LA-UR-97-2772

Approved for public release;
distribution is unlimited

Title: Nonequilibrium Dynamics of the Quark-Gluon
Plasma in Heavy Ion Collisions

Author(s): E. Mottola, T-8
F. Cooper, T-8
S. Habib, T-8
Y. Kluger, T-8
J. P. Paz, T-6

MASTER

Submitted to: DOE Office of Scientific and Technical Information (OSTI)

DISCLAIMER

This report was prepared as an account of work sponsored by an agency of the United States Government. Neither the United States Government nor any agency thereof, nor any of their employees, makes any warranty, express or implied, or assumes any legal liability or responsibility for the accuracy, completeness, or usefulness of any information, apparatus, product, or process disclosed, or represents that its use would not infringe privately owned rights. Reference herein to any specific commercial product, process, or service by trade name, trademark, manufacturer, or otherwise does not necessarily constitute or imply its endorsement, recommendation, or favoring by the United States Government or any agency thereof. The views and opinions of authors expressed herein do not necessarily state or reflect those of the United States Government or any agency thereof.

OF THE TOTAL OF THIS DOCUMENT IS UNLIMITED

Los Alamos
NATIONAL LABORATORY

Los Alamos National Laboratory, an affirmative action/equal opportunity employer, is operated by the University of California for the U.S. Department of Energy under contract W-7405-ENG-36. By acceptance of this article, the publisher recognizes that the U.S. Government retains a nonexclusive, royalty-free license to publish or reproduce the published form of this contribution, or to allow others to do so, for U.S. Government purposes. Los Alamos National Laboratory requests that the publisher identify this article as work performed under the auspices of the U.S. Department of Energy. Los Alamos National Laboratory strongly supports academic freedom and a researcher's right to publish; as an institution, however, the Laboratory does not endorse the viewpoint of a publication or guarantee its technical correctness.

DISCLAIMER

**Portions of this document may be illegible
in electronic image products. Images are
produced from the best available original
document.**

Nonequilibrium Dynamics of the Quark-Gluon Plasma in Heavy Ion Collisions

Emil Mottola,* Fred Cooper, Salman Habib,
Yuval Kluger and Juan P. Paz

RECEIVED

NOV 03 1997

OSTI

Abstract

This is the final report of a three-year, Laboratory Directed Research and Development (LDRD) project at the Los Alamos National Laboratory (LANL). We have developed field theory and numerical methods for the general problem of quantum back reaction on classical fields, with applications to a wide variety of physical systems. Our main focus was on particle production processes in the time evolution of the quark-gluon plasma following an ultrarelativistic heavy-ion collision. In particular, we studied in some detail the evolution of a disoriented chiral condensate (DCC) produced in the chiral phase transition of nuclear matter in heavy-ion collision experiments. We have also studied dissipation and decoherence as a result of particle production in time-varying mean fields. Numerical codes previously developed for particle production in strong electric fields in quantum electrodynamics (QED) have been modified for the quantum chromodynamics (QCD) problem. We have made specific predictions for energy-momentum flow and pion production in the central rapidity region of experiments to be performed at the Relativistic Heavy-Ion Collider (RHIC).

Background and Research Objectives

Until recently, most elementary-particle calculations involved determining probabilities (cross sections) for finding different particles with particular energies and angles following a collision of two incident particles. As successful as this scattering theory has been, it is clear that it is capable of addressing only a very limited subclass of questions one might hope to answer in particle physics or quantum field theory. Lattice quantum chromodynamics (QCD) calculations are an exception to this rule, but they apply easily only to static or equilibrium situations. In the last few years it has become clear that there are many situations of direct physical interest involving *time-dependent* dynamical evolution in which a perturbative scattering formalism is wholly inadequate. This is the case for strong field electrodynamics in astrophysical plasmas in nuclear collisions of heavy ions during which a phase transition to a quark-gluon plasma is expected to take place, and in the hot, dense early universe. These problems require a detailed knowledge of the dynamical time evolution of the field configurations and energy flow.

*Principal Investigator, E-mail: emil@pion.lanl.gov

Hydrodynamical models of nuclear collisions were first investigated very thoroughly for the case of pp and e^+e^- collisions by Cooper and his collaborators in the 1970s. These models assume that an equation of state (based on static equilibrium considerations) is applicable to these processes. The original kinetic theory formalism developed by Cooper, Carruthers, and others in the 70s was formulated for non-QCD model field theories and was developed to try to justify hydrodynamical assumptions. It is important to emphasize that such hydrodynamical models are completely ad hoc and that their connection to the underlying microscopic physics is unclear. A fully consistent field theoretic approach is necessary in order to calculate the evolution of the quark-gluon plasma from first principles of QCD. This is precisely the gap that we addressed.

Several years ago, Cooper and Mottola pioneered the development of techniques to study initial value problems both in the functional Schrödinger picture and in the Heisenberg picture. The generic quantum radiation reaction problem was reduced to solving a well-defined set of finite, coupled integro-differential equations with given initial value data. Thus, a consistent theoretical formulation, coupled with the development of high-speed supercomputing finally makes the radiation reaction problem amenable to analysis, as well as timely in its applications to heavy-ion collider experiments and other areas of current active research.

In the past few years, Cooper, Mottola, and Y. Kluger (then at Tel Aviv University) have developed numerical codes to solve for the time evolution of electrons and positrons produced by strong electric fields. Already it is clear that previous attempts to study pair production phenomenologically using a Boltzmann approach failed to correctly include Pauli-blocking effects and thus gave wrong particle spectra results. We have calculated production rates, determined an effective dynamical equation of state for the plasma, and watched the dissipation of the field with concurrent particle production and plasma oscillation. Interactions between the produced particles first appear at order $1/N$ in our systematic, large- N expansion. In transport theory language this is equivalent to adding collision terms in the Vlasov equation. Particle creation processes of exactly this sort are conjectured to take place in the vicinity of rapidly rotating neutron stars. Our calculation (now in progress) of the time scale for shorting out of the electric field energy into e^+e^- pairs will provide the first a priori calculation of the dynamics of this mechanism directly from the Lagrangian of quantum electrodynamics (QED), and may eventually constrain some of the astrophysical models of energy transport in pulsar magnetospheres.

It is believed from lattice QCD calculations that under extreme conditions of temperature and density, a new phase of matter may be produced, namely the quark-gluon plasma. Estimates of the critical baryon number density are around $n_c = .2 \text{ fm}^{-3}$ and for the

critical temperature $T_c = 200$ MeV. Such critical densities of baryon number are expected to occur at the Relativistic Heavy-Ion Collider (RHIC) at Brookhaven National Laboratory. An understanding of the dynamics of this process is especially important for the theoretical interpretation of the data to be produced by RHIC experiments within a few years. The problem of lattice QCD calculations is that they can only study the plasma in a static condition (i.e., in equilibrium at a fixed temperature), whereas the conditions following a heavy ion collision are clearly very far from equilibrium, at least initially. One would like to know how the plasma is produced, how efficiently it thermalizes on what time scale, how it evolves, and what are the special signatures (in terms of flow of energy, production of particles, correlations, etc.) of this new state of matter.

In our simulations, we find that the system goes through a nonequilibrium phase transition, during which time large numbers of low-momentum pions are produced that distort the final spectrum of secondaries away from an equilibrium distribution. These low-momentum pions are produced by a Bose-Einstein condensate, which is a coherent collective structure that later decays into individual pions (a pion "laser") as the plasma expands and cools. In the proposed experiments at RHIC, the PHENIX group will look for the predicted distortion of the pion spectrum that would be the first experimental evidence for the chiral phase transition in the strong nuclear interactions.

Our objective was to study in detail the evolution of the quark-gluon plasma following a heavy ion collision. Using our methods, we will be able to check which (if any) of the assumptions of the various hydrodynamical models are valid, and also to obtain numerically the dynamical equation of state of the quark-gluon plasma as a function of the proper time coordinate in the future light cone of the collision event. The effort at Los Alamos is unique in implementing this microscopic approach to a detailed description of the quark-gluon plasma from fundamental theory. Eventually this will make possible the first detailed calculation of transport coefficients, damping rates, and energy loss characteristics of this new phase of matter from first principles of QCD.

Although our primary focus was the strong field problem in the QCD quark-gluon plasma, our methods are applicable to a wide range of other physical problems. For example, the time evolution of the order parameter in a phase transition may be studied by these techniques. These dynamics are of great interest in statistical mechanics (spinodal decomposition) and in early universe cosmology. In the time evolution of the early universe, particle production effects are important and may lead to the dynamical decay of the cosmological constant and alter the large-scale structure of the universe.

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

The underlying microscopic theory of nonequilibrium evolution in the context of quantum field theory and many-body theory has been developed in great part at Los Alamos in the Theoretical (T) Division. In fact, hydrodynamical models of nuclear collisions were first investigated in pioneering work by F. Cooper and his collaborators in the 1970s. The recent work by the authors has transformed the formal theoretical methods into practical algorithms, a feat only made possible by the advent of parallel supercomputers at the Advanced Computing Laboratory (ACL) at LANL. These methods have been applied to the quark-gluon and chiral phase transitions of nuclear matter. It is this phase transition that will be probed by RHIC at Brookhaven National Laboratory. Los Alamos is a major participant in the effort at RHIC through the efforts of Barbara Jacak, Physics Division, and her collaborators in the PHENIX experiment.

The computational requirements of our proposal are a challenge to the most powerful supercomputers available today. With the world's largest computer, the Connection Machine (CM-5) at the ACL, Los Alamos is the optimal location for this research. A major component of the Laboratory's strategic plan is the High Performance Computing Initiative. Our theoretical physics project demands high-performance supercomputing and, as such, is a prime example of a basic scientific research effort driving cutting-edge technology in an area of great importance to the future of the Laboratory.

Scientific Approach and Accomplishments

Our effort in understanding quantum field theory in nonequilibrium domains made progress on two fronts. First, we were able to relate our calculations of the nonequilibrium chiral phase transition to an experimentally measurable effect, namely an anomalous transverse distribution of pions at low momentum, and we also are about to use our density matrix to make an event generator for the experimental collaboration PHENIX. The calculation of the particle spectrum was done both in boost-invariant geometry as well as for a spherically expanding chiral phase transition. Second, we have exciting new results showing that the production of zero mass particles can cause apparent dissipation in quantum systems that are described by Hamiltonian dynamics. We were able to identify an appropriate entropy and understand decoherence. We also were able to predict analytically

by linear response theory the intermediate and final stages of the time evolution of massless ϕ^4 field theory starting from an initial thermal distribution.

We are also making progress understanding how to include scattering corrections to our mean field calculations in both the Heisenberg and Schrödinger equations. In the Heisenberg picture, a large N expansion leads to integro-differential equations that we studied in quantum mechanics. The advantage of the Schrödinger picture is that one gets ordinary, first-order differential equations for the variational parameters. We have found that the large- N expansion is related to trial wave functions that are Gaussian time polynomials. More work is needed to understand the accuracy of the next order by comparing with exact results in quantum mechanics. The closed-time-path formalism of Schwinger and Keldysh was used to derive equations appropriate for studying time-dependent initial value problems and nonequilibrium processes in quantum field theory. This formalism will allow us to do a systematic $1/N$ expansion in the number of fermion species or flavors in a way that ensures causality and gauge invariance at every order of the expansion. Once the relevant equations have been derived from the path integral, the analysis of renormalization divergences is straightforward and manifestly finite equations were derived that are suitable for numerical integration.

We developed parallel codes to take full advantage of the computer power at Los Alamos, in particular the CM-5. The complexity of the computational problem can be appreciated by noting that present codes consist of several thousand coupled nonlinear integro-differential equations and require a few weeks of running time on the FPS machine at the ACL.

Our specific accomplishments include:

- Detailed results on particle production in the central rapidity region of a heavy-ion collision, such as energy-momentum flow, entropy production, and effective equation of state as well as comparison with phenomenological hydrodynamic models and Boltzmann-Vlasov transport theory.
- The first study of the quantum evolution of a disoriented chiral condensate (DCC), including the distribution of pions at low transverse momentum that could be used as an experimental signature for the chiral phase transition of nuclear matter, probed in heavy-ion collisions.
- Detailed calculation of time evolution of order parameters and correlation functions in spinodal decomposition in second-order phase transitions described by a Landau-Ginzburg free-energy function, including identification of the true nonequilibrium effective potential of the evolution, dissipation and decoherence by particle production

effects, first principles calculation of the damping rate in the plasma, the growth of effective particle entropy, and the transition from quantum to classical behavior.

- Extension of the $1/N$ expansion previously developed for strong field electrodynamics to QCD, so that the effect of color and the nonlinear gluon interactions can be included in a systematic way.

Publications

- [1] F. Cooper, J. M. Eisenberg, Y. Kluger, E. Mottola, and B. Svetitsky, "Particle Production in the Central Rapidity Region," *Phys. Rev.* **D48**, 190 (1993).
- [2] E. Mottola, "Nonequilibrium Electrodynamics in the Large N Expansion," Invited Talk at the Banff Workshop on Thermal Field Theory}, F. C. Khanna, R. Kobes, G. Kunstatter, and H. Umezawa, Eds., World Scientific Press, Singapore, 1994.
- [3] F. Cooper, S. Habib, Y. Kluger, E. Mottola, J. P. Paz, and P. R. Anderson, "Nonequilibrium Quantum Fields in the Large N Expansion," *Phys. Rev.* **D50**, 2848 (1994).
- [4] F. Cooper, Y. Kluger, E. Mottola, and J. P. Paz, "Nonequilibrium Quantum Dynamics of Disoriented Chiral Condensates," *Phys. Rev.* **D51**, 2377 (1995).
- [5] E. Mottola, "Nonequilibrium Evolution of Disoriented Chiral Condensates," Electroweak Physics and the Early Universe, NATO ASI Series B: *Physics* **338**, J. C. Romnao and F. Freire, Eds., Plenum Press, New York, (1994).
- [6] E. Mottola, "Nonequilibrium Quantum Fields: The Chiral Phase Transition in Heavy Ion Collisions," in *Proceedings of the Eight International Seminar Quarks '94*, D. Yu. Grigoriev, V. A. Matveev, V. A. Rubakov, D. T. Son, and A. N. Tavkhelidze, Eds., World Scientific Press, Singapore, 1995.
- [7] Y. Kluger, S. Habib, E. Mottola, and J. P. Paz, "Dissipation and Decoherence in Mean Field Theory," submitted to *Phys. Rev. Lett.*
- [8] F. Cooper, S. Habib, Y. Kluger, and E. Mottola, "Nonequilibrium Dynamics of Symmetry Breaking in $\lambda\phi^4$ Field Theory" submitted to *Phys. Rev. D*.
- [9] F. Cooper, Y. Kluger, and E. Mottola, "Anomalous Transverse Distribution of Pions as a Signal for the Production of DCC," to be published in *Phys. Rev.* **C54**, (1996).

Figure 1. Signature of the chiral phase transition in heavy-ion collisions. The curve labelled "mean field approximation" is the expected distribution of pions as a function of momentum perpendicular to the collision axis if a region of DCC is produced in the collision. For comparison the other two curves are the pion distributions expected from strict adiabatic evolution from equilibrium at two different temperatures.

Figure 2. Evolution of Boltzmann entropy and effective entropy of the adiabatic particle number density in a second-order phase transition.

Figure 3. Equation-of-state evolution for massless particles in a second-order phase transition.

Figure 4. Particle number distributions as functions of transverse (p) and longitudinal (k_η) momentum for initial conditions corresponding to the formation of DCC (upper panels) compared to the locally thermal equilibrium number density (lower panels). Notice the strong enhancements at low p and low k_η in the case where DCC is formed in the collision event.