

FINAL REPORT

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entitled

Modeling and Analysis of Ultra-Relativistic Heavy-Ion Collisions

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1 Research Motivation

Hadronic, i.e. strongly interacting, matter is described by the theory of quantum chromodynamics (QCD). The basic constituents of QCD, quarks and gluons, are normally confined to hadrons, but it is believed that under extreme conditions, such as shortly after the creation of the universe, quarks and gluons can exist as independent particles in a new state of matter, called a quark-gluon plasma (QGP). Due to the rapid expansion of the universe, this plasma went through a phase transition to form hadrons – most importantly nucleons – which constitute the building blocks of matter as we know it today. The investigation of the QGP under laboratory conditions will yield important novel insights into the development of the early universe and the behavior of matter under extreme conditions.

This study is presently the subject of the physics program of the Relativistic Heavy Ion Collider (RHIC) at Brookhaven National Laboratory. First data from the $\sqrt{s_{NN}} = 130$ GeV and $\sqrt{s_{NN}} = 200$ GeV Au+Au runs at RHIC have yielded many interesting and sometimes surprising results [1, 2, 3, 4]. While many theoretical predictions [5, 6] have been confirmed, some of the experimental results have brought surprises and indicate that RHIC is, indeed, probing a new physics regime of QCD matter.

2 Personnel and distribution of tasks

The Nuclear Theory group at Duke involved in research relevant to the RHIC program consists of two faculty (B. Müller and S.A. Bass), one associate (A. Majumder) and two graduate students (B. Neufeld and N. Demir). Over the past reporting period, the DOE has supported the group through a group grant (B. Müller as PI and S.A. Bass) as well as through an OJI award for S.A. Bass.

The research emphasis of the Duke group lies in two areas, both of high relevance to the ongoing experimental program at RHIC:

- **Hard Probes of the Medium**

A central goal of the RHIC science program is the investigation and characterization of QCD matter at the highest energy densities. In particular, the interactions between hard probes and bulk QCD matter are of paramount importance for the understanding of high temperature and density QCD. They give rise to well-known phenomena such as jet quenching, di-hadron correlations, heavy flavor production and electromagnetic radiation, as well as more speculative ones like the possible creation of Mach cones in the medium. The Duke group is currently active in all of the above mentioned areas and has played a pioneering role in the area of possible Mach cone formation at RHIC.

- **Modeling of Relativistic Heavy-Ion Collisions**

The Duke group has a long-standing tradition and know-how in the field of modeling of Relativistic Heavy-Ion Collisions. Its expertise ranges from purely hadronic transport approaches, such as the Ultra-Relativistic Quantum Molecular Dynamics approach (developed

by S.A. Bass and co-workers), to purely partonic approaches such as the Parton Cascade Model (developed by B. Müller and K. Kinder-Geiger, subsequently taken up by S.A. Bass) as well as hybrid macro+micro transport approaches for treating the bulk properties of both, the deconfined as well as the confined reaction phases (developed by S.A. Bass and A. Dumitru). Current research focuses on the further development of a fully 3D hydrodynamical plus microscopic hybrid transport approach and its application to RHIC physics.

Both of the above areas are being addressed by the research conducted on the OJI grant. A. Majumder's salary is funded 50% by the OJI award and 50% by the group grant. S.A. Bass receives 1 month of summer salary through the OJI award. N. Demir is fully funded through the OJI award. Table 1 shows a detailed breakup of personnel resources between the two grants with respects to the physics tasks.

task	Müller	Bass	Majumder	Demir	Neufeld
Hard & Electromagnetic Probes:					
Mach Cones	GG				GG
Longitudinal Jet Broadening	GG	GG	GG		
Modeling of Collision Dynamics					
3D-Hydro plus micro		OJI			
Anomalous QGP Viscosity	GG	GG			
Transport Coefficients		OJI		OJI	
Jets in Hydrodynamic Medium		OJI	OJI		

Table 1: Distribution of funding between the OJI grant (OJI) and group grant (GG) among the different tasks.

3 Progress on proposed research

3.1 Jet-medium interactions

The early partonic collisions that lead to the formation of the QGP often engender hard scattering which leads to the formation of two back-to-back hard partons. These traverse the dense medium, losing energy and finally fragment into hadrons – a phenomenon which has been called *jet-quenching* [7, 8, 9, 10]. There now exists a wealth of experimental data on a variety of observables based on such high momentum hadrons including but not limited to the nuclear modification factor R_{AA} , the elliptic flow v_2 at high p_T (as a measure of the azimuthal anisotropy of the jet cross section) and a whole array of high p_T hadron-hadron correlations (usually one compares the ratio of the correlation in a heavy-ion collision to that in a $p-p$ collision for both differential as well as integrated observables) [11, 12, 13]. Experimental data for most of these observables exist as a function of rapidity, centrality as well as the p_T of the produced particle or particles. Computations of such jet

modifications have acquired a certain sophistication as regards the incorporation of the partonic processes involved. However, the role of the medium has so far been relegated to a furnishing of an overall density and its variation with time. Even in this regard, most jet quenching calculations assume merely a one-dimensional Bjorken expansion.

The availability of a three-dimensional hydrodynamic evolution code allows for a much more detailed study of jet interactions in a longitudinally and transversely expanding medium. The variation of the gluon density in such a medium is quite different from that in a simple Bjorken expansion. This allows for a step-by-step approach to the study of jet-medium interactions.

We recently made use of our 3-D hydrodynamics results to perform fully dynamical calculations of jet quenching using three different theories of radiative parton energy loss. In [14] we used the quenching weights of Armesto et al. obtained in the BDMPS/ASW approach; in [15] we used the higher-twist formalism of Guo-Majumder-Wang, and in [16] we used the Arnold-Moore-Yaffe approach. One of the significant results of [14] was an estimate of the theoretical error-bar of jet energy-loss calculations induced by the choice of the medium parametrization, which was found to be as large as 50%.

Over the current reporting period we have been in the process of preparing a detailed comparison of the three approaches. We found that the parameters of all three calculations [14, 15, 16] can be adjusted to provide a good description of inclusive data on R_{AA} vs. transverse momentum. However, they differ somewhat in their predictions for the centrality- and azimuthal angular dependence of R_{AA} vs. p_T . The angular variation of R_{AA} with respect to the reaction plane allows for a controlled variation of the in-medium path-length of the jet and thus provides sensitivity to the initial gluon distribution and the temporal evolution of the medium, which will allow for the verification or falsification of these approaches with a rigorous comparison to high-precision data. Our investigation was also able to confirm that the value of the transport coefficient \hat{q} needed in the BDMPS/ASW approach to describe the data is significantly higher than the \hat{q} value used in HT and that which may be derived from AMY, excluding differing initial conditions and medium evolution assumptions as cause for this difference. A first preliminary report on the comparison was presented at the Quark Matter 2008 conference and submitted for publication in the proceedings volume of the conference [P1]. We expect the manuscript containing the detailed comparison to be submitted in June/July 2008.

3.2 Hadronic final state interactions in a hybrid approach

The reach of RFD can be extended and the problem of having to terminate the calculation at a fixed freeze-out temperature and renormalizing the spectra can be overcome by combining the RFD calculation with a microscopic hadronic cascade model – this kind of hybrid approach (dubbed *hydro plus micro*) was pioneered by A. Dumitru and myself in [17] and has now been adopted by other groups [18, 19, 20]. Its key advantages are that the freeze-out occurs naturally as a result of the microscopic evolution and that flavor degrees of freedom are treated explicitly through the hadronic cross sections of the microscopic transport. Due to the Boltzmann equation being the basis of the microscopic calculation in the hadronic phase, viscous corrections for the hadronic phase are by default included in the approach – the full treatment of viscosity in the deconfined

phase in a 3+1D hydrodynamic calculation remains a challenge for the future.

Hybrid macro+micro transport calculations have proven themselves to be the most successful approach for describing the soft physics at RHIC [21, 22]. As part of the ongoing development of these approaches my collaborators at the University of Frankfurt and I have completed work on a new revision of the Ultra-Relativistic-Quantum-Molecular-Dynamics model [P2], which serves as the hadronic stage of the 3D hybrid hydro+micro model.

3.3 Transport Coefficients

The determination of transport coefficients, such as shear viscosity, heat capacity and diffusion coefficients is among the major challenges for the near- and medium-term future of the RHIC program. Renewed interest in first principles calculations of transport coefficients was sparked by an estimate of the shear viscosity in finite-temperature $N=4$ supersymmetric Yang-Mills theory in the large N , strong-coupling regime based on the absorption cross section of low-energy gravitons by a near-extremal black three-brane using the anti-de Sitter/conformal field theory correspondence [23]. This estimate postulates a surprisingly small lower bound of $(\eta/s)_{\min} = 1/4\pi$, often referred to as the KSS bound [24], well in tune with the success of ideal hydrodynamic calculations at RHIC.

Utilizing lattice calculations, a first attempt on determining the shear viscosity has been made in [25], however with large error-bars. Charge diffusion and electric conductivity has been studied in [26] – these calculations benefit from the correlator on the lattice being less noisy than for the viscosity, so progress in this area should be possible on shorter time-scales. Overall, the study of heavy-quark diffusion should be easiest on the lattice, whereas no work so far has been done on the extraction of the heat capacity, which might be the most difficult to obtain.

Transport coefficients, such as viscosities and heat capacities can in principle be calculated directly from the microscopic interactions among the degrees of freedom of the system, if the system is in an equilibrium state. Unfortunately, in reality such ab-initio calculations are only possible for idealized systems (e.g. a pion gas at fixed temperature) and not for the medium created in ultra-relativistic heavy-ion collisions.

With the advent of sophisticated microscopic transport models, however, it has become feasible to extract transport coefficients directly from these models, which provide a fairly realistic description of the partonic or hadronic medium produced in the time-evolution of a heavy-ion reaction. The basis for this kind of calculation has been laid in [27], which for the first time explored the infinite time and infinite size equilibrium limit of a full-fledged microscopic transport model. Based on the techniques outlined there, first attempts have been made in [28, 29] to extract the shear viscosity from a hadronic transport model in the infinite size and time equilibrium limit. In both cases the extraction of the shear viscosity is performed utilizing linear response theory and the Kubo formalism [30], which is easily applicable to microscopic transport calculations. Unfortunately, the results of the two aforementioned calculations disagree by a factor of two to three – a matter which we intend to resolve in our analysis. This work is part of the on-going Ph.D. thesis project of my graduate student Nasser Demir.

Using the techniques described above, we have calculated η/s as a function of temperature for zero

chemical potential(s). Our calculations are in good agreement with the result for chiral pions – they indicate that the minimum viscosity in a hadron gas indeed should occur in the vicinity of the deconfinement transition temperature [31]. The minimum value found for η/s for the zero chemical potential case is ≈ 0.6 , significantly higher than the KSS bound of $\eta/s \approx 0.08$. If the minimal value of η/s for QCD matter is indeed found at T_C [31], or result of $\eta/s \approx 0.6$ would pose a serious problem to viscous hydrodynamics calculations, since a value close to the KSS bound is needed in these calculations to describe the elliptic flow data at RHIC [32, 33, 34, 35].

However, calculating η/s for zero chemical potential(s), as has so far been common practice, may be an unsatisfactory approximation: a statistical model analysis of particle yields and ratios at RHIC indicate a chemical freeze-out temperature in the vicinity of $T_{chem} \approx 160$ MeV [36, 37], whereas hydrodynamic calculations show that a kinetic freeze-out temperature of $T_{kin} \approx 130$ MeV is required to describe the momentum distributions of final state hadrons [38, 39, 40, 22]. The separation of temperatures (and thus time-scales) for chemical and kinetic freeze-out in the hadronic phase of the reaction imply non-zero particle species dependent fugacities/chemical potentials in the later reaction stages [38, 39]. One should note, however, that microscopic calculations [17, 22] of the hadronic evolution do not require explicit introduction of such chemical potentials, since the respective phenomena are the result of dynamically changing collision rates for inelastic vs. elastic hadronic rescattering processes. Within the context of our microscopic hadron gas calculations, a baryon chemical potential can be induced by initializing the system with an initial baryon density and a pion chemical potential can likewise be induced by initializing the system with a pion density higher than the $\mu_\pi = 0$ value for the corresponding temperature. In our calculations, which we are currently preparing for publication, we show that the inclusion of a pion chemical potential, will keep the value of η/s sufficiently small to ensure the successful application of (viscous) hydrodynamics to collisions at RHIC. We expect to submit our results for publication in June/July 2008.

In addition to the work on the hadronic viscosity described above, we have started applying our techniques to the extraction of the shear viscosity from a Parton Cascade Model calculation. This calculation will allow for a realistic estimate of the viscosity of a deconfined system driven by pQCD interactions (note that such a system may not necessarily be realized at RHIC, but could possibly be created at the LHC).

4 Publications

- P1 *Systematic Comparison of Jet Energy-Loss Schemes in a 3D hydrodynamic medium*
S.A. Bass, C. Gale, A. Majumder, C. Nonaka, G.-Y. Qin, T. Renk and J. Ruppert
submitted to Journal of Physics **G**, e-Print: arXiv:0805.3271 [nucl-th].
- P2 *UrQMD v2.3: Changes and Comparisons*
H. Petersen, M. Bleicher, S.A. Bass and H. Stöcker
e-Print: arXiv:0805.0567 [hep-ph]

5 Presentations

5.1 Presentations by S.A. Bass

- 09/07/07 *The Quest for the Quark-Gluon-Plasma*
Physics Department Colloquium at the University of North Carolina - Wilmington, Wilmington, NC, USA.
- 10/13/07 *Probing the QGP Structure at RHIC with Jet-Medium Correlations*
Invited talk at the APS Division of Nuclear Physics fall meeting, Newport News, VA, USA.
- 02/05/08 *Comparison of Jet Energy-Loss Schemes in a 3D Hydrodynamic Medium*
Quark Matter 2008: 20th International Conference on Ultra Relativistic Nucleus Nucleus Collisions, February 4–10, 2008, Jaipur, India.

5.2 Presentations by A. Majumder

- 02/13/08 *Jet Modification: The Perturbative Probe of Nonperturbative QCD Matter*
Theory Center Seminar at Jefferson Lab, Newport News, VA, USA.
- 02/14/08 *Studying QCD matter in the laboratory: from atomic nuclei to Quark Gluon Plasma*
Physics Department Colloquium at the College of William & Mary, Williamsburg, VA, USA.
- 05/06/08 *Jet quenching - status and open questions*
Workshop on Theory-Experiment Collaboration for Hot QCD Matter (TECHQM), May 6-7 2008, Brookhaven National Laboratory, Upton, NY, USA.

5.3 Presentations by N. Demir

- 10/11/07 *Transport Coefficients of Hadronic Matter*
APS Division of Nuclear Physics fall meeting, Newport News, VA, USA.
- 04/22/08 *Transport coefficients in the hadronic phase from transport models*
RBRC Workshop on Hydrodynamics in Heavy Ion Collisions and QCD Equation of State, Brookhaven National Laboratory, Upton, NY, USA.

6 Community Service by S.A. Bass

- Chair, NSF Nuclear Theory Panel 2008

Name of Student	Entered Graduate School	Joined Research Group	Mentor	Graduat. Expected
Nasser Demir	8/2004	5/2005	S.A. Bass	PhD 2010

Table 2: Graduate students supervised by this grant.

7 Graduate Students

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