collisions, to the multi-fragmentation of buckyballs.

Clearly the field of nuclear dynamics has a bright future. The understanding of the nuclear equation of state in all of its manifestations is being expanded on all fronts both theoretically and experimentally. Future Workshops on Nuclear Dynamics will certainly have much progress to report.

Gary D. Westfall
Wolfgang Bauer
Michigan State University

PREVIOUS WORKSHOPS

The following table contains a list of the dates and locations of the previous Winter Workshops on Nuclear Dynamics as well as the members of the organizing committees. The chairpersons of the conferences are underlined.

1. Granlibakken, California, 17-21 March 1980
   W.D. Myers, J. Randrup, G.D. Westfall
2. Granlibakken, California, 22-26 April 1982
   W.D. Myers, J.J. Griffin, J.R. Huizenga, J.R. Nix, F. Plasil, V.E. Viola
3. Copper Mountain, Colorado, 5-9 March 1984
   W.D. Myers, C.K. Gelbke, J.J. Griffin, J.R. Huizenga, J.R. Nix, F. Plasil, V.E. Viola
4. Copper Mountain, Colorado, 24-28 February 1986
   J.J. Griffin, J.R. Huizenga, J.R. Nix, F. Plasil, J. Randrup, V.E. Viola
5. Sun Valley, Idaho, 22-26 February 1988
   J.R. Huizenga, J.I. Kapusta, J.R. Nix, J. Randrup, V.E. Viola, G.D. Westfall
6. Jackson Hole, Wyoming, 17-24 February 1990
   B.B. Back, J.R. Huizenga, J.I. Kapusta, J.R. Nix, J. Randrup, V.E. Viola, G.D. Westfall
7. Key West, Florida, 26 January - 2 February 1991
   B.B. Back, W. Bauer, J.R. Huizenga, J.I. Kapusta, J.R. Nix, J. Randrup
8. Jackson Hole, Wyoming, 18-25 January 1992
   B.B. Back, W. Bauer, J.R. Huizenga, J.I. Kapusta, J.R. Nix, J. Randrup
9. Key West, Florida, 30 January - 6 February 1993
   B.B. Back, W. Bauer, J. Harris, J.I. Kapusta, A. Mignerey, J.R. Nix, G.D. Westfall
10. Snowbird, Utah, 16-22 January 1994
    B.B. Back, W. Bauer, J. Harris, A. Mignerey, J.R. Nix, G.D. Westfall
11. Key West, Florida, 11-18 February 1995
    W. Bauer, J. Harris, A. Mignerey, S. Steadman, G.D. Westfall
12. Snowbird, Utah, 3-10 February 1996
    W. Bauer, J. Harris, A. Mignerey, S. Steadman, G.D. Westfall
13. 1997 Committee
    W. Bauer, J. Harris, A. Mignerey, H.G. Ritter, E. Shuryak, S. Steadman, G.D. Westfall

CONTENTS

Advances in
Nuclear Dynamics 2

INTRIGUING CENTRALITY DEPENDENCE OF THE AU-AU SOURCE SIZE AT THE AGS

Mark D. Baker,[1] for Experiment E866 (The E802 Collaboration[2])

[1]Massachusetts Institute of Technology, Cambridge, MA 02139
[2] ANL-BNL-UCBerkeley-UCRiverside-Columbia
INS(Tokyo)-Kyoto-LLNL-MIT-NYU-Tokyo-Tsukuba

INTRODUCTION

One of the main goals of high energy heavy ion physics is to establish the existence of a deconfined phase of nuclear matter — the quark-gluon plasma — at high temperatures or densities. One possible signature of such a phase transition, especially if it were first order, would be a larger source size or lifetime than a similar hadronic system. At current AGS energies, we attempt to form a quark-gluon plasma by achieving a high baryon density for a period of time in the center of the collision region[1]. For a given density threshold, the size of this high density region should be a strong function of the impact parameter: the more central the event, the larger the high density region. Therefore, one possible signature of a quark-gluon plasma would be a sudden change in system lifetime or size as a function of the centrality of the collision.

In this talk we present an intriguing effect which was not predicted for simple hadronic systems: a rapid increase of the HBT-measured source radius parameter for pion pairs with increasing centrality for *Au-Au* collisions at a beam momentum of 11.45 A GeV/c on a fixed target. Experience has shown, however, that we must be cautious in our interpretation. A complete understanding of the collision dynamics at a given energy must be built up from several measurements and new, but conventional, hadronic explanations must be considered for such unexpected effects. More study is needed, therefore, before any strong conclusions can be reached.

HBT "SOURCE SIZE" MEASUREMENT

Two-pion correlation functions for bosons, called Hanbury-Brown Twiss (HBT) or Bose-Einstein correlations, provide information about the length and time scales which characterize the pion source. In the simplest cases, we can directly relate the correlation function to the fourier transform of the source distribution and therefore

Advances in Nuclear Dynamics 2
Edited by Bauer and Westfall, Plenum Press, New York, 1996

the rms geometric size and lifetime of the source. In practice, this simple interpretation is complicated by two effects: dynamical correlations and the mixing of space and time.

Dynamical correlations are correlations between the spacetime position of pion emission and the pion momentum. These lead to effective "coherence lengths": emission points that are too far apart spatially cannot easily generate pairs which are close in momentum, making the measured source size parameter smaller than the geometric source size. HBT correlations measure the shortest length scales available, not necessarily the geometric length scale in which we are interested. Some progress has been made in studying the effect of dynamical correlations both theoretically[2] and experimentally[3, 4], but we will ignore them for the purposes of this talk. Since we are interested in radius changes rather than absolute sizes, and since dynamical correlations will tend to wash out any interesting geometric effect rather than cause a centrality dependence, we are probably justified in ignoring them for now.

The mixing of space and time occurs because most of the HBT "source size" fit parameters which we can measure involve a mixture of the space and time length scales in the reference frame of interest: the collision center-of-mass frame. In general, this means that the "source duration of emission" fit parameter, τ, is hard to extract. In some fit forms, this manifests itself as a poor phase-space coverage of the correlation function in the τ direction. In others, it manifests itself as τ being the difference between large numbers.

Even in the presence of these complications, we should be able to extract useful information. The one-dimensional variable $Q_{R=\tau}$, defined as $\sqrt{|\vec{q}|^2 + q_0^2}$, is conjugate to a quantity $R_{R=\tau}$ which has a well understood mixture of space and time scales:

$$R_{R=\tau} = \sqrt{\frac{R^2 + \tau^2 \langle \beta_{\pi\pi}^2 \cos^2\theta \rangle}{1 + \langle \beta_{\pi\pi}^2 \cos^2\theta \rangle}} \approx \sqrt{\frac{R^2 + \tau^2}{2}},$$

where R is the gaussian-equivalent radius parameter, τ is the gaussian-equivalent emission duration, $\beta_{\pi\pi}$ is the pair velocity given by $(\vec{p}_1 + \vec{p}_2)/(E_1 + E_2)$, and θ is the angle between $\vec{q} = \vec{p}_1 - \vec{p}_2$ and $\beta_{\pi\pi}$. In our spectrometer acceptance, $\langle \beta_{\pi\pi}^2 \cos^2\theta \rangle \sim 1$. Therefore, we can control the mixing of R and τ by fitting the correlation function to a gaussian in $Q_{R=\tau}$: $1 + \lambda \exp\{-Q_{R=\tau}^2 R_{R=\tau}^2\}$. Interesting physics could show up as an increased geometric size or a longer lifetime; $R_{R=\tau}$ is sensitive to either or both signals.

For this particular measurement — pion pairs near mid-rapidity in a symmetric collision — the collision CM frame is the same as the longitudinal comoving system frame and we are not plagued by questions of which frame to use[5]. This means that the one-dimensional fit parameter $R_{R=\tau}$ can provide us with much of the information contained in the more sophisticated multi-dimensional fits without requiring as many pion pairs. The more common one-dimensional fit parameter R_{inv}, conjugate to $Q_{inv} \equiv \sqrt{|\vec{q}|^2 - q_0^2}$, is much more difficult to interpret.

APPARATUS

Experiment 866 at the BNL AGS is a fixed target experiment with a two-arm spectrometer[6, 7]. Most of the data presented here are from the 1992 *Au* beam when only one spectrometer (the wide-angle Henry Higgins), configured as in E859, was used. The data discussed in this talk were taken with the spectrometer at the "21°" setting.

Only negatively charged particles with momenta below 1.8 GeV/c which were identified as pions by the time-of-flight detector were considered for this analysis. The acceptance for negative pions at this setting is shown in Figure 1. The data set consists of about 90000 negatively charged pion pairs.

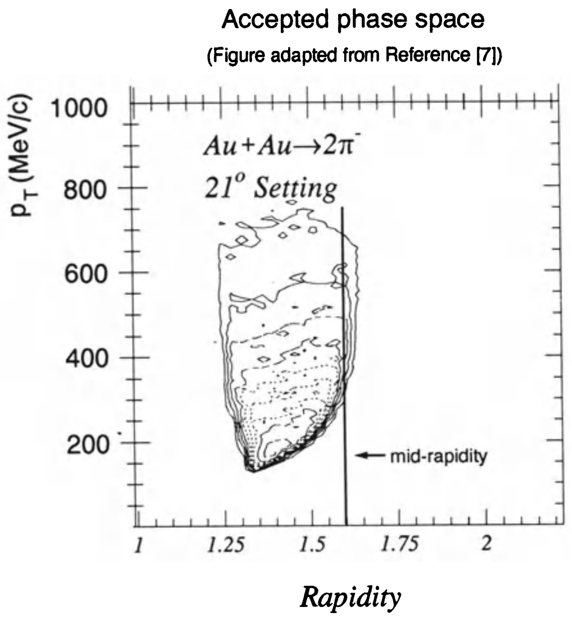
We measure the violence of the collision using a zero-degree hadronic calorimeter (ZCAL) which measures the hadronic energy in roughly a forward cone $\theta_{lab} < 1.5°$. The fragments from the spectator breakup should be mostly contained within the ZCAL, so the ZCAL energy is proportional to the number of projectile spectator nucleons. From the number of projectile spectators, we can easily find the number of projectile participants (N_{pp}). We expect the violence of the collision, as measured by N_{pp}, to be correlated with the impact parameter of the collision: the more central the event, the larger the N_{pp}.

RESULTS

For central events, the length scale (e.g. radius) of the initial collision region should be proportional to $N_{pp}^{1/3}$ since the volume is proportional to N_{pp}. Previous measurements of HBT radii have always yielded results which scaled roughly linearly with $N_{pp}^{1/3}$. Furthermore, the slopes have always been gentle in the sense that straight line fits through the data, $R = a + bN_{pp}^{1/3}$, have yielded intercept values, a, larger than zero[7, 8].

Figure 2 shows the gaussian $R_{R=\tau}$ fit parameter from pion pairs near midrapidity for *Au*-*Au* collisions from E866. Figure 2a shows $R_{R=\tau}$ vs. E_{ZCAL}. The measured results cover a span of about 30% of the full spectator energy range available from the collision or the most central 15% of the cross-section. It should be noted that we are operating the ZCAL in an energy range where it is known to behave linearly and that the bin width is large compared to the resolution (3–5σ). Figure 2b shows the dependence of $R_{R=\tau}$ on the calculated quantity $N_{pp}^{1/3}$. The dashed line $R_{R=\tau} = 1.2\text{fm} \cdot N_{pp}^{1/3}/\sqrt{10}$ is the expected value for $R_{R=\tau}$ based on the transverse size of the original interaction region using hard-sphere geometry and assuming that $R_{R=\tau} = R_L = R_T = \tau$. The factor of $\sqrt{10} = \sqrt{2} \cdot \sqrt{3} \cdot \sqrt{5/3}$ comes from converting a hard sphere value to the gaussian form used in the fit, given the same rms. In the data, the growth of $R_{R=\tau}$ with centrality is steeper than expected, rising 40% in R while $N_{pp}^{1/3}$ rises only by 7%. Furthermore, the value is larger than the original interaction region (assuming $R_L, \tau \leq R$ as indicated in Refs. [7, 8]). Given the presence of dynamical correlations, the true source size might be even larger.

One possible mundane explanation for this effect is that we are seeing a pion freezeout radius and that the number of pions per participant is larger for central collisions due to secondary interactions. Preliminary measurements of the centrality dependence of the pion yield[9] are not yet conclusive, but the dependence does not appear to be strong enough to cause such a steep change in the radius. Further studies are underway[10]. It is still possible that some smaller secondary effect coupled with a statistically unlikely fluctuation has caused this steep rise in the data.


Accepted phase space

(Figure adapted from Reference [7])

Figure 1. The acceptance for negative pions in the E866 apparatus for the data set discussed in this talk.

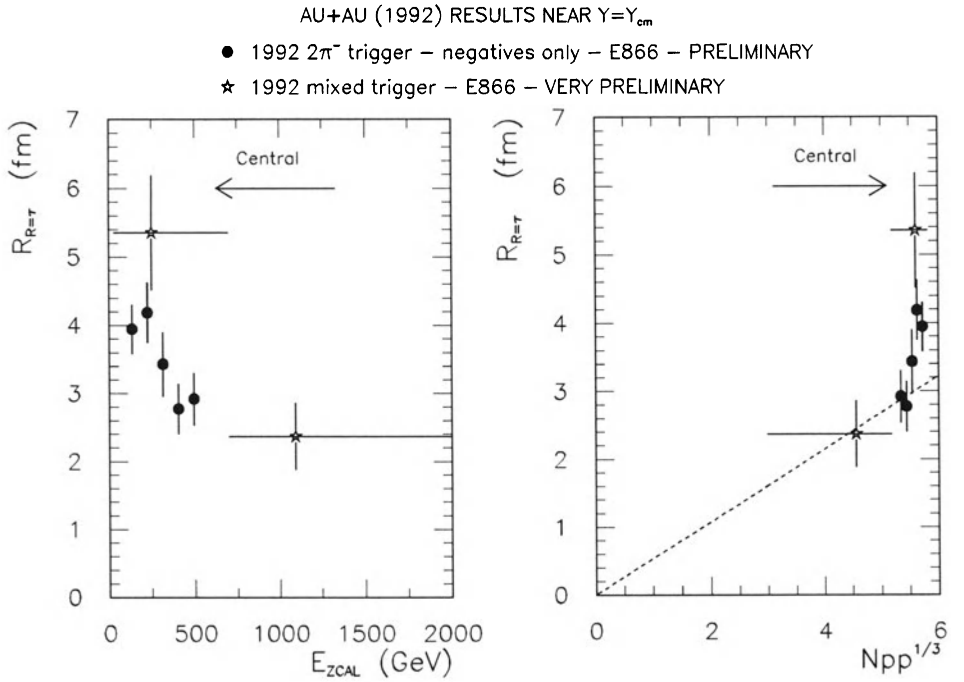


Figure 2. The centrality dependence of $R_{R=\tau}$ (a) vs. ZCAL Energy, (b) vs. $N_{pp}^{1/3}$. The solid points are from the $2\pi^-$ data set described in the text. The open stars are from a related data set with a mixture of $2\pi^+$ and $2\pi^-$ data taken at 24°. The horizontal error bars show the bin sizes, the vertical error bars show the error on the fit parameters, and the dashed line shows the simple geometric expectation based on the transverse size of the original participant zone.

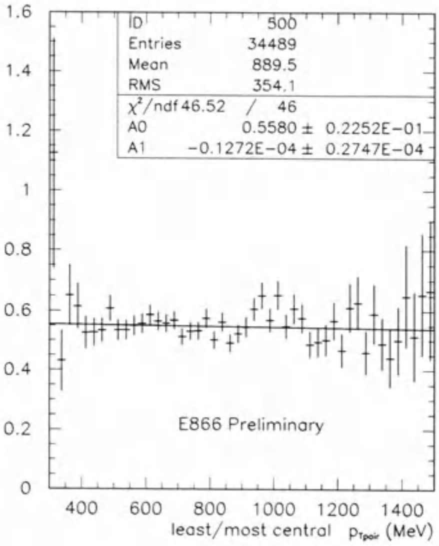


Figure 3. The p_T ratio for pairs between the most central and least central bin of the $2\pi^-$ data sample. The solid line is a straight line fit, showing a statistically negligible slope. The normalization, which is related to the relative sample size in the least and most central bin, is arbitrary.

SYSTEMATIC CONSIDERATIONS

As we pointed out above, it is difficult to understand how dynamical correlations alone could cause a rapid apparent growth of $R_{R=T}$, but we must be careful. If the m_T distribution of the pion pairs softened with centrality, this would cause an apparent increase in the source size parameter with centrality since lower m_T pairs tend to have a longer coherence length in the presence of dynamical correlations. Figure 3, however, shows that the p_T $(= |(\vec{p}_1 + \vec{p}_2)_T|)$ distribution (and therefore the m_T distribution) for accepted pairs is identical within errors between the most and least central bins discussed. Any small difference in the m_T distribution allowed by the data would have a completely negligible effect on Figure 2.

We also performed another systematic test in order to validate the physics results. The test involved varying the binning and the two-particle cuts applied to the data and checking that the results did not change significantly. No significant variations were seen with cut changes or binning changes for any of the centrality bins individually or for the whole data set taken together. Also the χ^2 values for all of the fits were reasonable. The success of this procedure gives us confidence in our handling of two-track efficiencies, in the lack of ghosts in our data, and in the stability of the fit procedure.

The final systematic consideration is the validity of the point-source Gamow correction which was applied to the data to correct for Coulomb effects before fitting. The point-source procedure has been compared to an iterative procedure which takes finite-size effects into account, leading to the conclusion that the point-source correction works well enough, especially for pions and for small data samples such as the one considered here[11].

SUMMARY AND OUTLOOK

We have observed a possible unpredicted, sharp rise in the variable $R_{R=\tau}$ versus centrality ($N_{pp}^{1/3}$) for the most central events at AGS energies. The apparent source size is larger (or longer-lived) than the initial *Au-Au* overlap region. Further experimental study is needed to improve the statistical significance of the result and to determine whether it can be explained by conventional hadronic means or whether more exotic explanations can be admitted.

The E866 data set currently being analyzed contain millions of pion pairs which will allow us to examine multidimensional fits vs. both centrality and $m_{T pair}$. This data set also includes three global event characterization measurements: forward energy, multiplicity, and forward-particle reaction plane. Furthermore these pion pairs will cover a broad range in N_{pp}. This data set should allow us to understand the origin of the intriguing rise in $R_{R=\tau}$ with centrality.

ACKNOWLEDGEMENTS

The author would like to thank Ray Nix for his comments, which sharpened the discussion of frame-dependence in HBT measurements. Several members of the "E802 collaboration" contributed code or advice to the analysis that led to this talk. Vince Cianciolo, James Dunlop, Craig Ogilvie, and Ron Soltz made the most extensive contributions. Further advice came from: Larry Ahle, Chellis Chasman, Brian Cole, Lou Remsberg, Steve Steadman, George Stephans, Mike Tannenbaum, Fuqiang Wang, and Bill Zajc.

Experiment 866 is supported by the U.S. Department of Energy (ANL, BNL, UC-Berkeley, UC-Riverside, Columbia, LLNL, and MIT), by NASA (UC-Berkeley), and by the US-Japan High Energy Physics Collaboration treaty.

REFERENCES

1. S. Kahana et al., Searching for high baryon density at the AGS with ARC, *Nucl. Phys.* A566:465c (1994).
2. U.A. Wiedemann, P. Scotto, and U. Heinz, Transverse momentum dependence of Hanbury-Brown-Twiss correlation radii, PREPRINT TPR-95-06 (1995).
3. T. Alber, Two-pion interferometry in central nucleus-nucleus collisions at the CERN SPS - results from experiments NA35 and NA49, *Nucl. Phys.* A590:453c (1995).
4. B. Jacak, et al., Recent results from NA44 and a review of HBT, *Nucl. Phys.* A590:215c (1995).
5. S. Chapman, R. Nix, U. Heinz, Extracting source parameters from gaussian fits to two particle correlations, *Phys. Rev.* C52:2694 (1995).
6. T. Abbott et al., NIM A **290** (1990) 41.
7. R.A. Soltz. "Two-pion Correlation Measurements for 14.6 A GeV/c Si+X and 11.6 A GeV/c Au+Au" PhD thesis, MIT (1994).
8. B. Cole, et al., Recent results from experiment 859 at the BNL AGS, *Nucl. Phys.* A590:179c (1995).
9. D. Zachary. PhD thesis, MIT (1994).
10. Fuqiang Wang. PhD thesis, Columbia U. (in preparation).
11. V. Cianciolo. "2 K^+ Correlation Measurement" PhD thesis, MIT (1994).

REALISTIC EXPANDING SOURCE MODEL FOR RELATIVISTIC HEAVY-ION COLLISIONS

Scott Chapman[1] and J. Rayford Nix[1]

[1]Theoretical Division
Los Alamos National Laboratory
Los Alamos, New Mexico 87545

INTRODUCTION

An international search is currently underway for the quark-gluon plasma—a predicted new phase of nuclear matter where quarks roam almost freely throughout the medium instead of being confined to individual nucleons.[1,2] Such a plasma could be formed through the compression and excitation that occur when nuclei collide at relativistic speeds. With increasing compression the nucleons overlap sufficiently that they should lose their individual identity and transform into deconfined quarks, and with increasing excitation the many pions that are produced overlap sufficiently that they should lose their individual identity and transform into deconfined quarks and anti-quarks.

Experimental identification of the quark-gluon plasma, as well as understanding other aspects of the process, will require knowing the overall spacetime evolution of the hot, dense hadronic matter that is produced in relativistic heavy-ion collisions. The spacetime evolution of this hadronic matter can in principle be extracted from experimental measurements of invariant one-particle multiplicity distributions and two-particle correlations in emitted pions, kaons, and other particles. The foundations for two-particle correlations were laid in the 1950s by Hanbury Brown and Twiss,[3] who used two-photon correlations to measure the size of stars, and by Goldhaber et al.,[4] who used two-pion correlations to measure the size of the interaction region in antiproton annihilation. Following this pioneering work, many researchers have already analyzed correlations among pions and among kaons produced in relativistic heavy-ion collisions in terms of simple models to obtain some limited information about the size and duration of the emitting source. However, because of the simplicity and/or lack of covariance of the models that have been used, the spatial and time extensions of the emitting source resulting from these analyses have frequently been intertangled, and most of the presently available results may therefore be regarded as exploratory.

Advances in Nuclear Dynamics 2
Edited by Bauer and Westfall, Plenum Press, New York, 1996

SOURCE MODEL

We introduce here a new realistic expanding source model for invariant one-particle multiplicity distributions and two-particle correlations in nearly central relativistic heavy-ion collisions that contains nine adjustable parameters, which are necessary and sufficient to properly characterize the gross properties of the source during its freezeout from a hydrodynamical fluid into a collection of noninteracting, free-streaming hadrons. These nine physically relevant parameters fall into three categories of three parameters each, with the first category corresponding to the source's longitudinal motion, the second category corresponding to its transverse motion, and the third category corresponding to its intrinsic properties.

The three longitudinal parameters are the rapidity $y_{\rm s}$ of the source's center relative to the laboratory frame (in terms of which the velocity $v_{\rm s}$ of the source's center relative to the laboratory frame is given by $v_{\rm s} = \tanh y_{\rm s}$), the longitudinal spacetime rapidity η_0 of the right-hand end of the source in its own frame (in terms of which the velocity v_ℓ of the right-hand end of the source in its own frame is given by $v_\ell = \tanh \eta_0$), and the longitudinal freezeout proper time $\tau_{\rm f}$ (in terms of which the longitudinal radius at the end of freezeout is given by $R_\ell = \tau_{\rm f} \sinh \eta_0$). We assume that the source is boost invariant within the limited region between its two ends,[5,6] and that it starts expanding from an infinitesimally thin disk at time $t = 0$.

The three transverse parameters are the transverse velocity $v_{\rm t}$ and transverse radius $R_{\rm t}$ of the source at the beginning of freezeout and a transverse freezeout coefficient $\alpha_{\rm t}$ that is related to the width $\Delta\tau$ in proper time during which freezeout occurs and that determines the shape of the freezeout hypersurface. The transverse velocity at any point on the freezeout hypersurface is assumed to be linear in the transverse coordinate ρ. As illustrated in Fig. 1 for the reaction considered here,[7–9] freezeout proceeds inward from the initial point $\rho = R_{\rm t}$, $z = 0$ to the source's center and then to the source's ends.

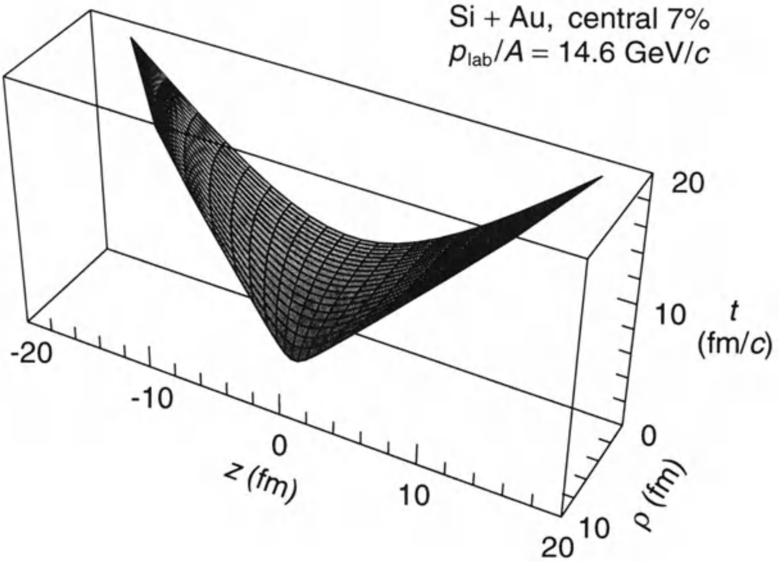


Figure 1. Freezeout hypersurface, which specifies the positions in spacetime where the expanding hydrodynamical fluid is converted into a collection of noninteracting, free-streaming hadrons.