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The QCD Phase Transition in Relativistic Heavy Ion Collisions

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Abstract

This is the final report of a three-year, Laboratory-Directed Research and Development (LDRD) project at the Los Alamos National Laboratory (LANL). The objective of the research was to develop practical numerical methods using a first principles field theory approach to describe and study nonequilibrium phase transitions of nuclear and quark matter in ultrarelativistic heavy ion collisions at the Brookhaven Relativistic Hadron Ion Collider (RHIC). Our approach was based on a systematic $1/N$ expansion, and a density matrix formalism was developed to enable us to generate statistical ensembles of hypothetical experimental events. We performed numerical simulations of the chiral phase transition and determined experimental signatures such as distortion of pion and dilepton spectra as a result of the production of disoriented chiral condensates. We obtained an effective transport as well as hydrodynamic description of our mean field theory results. We found that a naïve use of the $1/N$ expansion led to secular behavior and thus resummation methods were needed before being compared with experiment.

Background and Research Objectives

The objective of the research was to develop practical numerical methods using a first principles field theory approach to describe and study nonequilibrium phase transitions of nuclear and quark matter in ultrarelativistic heavy ion collisions at RHIC. At the beginning of our research, only mean-field methods were available to study this type of problem. To go beyond mean field theory we developed a $1/N$ expansion method using Schwinger's Closed Time Path formalism. We hoped this would allow us to determine important rethermalization times and give us more solid predictions for experimentalists at RHIC on how nonequilibrium effects distort pion and dilepton spectra from those expected in the local thermal equilibrium scenario then being assumed. On the computational side we hoped to be able to develop algorithms for solving inhomogeneous initial value problems so that various topological configurations could be studied and their effects understood.

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

The research in this project uses methods that are related to those being developed to study nonequilibrium phenomena in general in the core competency area of nonequilibrium science. The RHIC accelerator at Brookhaven is the major DOE Nuclear Physics experimental physics facility for understanding the production of the quark-gluon plasma and the physics related to the evolution of the early universe. Our research was to understand the nonequilibrium aspects of the quark-gluon plasma expected to be formed during the ultrarelativistic heavy ion collisions at RHIC. In particular the laboratory has played a leading roll in the devleopment of the PHENIX detector that is one of the main detectors at the RHIC facility.

Scientific Approach and Accomplishments

Exact simulations of non-equilibrium phenomena in quantum field theory are not possible because the exact theory is equivalent to an infinite number of coupled nonlinear partial differential equations for the correlation functions describing the quantum fluctuations. Thus it is necessary to develop approximation methods where at lowest order the main features are captured. Mean field theory is a reasonable first approximation in that it describes the equilibrium phase structure of many theories quite well. The main problem has been to develop a systematic expansion around mean field theory which is well behaved and captures in low orders the major physics ingredients left out of the mean field calculation. During the time period of this proposal, we investigated an expansion around mean field theory based on a small parameter $1/N$ where N was the number of species of particles. In the context of mean-field theory we studied several effective field theories having the same chiral phase transition expected for the quark-gluon plasma. We found evidence that the non-equilibrium nature of the phase transition could effect the distribution of various particles produced following a heavy ion collision such as the spectrum of pions and dileptons. We were also able to give algorithms for studying inhomogeneous evolution of the plasma which would allow one to study various coherent phenomena such as textures, disoriented chiral condensates or vortices in plasmas. These algorithms are just being implemented in model field theories as this review is being written.

To understand the domain of validity of the expansion in $1/N$ we studied an exactly solvable quantum mechanics problem with N coupled anharmonic oscillators.

In quantum mechanics we found a phase transition in the parameter $1/N$, making it unsuitable for simulations at modest $N < 20$. For $N < 20$, the expansion worked well at short times but then failed for times (measured in the oscillation frequency of a particle of mass m) of order N . This result then led us to explore methods of improving on the $1/N$ approximation. These improvements have been accomplished by us after the completion of this project. During the time-period of this project, other investigators showed that the phase structure of QCD had some new features at finite chemical potential--namely the existence of a superconducting phase where pairs of quarks form the order parameter.

We then switched our attention to producing a simple model with this property in order to study the dynamics of out of equilibrium phase transitions at finite chemical potential. Subsequent to the ending of this project we have been able to perform simulations of these phase transitions,

The achievements of the project were to perform the first out of equilibrium field theory evolution of the disoriented chiral condensates formed following a chiral phase transition. We also determined the distortion of the pion and dilepton spectra in a mean field approximation and published these spectra so that the experimentalists could look for these signatures. We also were able to give a consistent formalism for obtaining the evolution of inhomogeneous condensates in various quantum field theory settings. We were able to give the first derivation of how to obtain a quantum transport equation directly from a first principles field theory approach. We also invented a 4-Fermi model which had the same phase structure QCD at finite density and temperature which we subsequently have used to study phase transitions at non-zero baryon density.

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