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Submitted to: DOE OFFICE OF SCIENTIFIC AND TECHNICAL
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Observables in Relativistic Heavy-Ion Collisions

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Abstract

This is the final report of a one-year, Laboratory Directed Research and Development (LDRD) project at the Los Alamos National Laboratory (LANL). We used several complimentary models of high-energy nuclear collisions to systematically study the large body of available data from high energy ($p_{\text{beam}}/A > 10 \text{ GeV}/c$) heavy ion experiments at BNL and CERN and to prepare for the data that will come from RHIC. One major goal of this project was to better understand the space-time history of the excited hadronic matter formed in these collisions and to use this understanding to improve models of this process. The space-time structure of the system can be extracted from measurements of single-particle p_T distributions and multiparticle correlations. We looked for experimental effects of the formation of the quark-gluon plasma. Understanding the hadronic phase of the interaction determines the sensitivity of experimental measurements to the presence of this exotic state of matter.

Background and Research Objectives

The theory of strong interactions -- quantum chromodynamics -- predicts the existence of a state of matter in which quarks and gluons are no longer confined within hadrons. Hadrons are the ordinary strongly interacting particles that are made from either two or three quarks each. Examples are protons, neutrons, pions and kaons. This state, called the Quark-Gluon Plasma (QGP), is expected to be produced when hadronic matter is excited to sufficiently high energy density. The QGP is believed to have existed for the first 10 micro-seconds or so of cosmological time and possibly still does exist in the center of neutron stars. Ongoing experiments at the BNL (Brookhaven National Lab) AGS (Alternating Gradient Synchrotron) and the CERN (European Particle Physics Laboratory) SPS (Super Proton Synchrotron) accelerators are attempting to produce and study the QGP in the laboratory; further experiments will be carried out at the Relativistic Heavy Ion Collider (RHIC), which is now under construction at BNL.

As in the early history of the universe, systems produced in the laboratory expand and cool and the QGP, if produced, undergoes a phase transition to a hot dense system of hadrons, which continues to expand until the particles stop interacting (freeze-out). The

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expansion continues until some or all of the hadrons ultimately reach the detectors. Experimental identification of the QGP requires an understanding of the expansion and cooling of both the QGP and the hadronic matter created as it cools back below the transition temperature. The measurements should help answer some of the most tantalizing questions confronting contemporary astrophysics and cosmology. By producing a “little bang” through relativistic heavy ion collisions, experimenters can simulate the conditions that exist when a star dies or that existed shortly after the big bang. The discovery of deconfined quarks and gluons in an entirely new phase of matter would rank as one of the most important milestones of the century.

The properties of the system, such as the lifetime, expansion velocity, and the size and temperature at freeze-out can be extracted from experimental measurements of one-particle p_T distributions and two-particle correlations in emitted pions, kaons, and other particles. However, because of the simplicity of previous models used to fit the data, the resulting spatial and time extensions of the emitting source have frequently been intermingled. We attempted to put the analysis on a more scientifically sound footing using a new procedure (ref. [1]) which simultaneously uses single particle p_T spectra and two-particle correlation measurements to extract properties of the system at freeze-out. In addition to disentangling the spatial and time extensions of the source, this procedure removes the ambiguity inherent in trying to determine both the system’s expansion velocity and temperature from p_T spectra.

Our objective was to understand the physics relevant to experiments on relativistic nucleus-nucleus collisions at the AGS (10-15 GeV/nucleon beams incident on fixed targets), SPS (160-200 GeV/nucleon beams incident on fixed targets), and RHIC (two colliding 100 GeV/nucleon beams) accelerators. The intent was to develop a better understanding of the nature of hadronic matter in the regime between normal nuclear density and the quark-gluon phase transition. We used models of relativistic heavy ion collisions to study the problems of thermodynamic and chemical equilibrium and the equation of state (EOS) of nuclear matter in this regime. These models were used to study some of the experimental measurements that are potentially sensitive to quark-gluon plasma formation: transverse momenta and the longitudinal and transverse sizes of hadronic sources obtained by two-particle interferometry.

Importance to LANL's Science and Technology Base and National R&D Needs

The ultimate goal of this project was to define and implement approaches to be used in the analysis and understanding of data from existing experiments at BNL and CERN and which will eventually be used in the analysis of RHIC data. RHIC is the highest priority construction project in the U.S. Nuclear Physics program. Our LDRD project both took advantage of and added to the Laboratory's core competency in "theory, modeling, and high-performance computing". We used existing theoretical models, developed at Los Alamos, and contributed to improving them. Similarly, we took advantage of existing expertise in the core competency area of "nuclear science, plasmas, and beams" and expanded on it.

Scientific Approach and Accomplishments

One goal of this work was to calculate observables that are of current experimental interest. The key observables we addressed were two-particle correlations, transverse flow, and the freeze-out temperature of the system. The motivation was to measure the equation of state of dense hadronic matter, i.e., to measure the dependency of energy density, pressure, and entropy density on temperature and baryochemical potential. A discontinuity in one these dependencies is a signal for a first-order phase transition to a quark-gluon plasma (QGP).

Two-particle correlations (also known as Bose-Einstein correlations) can be used to measure the size and lifetime of the excited system formed in heavy ion collisions at freeze-out. There is an enhanced probability for two bosons (such as pions, kaons, and photons) to have the same momentum. The width in momentum difference (q) of this enhancement is inversely related to the size of the source. This idea is used to measure the size of the source that emits the bosons. Applied to photons, the idea has been used to measure the size of stars. These measurements are interesting because the system is expected to live longer and expand to a larger size when a QGP is formed.

The velocity of the transverse expansion of the excited system is a measure of pressure in the source and is therefore sensitive to the equation of state. In a hydrodynamic picture, the differences in the slope parameters of different produced particles are sensitive to the combination of the expansion velocity and the system's temperature. The transverse expansion velocity and the temperature are strongly correlated ---increasing either quantity has a similar effect on the shape of the p_T spectrum. The two quantities can only be disentangled by looking simultaneously at data from many types of produced particles.

Our realistic expanding source model (ref. [1]) for heavy ion collisions predicts single-particle p_T distributions and two-particle correlations of pions, kaons, and other particles produced in nearly central relativistic heavy ion collisions. It uses nine independent properties of the source at freeze-out. These nine properties are:

1. Central baryon density (n)
2. Temperature (T)
3. Transverse expansion velocity (v_t)
4. Longitudinal expansion velocity (v_l)
5. Source velocity (v_s)
6. Transverse radius (R_t)
7. Longitudinal proper time (t_f)
8. Width in proper time ($\Delta\tau$)
9. Pion incoherence fraction (λ_π)

The values of these freeze-out properties and the associated uncertainties are obtained from a chi-square minimization involving calculated and experimental one-particle p_T distributions and two-particle correlations.

Los Alamos staff members developed the first 3+1 dimensional relativistic fluid code for application to heavy ion collisions and have continued to develop such models over the years. In our study, we used the HYLANDER model (ref. [2]). This code has complete flexibility with respect to the EOS, impact parameter, initial conditions, and target-projectile choice. We have implemented an EOS derived from parton cascade models. Parton cascade models assume that the dynamics of a nuclear collision can be calculated based on a series of two-particle collisions along with knowledge of the two-particle cross-sections. Such models predict rapid thermalization at sufficiently high energies. One can calculate the multiplicities of direct particles, their decay products, and other observables.

The fluid dynamical calculations depend on the assumed initial conditions, the freeze-out criterion, and the EOS. Assumptions are made about each of these and the model is then used to calculate experimentally observable quantities. The sensitivity of the observables to the fluid dynamical model's input assumptions is tested by varying the assumptions. The expanding source model (ref. [1]) determines the properties of an expanding system at freeze-out by making a fit to the experimentally observable quantities. The first step of our study was to apply the source model to the results of a fluid dynamical calculation. In this case, we know the "correct" answers and can use this result as a "calibration" of the expanding source model.

We first generated a set of one-particle and correlation data generated from the HYLANDER hydrodynamical model. These calculations assumed a high freeze-out temperature and an extremely low transverse velocity. The expanding source model was applied to these “data” and was able to reproduce the source properties within reasonable uncertainties. The results of this study demonstrated that the model is capable of reproducing the underlying freeze-out properties even when their values were chosen to lie in unanticipated regions. This study can be considered a “calibration” of the expanding source model.

Because the expanding source model worked for this case where the answers were known, we felt confident in applying the model to experimental data. We performed four separate studies of experimental data with the model. Our first three studies used experimental data for nearly central collisions of Si+Au at $p_{\text{LAB}}/A = 14.6 \text{ GeV}/c$ (ref. [3]). In the first study, where we considered separately the one-particle data and the correlation data, we learned that the first five properties (n, T, v_t, v_p, v_s) are determined primarily by single-particle p_T distributions and that the last four properties ($R_t, t_f, \Delta\tau, \lambda_\pi$) are determined primarily by two-particle correlations. In the second study, where we considered separately the kaon data and the pion data, we learned that although kaon freeze-out occurs slightly earlier than the pion freeze-out, the 99% confidence level error-bars associated with the two freeze-out times overlap. In the third study, where we changed the shape of the freeze-out hypersurface, we learned that the precise shape of the freeze-out hypersurface is relatively unimportant.

In the fourth study of experimental data, the expanding source model was applied to preliminary NA44 data in which the normalizations of the experimental single-particle data were unknown. Several of the model’s properties are poorly constrained without the normalizations since they depend strongly on the relative yields of different particles. The data in this study were from Pb beams at $p_{\text{LAB}}/A = 158 \text{ GeV}/c$ and included two-particle correlations of π^+ pairs as well as the shapes of single-particle p_T distributions of π^+ , π^- , K^+ , and K^- . One interesting result of this preliminary study is that, as when the model was applied to E802 AGS data (ref. [1]), the temperature of the system is around 90-100 MeV and the transverse velocity is around 0.67c (where c is the speed of light). This is an unexpected result. Other approaches, which used simplified model and subsets of the data have concluded that the temperature is higher (around 140 MeV) and the expansion velocity is lower (around 0.4c). We hope to study this question further.

Using the HYLANDER hydrodynamical model, we improved our understanding of the limitations and usefulness of two-particle correlation measurements. We found excellent agreement between the calculations and rapidity spectra of negative hadrons and

protons and with the correlation measurements in two experiments: S+S at 200 GeV/nucleon and Pb+Pb at 158 GeV/nucleon (pub. [2]). Within our model this implied that for Pb+Pb (S+S) a quark-gluon plasma of initial volume 174 fm^3 (24 fm^3) with a lifetime of 3.4 fm/c (1.5 fm/c) was formed. It was also found that the Bose-Einstein correlation measurements do not determine the maximal effective radii of the pion sources because of the large contributions from resonance decay at small momentum.

We have also studied (pub. [3]) the implications of the formation of a Bose condensate on one- and two-particle spectra. A Bose condensate is a state of matter that forms when the pion chemical potential exceeds the pion mass -- leading to a large number of pions with small momenta (measured in the rest frame of the source). It was found that single particle spectra are considerably enhanced at low momentum. For pion pairs in the central region a two-component structure may appear in the correlation function and the chaoticity parameter is strongly momentum dependent.

The space-time extensions of kaon emission zones were calculated directly from space-time densities and compared to the inverse widths of two-kaon Bose-Einstein correlation functions (pub. [8]). The comparison showed a satisfactory agreement and it is concluded that because of the Gaussian shape of the kaon correlation functions, the space-time parameters of the kaon source can be calculated directly from space-time densities. This skips the time consuming process of calculating the kaon correlation function from the model in order to get these size parameters ---which come from a fit to the correlation function. For two-pion correlations this simplification is not recommended because of the important effects of resonance decays.

In summary, this project was a successful collaboration between experimental and theoretical groups in Los Alamos. We worked in a research area of high national and international priority. The expanding source model was "calibrated" by applying it to results of a hydrodynamical model. For the case of a high temperature and a low expansion velocity the model gives the correct result. We applied the expanding source model to both AGS and preliminary NA44 data and found reasonably good agreement. The temperature was around 90-100 MeV (which is surprisingly low) and the expansion velocity was around 0.67c (which is surprisingly high) in each case. We hope to further pursue the explanation for this unexpected result. The hydrodynamic model was compared to data and good agreement was found. The sensitivity of the data to different assumptions about the size of the system and to the formation of a Bose condensate was studied. The data are consistent with the assumption that a QGP was formed, but explanations that do not make this assumption are also possible.

Publications

1. Schlei, B., *et al.*, "Particle Spectra and Bose-Einstein Correlations for Pb+Pb at SPS Energies from Hylander," Nucl. Phys. A610, 570c (1996).
2. Ornik, U., "Hydrodynamical Analysis of Symmetric Nucleus-Nucleus Collisions at CERN/SPS," Phys. Rev. C, **54**, 1381 (1996).
3. Ornik, U., *et al.*, "The Effects of Bose-condensates on Single Inclusive Spectra and Bose-Einstein Correlations," Phys. Rev. C, **56**, 412 (1997).
4. Schlei, B. and Strottman, D., "Hydrodynamical Analysis of Symmetric Nucleus-Nucleus Collisions at SPS Energy," Proc. of the workshop on nuclear physics at the turn of the millenium, 458 (1996).
5. Chapman, S. Nix, J., "Freeze-out Properties in Relativistic Heavy-ion Collisions," Bulletin of the Amercian Chemical Society abstracts of papers, **213**, 91 (1997).
6. Schlei, B., *et al.*, "Equation of State of Nuclear Matter in 158 AGeV Pb+Pb Collisions," Phys. Rev. Lett., **80**, 3467 (1998).
7. Schlei, B., Xu, N., "Mt Dependence of Bose-Einstein Correlation Radii," Phys. Rev. C, **54**, R2115 (1996).
8. Schlei, B., "Space-time Extensions from Space-time Densities and Bose-Einstein Correlations," Phys. Rev. C, **55**, 954 (1997).
9. Schlei, B., *et al.*, "The Linear Correlation Coefficient vs. the New Cross Term in Bose-Einstein Correlations," LAUR-97-0324, Phys. Lett. B (in press) (1998).
10. Schlei, B., Strottman, D., "Probing the Equation of State of Nuclear Matter with Relativistic Hydrodynamics," Proc. of American Chemical Society meeting in Las Vegas, Nevada, **214**, NUCL-045 (1997).
11. Schlei, B., "Extracting the Equation of State of Nuclear Matter through Hydrodynamical Analysis," ACTA Physica Hung. (Heavy Ion Phys.), **5**, 403 (1997).
12. Schlei, B., *et al.*, "Effects of the Equation of State of Nuclear Matter in 158 AGeV Pb+Pb Collisions," Bulletin of the American Physical Society, **X**, CF.03 (1997).

References

- [1] Chapman, S., Nix, J., "Realistic Expanding Source Model for Invariant One-Particle Multiplicity Distributions and Two-Particle Corelations in Relativistic Heavy Ion Collisions," Phys. Rev. C, **54**, 866, (1996).
- [2] Ornik, U., *et al.*, "High-Energy Heavy-Ion Reactions and Relativistic Hydrodynamics in Three Dimensions," Phys. Rev. Lett., **63**, 2641, (1989).
- [3] Abbott, T., *et al.*, "Charged Hadron Distributions in Central and Peripheral; Si+A collisions at 14.6 AGeV/c," Phys. Rev. C, **50**, 1024, (1994).