Continuation Progress Report

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Nuclear Physics at High Energy Density

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Annual Report

1 Research Accomplishments

1.1 Parton Recombination Model

The recombination model has been developed for hadron production at intermediate transverse momenta of a few GeV/c. In [P6] we have investigated the effects of a more realistic treatment of hadron structure, i.e. the inclusion of higher Fock states in the hadron wave function, on the predictions of the recombination model. Our analysis shows that when recombination occurs by emission from a thermal medium, the yield of relativistic hadrons is independent of the detailed form of their internal wave functions. This remarkable result demonstrates that for a thermal ensemble the recombination mechanism is much less model dependent than commonly believed. Even with the admixture of higher Fock states, the elliptic flow of the emitted hadrons remains an almost linear function of the number of valence quarks in the hadron. Only small deviations from the constituent quark number scaling law of the elliptic flow are found. This means that the interpretation of elliptic flow data from RHIC proving the existence of free quarks in the bulk matter is still valid. The predicted small deviations from the valence quark scaling law have been observed in the RHIC Run-4 data, and thus may become by themselves supporting evidence for the validity of the model.

The question remains whether the recombination mechanism can be extended into the lower P_T domain. This requires that the issues of energy and entropy conservation are properly addressed. In [P10] we have conducted an analysis of the total entropy created in heavy-ion reactions at RHIC and contrasted it with results from lattice gauge theory on the entropy density of a system of quarks and gluons in the vicinity of the critical temperature T_c. Our results suggest that the entropy content of the hadronic phase at chemical freezeout is considerably larger than often assumed (mostly due to the large masses of hadronic resonances abundantly present in the hadron gas near T_c. Meanwhile, the entropy content of the deconfined plasma phase is significantly suppressed near T_c, possibly due to local correlations among the quarks and gluons due to their strong interactions. These two conclusions make the recombination picture of hadronization more compatible with the entropy constraint posed by the second law of thermodynamics.

In the same paper [P10] we have applied these findings to the analysis of net charge fluctuations. The most widely used measure for the entropy normalized net charge fluctuations is the D measure $[D = 4\langle(\Delta Q)^2\rangle/N_{\rm ch}]$ where $\langle(\Delta Q)^2\rangle$ denotes the event-by-event net charge fluctuation within a given rapidity window Δy, and $N_{\rm ch}$ is the total number of charged particles emitted in this window. For a free plasma of quarks and gluons $D \approx 1$, while for a free pion gas $D \approx 4$. Current experimental results for D yield a value generally somewhat smaller than 4, but much larger than the value predicted for a weakly interacting quark-gluon plasma. Applying the formalism of parton recombination to the charged particle fluctuation observables we find, however, that within the present systematic uncertainties parton recombination is compatible with the measured charged particle fluctuations. This finding is of significant importance, since the incompatibility of the charged particle fluctuation measurements with the deconfinement hypothesis was perceived as a possibly serious problem to the emerging picture of quark-gluon plasma formation at in Au=Au collisions at RHIC.

1.2 Parton Cascade Model

The Parton Cascade Model (PCM) was developed as a tool to describe the reaction dynamics leading to the formation of a thermalized quark-gluon plasma in relativistic heavy ion collisions. The basic assumption underlying the PCM is that the state of the dense partonic system can be characterized by a set of one-body distribution functions $F_i(x,p)$, where i denotes the flavor index and x, p are space and momentum coordinates. The time-evolution of the parton distribution is described by a relativistic Boltzmann equation, whose collision term includes the leading-order scattering processes involving quarks and gluons (as well as photons, if desired).

In [P14] we have studied the role played by the Landau-Pomeranchuk-Midgal (LPM) effect in relativistic collisions of hadrons and heavy nuclei. We have found that the LPM effect strongly affects the gluon multiplication due to radiation and considerably alters the space-time evolution of the dynamics of the collision. The LPM effect ensures a multiplicity distribution of hadrons in agreement with the experimental proton-proton data. In addition, we have studied the production of single photons in relativistic heavy ion collisions and have found that the inclusion of the LPM suppression leads to a reduction in the single photon yield at small and intermediate transverse momenta. The parton cascade calculation of the single photon yield including the LPM effect is shown to be in good agreement with the recent PHENIX data.

1.3 Electromagnetic Probes

In [P12] we studied self-consistently the finite temperature broadening of the ρ-meson and its implications for dilepton emission in heavy ion-collisions. For this purpose finite width effects at finite temperature due to the ρ-π interaction were investigated in a self-consistent Φ-functional approach. The temperature dependence of the ρ-meson and pion spectral functions could thus be obtained in the model. The resulting in-medium spectral functions show considerable broadening in comparison with a perturbative calculation on the one- loop level. Using these results, a comparison to dilepton emission data in Pb+Au collisions by the CERES NA49 collaboration were made with the help of a realistic evolution model. We demonstrated that non-perturbative finite width effects are sizeable even in a pion gas and would, in the absence of any other in-medium effects already be sufficient to explain the data. [Note: This work was completed out during our previous grant period, but forms part of the current proposal.]

Recent NA60 high precision dimuon measurements in In+In collisions make much more detailed tests of proposed theoretical models of the in-medium changes of the vector-mesons possible. At *Quark Matter* 2005 the data were compared with theoretical calculations by Rapp, which referred to the Rapp-Wambach model of in-medium modifications as the "naive" mass scaling model. The claim that the observed deviation from the data implied an invalidation of the Brown-Rho dropping mass scenario was recently rejected. The failure of this "naive" mass scaling model was shown to be mainly due the assumption that a strong drop of the ρ-meson mass near T_c would be compatible with the absence of any in-medium broadening effects of the ρ-meson.

Motivated by this dicussion we explored in our study [P22] how the mass and width of the ρ-meson in a nuclear medium is constrained by Brown-Rho scaling and QCD sum rules. We based our study on the observation that the QCD sum rule approach leads to correlations of the width and mass of the ρ-meson in vacuum and in the medium. We explored the range of values of the in-medium width of the ρ-meson at rest which is compatible with the QCD sum rules in a nuclear medium assuming vector meson dominance and a Brown-Rho scaling low of the ρ-mass with the chiral condensate. The lower and upper bounds for the in-medium width are found to be strongly increasing with the decreasing mass of the ρ-meson. We also studied the bounds for the in-medium width in models not satisfying the Brown-Rho scaling law. We showed that the in-medium width depends on how rapidly the mass decreases in comparison to the change of the quark condensate. The bound for the in-medium width increase with density only if the relative change of the quark condensate is stronger than the relative decrease in mass. Our study showed that tests of the Brown-Rho scaling law without taking proper account of the changed in-medium width of the ρ-meson violates the QCD sum rules and hence is unphysical.

1.4 Jet Interactions in the Medium

The energy loss of hard partons propagating through the medium created in relativistic heavy-ion collisions is one of the major topics in the RHIC physics program. In this context, we investigated the space-time pattern of energy loss and the way this energy reappears in the medium. Previous research primarily focused on the energy loss mechanism and treated the medium in a very schematic way (static medium with averaged gluon density). In [P18] we calculated the energy loss in a dynamic expansion model of the medium, taking into account the effects of collective flow. It turns out that the quenching power of the medium is greatly enhanced by flow effects as compared to what one would expect in naive estimates: While previous studies found discrepancies of factors $5-10$ compared to expectations based on pQCD, changing to a dynamical evolution can lessen this discrepancy to a factor of about 2.

The energy and momentum lost by a hard parton also has to be redistributed after the decoherence of the radiated quanta in the medium evolution. Apart from simply heating the medium (and inducing some flow due to momentum conservation), there is the possibility that collective modes are excited leading to the emergence of Mach cones or Cherenkov radiation. Recent two-particle correlation measurements by STAR and PHENIX at RHIC indicate that such phenomena may play an important role in understanding the jet-medium interactions.

In [P19] we contributed to this discussion by calculating the wake induced in a hot, dense QCD medium by a fast color charge in the framework of linear response theory. We discussed two different scenarios: (I) a weakly coupled quark gluon plasma (pQGP) described by hard-thermal loop (HTL) perturbation theory and (II) a QGP which had the properties of a quantum liquid. The most important difference in scenario (II) compared to scenario (I) is that the longitudinal plasmon is assumed to exhibit a dispersion relation extending into the space-like part of the ω-k plane. We showed that if the HTL approximation is applicable (scenario I) the parton is always accompanied by a co-moving screening cloud whereas in the scenario (II) the parton can travel sub- or supersonically with respect to the plasmon excitation. If it is traveling subsonically the situation is qualitatively analogous to scenario I, the parton is accompanied by a co-moving cloud, whereas if the parton is traveling supersonically a charge density is induced in the medium which exhibits a Mach cone structure. This phenomenon could be called colored sound in analogy to the existence of color-singlet density perturbations in a medium which are commonly called sound waves. Since phenomenology suggests that the coupling of energy loss to sound modes is strong, the dynamics of strong color forces would be a promising candidate for a microscopic excitation mechanism in the near zone around the hard parton.

In [P16] we investigated the phenomenological implications of a (colorless) sound mode in a dynamical evolution model. The energy and momentum lost by a hard parton propagating through hot and dense matter has to be redistributed in the nuclear medium. Apart from heating the medium, there is the possibility that collective modes are excited. We outlined a formalism that can be used to track the propagation of such a mode through the evolving medium if its dispersion relation is known. Under the assumption that a sound wave is created, we track the jet energy loss as a function of space and time and follow the resulting Mach cone throughout the fireball evolution. We compare with the angular correlation pattern of hard hadrons as obtained by PHENIX and find good agreement with the data provided that a large fraction of jet energy (about 90%) is deposited into a propagating mode and that the hot matter can be characterized by an EOS with a soft point (not necessarily a mixed phase). The result that the energy transfer mechanism to the mode must be very efficient. In order to account for the observed two-particle correlations puts strong constraints on microscopic models of this mechanism which will have to be developed in future research.

1.5 "Holistic" Collision Model

We started our collaboration with the Minnesota group (J. I. Kapusta, R. J. Fries, C. Nonaka, et al.) with the goal of developing a complete model of relativistic heavy ion collisions, beginning with the initial phase dominated by coherent fields, through the thermal phase into the freeze-out phase. Since we already have working parton cascade, fluid dynamics, and hadron cascade codes, we initially focused on the early phase, which is expected to be dominated by the dynamics of strong color fields. We derived a Taylor series expansion of the solution of the nonlinear Yang-Mills equation for two colliding sheets of color charge ("color glass condensates") in the proper time parameter τ. We are now in the process of calculating energy-momentum tensor for this solution and of studying its implied collective flow properties. We are also developing a dynamical model for the field generating color charges.

1.6 Decoherence and Entropy Creation

Two years ago, we had proposed that the decoherence of the initial wavefunctions of the colliding nuclei could be the source of a large fraction of the entropy generated in a heavy ion collisions. The argument was that the mere decoherence of a coherent quantum state contributes about one third of the entropy of a thermal ensemble with the same total energy. The main question left open was whether the decoherence really occurs early in the collision process and on which time scale. We have now been able to answer this question by a calculation of the decoherence time due to gluon-gluon scattering [P9]. We define this time as the decay time of the ratio $\mathrm{Tr}D^2/(\mathrm{Tr}D)^2$ of traces of the density matrix D. We find that this time is smaller or equal to $1/Q_s$, where the saturation scale Q_s is defined within the color glass condensate model of parton saturation. Our result supports the notion that the extremely rapid entropy production implied for the early stage of heavy ion collisions at collider energies is partially caused by the decoherence of the initial-state wave functions.

2 Documentation

2.1 Impact

I believe it is fair to state that our research continues to have considerable impact on the RHIC physics program and nuclear physics in the United States and worldwide. Members of our group were invited to present two plenary and two parallel talks at the Quark Matter 2005 conference. Our work on hadrons production by parton recombination has created a new focus area of research at RHIC, and our two original articles published in 2003 have garnered a combined total of almost 300 citations. The two senior members of the group were selected as co-chairs of working groups for the RHIC-II planning, and one of them is a member of the writing group for the RHIC-II white paper.

The success stories in the careers of the postdocs supported by our research group continue: Chiho Nonaka, who was at Duke during 2002-05 and developed a relaticistic hydrodynamics and hadron cascade code, has received the offer of a tenured assistant faculty position at the University of Nagoya (Japan) and will start there in April 2006 as an assistant professor.

We have substantial international collaborations, especially with Japan, Germany, and India. Our collaboration with Osaka University colleagues is supported by a three-year travel grant from the NSF; the collaboration with colleagues in Regensburg was supported by the Humboldt Foundation. One of us (BM) is a member of the Scientific Advisory Committee of the GSI/FAIR facility in Germany.

2.2 Publications

[P1] M. Asakawa and C. Nonaka, *Critical end point and its consequences,* arXiv:nucl-th/0509091.

[P2] S. A. Bass, *What do we learn from strangeness at RHIC?,* J. Phys. G **31**, S733 (2005).

[P3] S. A. Bass, R. J. Fries and B. Müller, *Correlations in the parton recombination model,* Nucl. Phys. **A** (in print), arXiv:nucl-th/0510084.

[P4] D. Y. Chang, S. A. Bass and D. K. Srivastava, *Perturbative dynamics of strangeness production at RHIC,* J. Phys. G **31**, S1005 (2005).

[P5] R. J. Fries, B. Müller and D. K. Srivastava, *Centrality dependence of direct photons in Au + Au collisions at s(NN)**(1/2) = 200-GeV,* Phys. Rev. C **72**, 041902 (2005) [arXiv:nucl-th/0507018].

[P6] B. Müller, R. J. Fries and S. A. Bass, *Thermal recombination: Beyond the valence quark approximation,* Phys. Lett. B **618**, 77 (2005) [arXiv:nucl-th/0503003].

[P7] B. Müller and J. Ruppert, *A colorful wake for Gerhard Soff,* arXiv:nucl-th/0507043.

[P8] B. Müller, *Quark matter 2005: Theoretical summary,* arXiv:nucl-th/0508062.

[P9] B. Müller and A. Schäfer, *The Decoherence Time in High Energy Heavy Ion Collisions,* arXiv:hep-ph/0512100.

[P10] C. Nonaka, B. Müller, S. A. Bass and M. Asakawa, *Possible resolutions of the D-paradox,* Phys. Rev. C **71**, 051901 (2005) [arXiv:nucl-th/0501028].

[P11] C. Nonaka, B. Müller, S. A. Bass, R. J. Fries and M. Asakawa, *Recombination plus fragmentation model at RHIC: Elliptic flow,* J. Phys. G **31**, S429 (2005).

[P12] J. Ruppert and T. Renk, *Non-perturbative finite T broadening of the rho meson and dilepton emission in heavy ion collisions,* Phys. Rev. C **71**, 064903 (2005) [arXiv:nucl-th/0412047].

[P13] T. Renk, *Photonic measurements of the longitudinal expansion dynamics in heavy-ion collisions,* Phys. Rev. C **71**, 064905 (2005) [arXiv:hep-ph/0503082].

[P14] T. Renk, S. A. Bass and D. K. Srivastava, *Dynamics of the Landau-Pomeranchuk-Migdal effect in Au + Au collisions at 200-AGeV,* Phys. Lett. **B** in print [arXiv:nucl-th/0505059].

[P15] T. Renk and J. Ruppert, *Flow dependence of high p(T) parton energy loss in heavy-ion collisions,* Phys. Rev. C **72**, 044901 (2005) [arXiv:hep-ph/0507075].

[P16] T. Renk and J. Ruppert, *Mach cones in an evolving medium,* Phys. Rev. C (Rapids) in print [arXiv:hep-ph/0509036].

[P17] T. Renk, *Rapidity dependence of HBT correlation radii in non-boost invariant models,* arXiv:hep-ph/0509053.

[P18] T. Renk, *The influence of flow on the jet quenching power in heavy-ion collisions,* arXiv:hep-ph/0510188.

[P19] J. Ruppert and B. Müller, *Waking the colored plasma,* Phys. Lett. B **618**, 123 (2005) [arXiv:hep-ph/0503158].

[P20] J. Ruppert, *Probing color response - wakes in a color plasma,* arXiv:hep-ph/0506328.

[P21] J. Ruppert, *Focus talk on interactions between jets and medium,* arXiv:hep-ph/0509133.

[P22] J. Ruppert, T. Renk and B. Müller, *Mass and width of the rho meson in a nuclear medium from Brown-Rho scaling and QCD sum rules,* arXiv:hep-ph/0509134.

[P23] J. Ruppert, *Jet-medium interactions: Wakes in the QCD medium,* arXiv:hep-ph/0510386.

2.3 Invited Talks

2.3.1 S.A. Bass

02/12/05 *Hadronization at RHIC: Interplay of Recombination and Fragmentation*
Invited plenary talk at the 5th International Conference of the Physics and Astrophysics of the Quark-Gluon-Plasma, Kolkata, India, February 8-12, 2005.

06/02/05 *The Quest for the Quark-Gluon-Plasma: Discoveries at RHIC*
Nuclear Theory Seminar at Osaka University, Osaka, Japan.

06/06/05 *Hadronization at RHIC: Interplay of Recombination and Fragmentation*
Nuclear Theory Seminar at Tokyo University, Tokyo, Japan.

06/07/05 *The Quest for the Quark-Gluon-Plasma: Discoveries at RHIC*
Nuclear Theory Colloquium at RIKEN main campus, Tokyo, Japan.

06/14/05 *Recreating the Big Bang in the Laboratory*
Public Lecture for the Chapel Hill Astronomical Society, East Chapel Hill HS, Chapel Hill, NC, USA.

06/21/05 *Hadronization at RHIC: Interplay of Fragmentation and Recombination*
Correlations & Fluctuations Workshop at the 2005 RHIC & AGS Annual Users' Meeting, Brookhaven National Laboratory, Upton, NY.

06/21/05 *Light from Cascading Partons in Relativistic Heavy-Ion Collisions*
Photon Workshop at the 2005 RHIC & AGS Annual Users' Meeting, Brookhaven National Laboratory, Upton, NY.

07/29/05 *Probing the QGP at RHIC: Lessons and Challenges*
STAR Collaboration Meeting, Warsaw, Poland.

09/22/05 *Probing the QGP at RHIC: Lessons and Challenges*
2nd joint meeting of the APS and JPS Divisions of Nuclear Physics, Maui, HI, USA.

10/07/05 *Parton Recombination: A comprehensive model for bulk hadronization at RHIC?*
Nuclear Theory Seminar at the Ohio State University, Columbus, OH, USA.

11/14/05 *Recreating the Big Bang in the Laboratory*
Colloqium at North Carolina A&T University, Greensboro, NC, USA.

12/02/05 *Parton Recombination: A comprehensive model for bulk hadronization at RHIC?*
Nuclear Theory Seminar at McGill University, Montreal, Canada.

2.3.2 B. Mueller

3/30/05 *Theoretical challenges from RHIC*
Modern Challenges for Lattice Field Theory, KITP Workshop, Santa Barbara, CA.

4/19/05 *Who is afraid of a quark-gluon plasma?*
Physics Colloquium, Andong National University, Andong (Korea).

4/21/05 *Quark-gluon plasma: An overview*
Heavy Ion Meeting, Ewha Women's University, Seoul (Korea).

4/22/05 *What have we learned from RHIC so far?*
Korean Physical Society Meeting, Seoul (Korea).

4/25/05 *A colorful wake for Gerhard Soff*
Gerhard Soff Memorial Symposium, Universitt Frankfurt, Frankfurt (Germany).

5/20/05 *The re-combinatorics of thermal quarks*
The Berkeley School, Lawrence Berkeley National Laboratory, Berkeley, CA.

6/2/05 *A nearly perfect ink*
Physics Division Colloquium, Los Alamos National Laboratory, Los Alamos, NM.

7/29/05 *A nearly perfect ink: Theoretical challenges from RHIC*
Lattice 2005, Dublin (Ireland).

8/9/05 *Theoretical Summary*
Quark Matter 2005, Budapest (Hungary).

8/12/05 *Summary Lecture*
Workshop on Quark-Gluon Plasma Thermalization, Vienna (Austria).

9/18/05 *A nearly perfect ink: The "strongly coupled" quark-gluon plasma at RHIC*
DNP Fall Meeting, Maui, Hawaii.

10/14/05 *Going with the flow: What the data from RHIC have taught us so far*
Physics Colloquium, Yale University, New Haven, CT.

10/17/05 *Going with the flow: What RHIC has taught us so far*
Physics Colloquium, Osaka University, Osaka (Japan).

10/27/05 *Going with the flow: What RHIC has taught us so far*
Invited Seminar, Tokyo Metropolitan University, Tokyo (Japan).

2.3.3 C. Nonaka

01/27/05 *Possible Resolution of D paradox from Recombination Approach*
Nuclear Theory Seminar at the University of Minnesota.

03/22/05 *Hadronization mechanism at RHIC*
KEK workshop for Nuclear Theory, Tsukuba, Japan, March 22, 2005.

03/05 *Hadronization at RHIC: Fragmentation and Recombination*
Invited talk at the 2005 Annual Meeting of Physical Society of Japan, Chiba, Japan, March, 2005.

09/21/05 *Quark Recombination at RHIC*
Mini-symposium on parton recombination, 2nd joint meeting of the APS and JPS Divisions of Nuclear Physics, Maui, HI, USA.

2.3.4 J. Ruppert

04/23/05 *Probing Color Response: Wakes in a Color Plasma*
Invited talk, Workshop on Correlations and Fluctuations in Heavy Ion Collisions, MIT, Cambridge, MA.

08/09/05 *Focus Talk on Jet-Medium Interactions*
Invited talk, Quark Matter 2005, Budapest (Hungary).

12/07/05 *Correlations of the Mass and Width of the ρ- Meson in a Nuclear Medium from QCD Sum Rules*
Invited talk, Stony Brook University, Stony Brook, NY.

12/09/05 *Mach cones in Au - Au collisions at RHIC*
Invited talk, Brookhaven National Laborator, Upton, NY.

2.3.5 T. Renk

02/08/05 *Hard Probes in Heavy Ion Collisions - Photons and Jet Quenching*
McGill University, Montréal (Canada).

05/24/05 *Heavy-Ion Collision Dynamics at RHIC - Bjorken, Landau and the HBT puzzle*
Brookhaven National Laboratory, Upton, NY.

06/06/05 *Dileptons from a Fireball and in-Medium Vector Mesons*
Workshop on Electromagnetic Probes of Hot and Dense Matter, ECT*, Trento (Italy).

06/14/05 *Hunting the Quark-Gluon Plasma - Bulk Matter Dynamics at RHIC*
Helsinki University, Helsinki (Finland).

06/14/05 *Hunting the Quark-Gluon Plasma - Bulk Matter Dynamics at RHIC*
University of Jyväskylä, Jyväskylä (Finland).

08/16/05 *Rapidity dependence of HBT correlation radii in non-boost invariant models*
Workshop on Particle Correlations and Femtoscopy, Kromeriz (Czech Republic).

2.4 TNT Lectures

The Triangle Nuclear Theory Colloquium, which has been funded by the grant is jointly organized and held at Duke University, the University of North Carolina at Chapel Hill (UNC) and the North Carolina State University (NC-State).

02/01/05 Charles Horowitz (Indiana)
Neutron rich matter in astrophysics and in the laboratory

02/22/05 Harald Griesshammer (Munich)
An Effective Tale of A Few Nucleons and Photons

02/25/05 Ping Wang (Adelaide)
Strange nucleon form factors, pi and sigma meson properties in a relativistic quark model

03/01/05 George Fuller (UCSD)
Neutrinos, Entropy, and Gravitation: Nature's Recipe for Nuclei

03/08/05 Walter Goldberger (Yale)
An Effective Field Theory of Gravity for Extended Objects

03/15/05 Hans-Werner Hammer (INT)
Universality in Few-Body Physics: from Light Nuclei to Cold Atoms

03/22/05 Roland Crocker (CFA Harvard)
Neutrons from the Galactic center

03/29/05 Thomas Papenbrock (ORNL)
Nuclear Shell Model Frontiers

04/05/05 Felipe Llanes Estrada (Madrid)
Slow gluons are heavy and rowdy

04/12/05 Werner Vogelsang (BNL)
Exploring the Proton Spin

04/26/05 Richard Brower (Brown)
Back to the Future: AdS/CFT interpretation of the Regge Limit for QCD

05/03/05 Robert Pisarski (BNL)
Deconfinement and Matrix Models

10/03/05 Mei Huang (Tokyo)
The role of phase fluctuations – avoiding magnetic instability in gapless superconductors

10/04/05 Adrian Dumitru (Frankfurt)
QCD plasma instabilitities and rapid isotropization at RHIC

10/11/05 Joe Carlson (LANL)
Strongly-Correlated Fermions

10/25/05 Robert Mawhinney (Columbia)
Physics from Lattice QCD with Domain Wall Fermions

11/08/05 Ralf Rapp (Texas A&M)
Quark-Gluon Plasma - Thermal Radiation and Heavy-Quark Probes

11/22/05 Dimitri Kharzeev (BNL)
From quantum black holes to relativistic heavy ions

12/06/05 Kostas Orginos (William & Mary)
Hadron physics from Lattice QCD with up, down and strange quarks in the vacuum abstract

12/13/05 Tijana Prodanovic (Illinois)
Probing dark matter and pre-Galactic lithium with hadronic gamma rays

2.5 Graduate Students

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

Table 1: Graduate students supported by this grant. Nasser Demir was supported during the summer of 2005; Bryon Neufeld will be supported during the summer of 2006. Funds for the support of Nasser Demir beginning June 2006 are requested in the renewal application for S.A. Bass' OJI grant. A source of support for Bryon Neufeld beyond summer 2006 have presently not yet been identified.

3 Proposed Research

3.1 Fragmentation and Recombination

The conversion of a high momentum parton into a jet of hadrons in QCD occurs through a non-perturbative process called fragmentation which is parametrized from data. The change of the parametrization with the energy scale of the process is predicted by QCD. Experimental evidence suggests that hadrons with transverse momenta between $2-5$ GeV may be formed by the coalescense of constituent quarks. The fragmentation formalism was recently generalized to include the dynamical process of recombination, when fragmentation occurs in the presence of a medium. We will extend this to a self consistent treatment of hadron formation in pp and heavy-ion collisions. The phenomenology will be developed to include not only the description of the single spectrum but also the correlations between produced hadrons. Such a treatment will incorporate all three processes of energy loss, fragmentation into a shower of constituent quarks, followed eventually by the recombination in a single framework.

3.2 Hadron Correlations and Jet-Medium Interactions

Correlations between two hadrons produced in a jet and their modification due to the propagation of the jet through dense matter has emerged as a major direction of research in heavy-ion experiments. The non-perturbative origin of such correlations and their variation with energy scale is understood within the formalism of the dihadron fragmentation functions and their evolution. The generalization of the formalism of jet fragmentation in the hot and dense medium of a heavy-ion collsion has, to date, been carried out rather haphazardly. We are correcting this by means of a detailed computation from first principles. This calculation, which will be completed soon, represents the first complete test of the medium modification formalism in the heavy-ion environment. This will include the modification of both the single and double hadron observables, and their dependence on centrality, collision geometry and momentum of the detected hadrons.

The modification of both the single and double fragmentation functions exists solely at the next-to-leading twist level. Current computations indicate that in many regions of phase space, the modification of the fragmentation functions is comparable in size to the fragmentation functions themselves. This indicates the need for an extension of the formalism to the the next-to-next-to-leading twist level. Such an extension will bring much needed completeness and consistency to the methodology of medium modified fragmentation functions.

A promising new technique in jet correlation studies involves reducing the momentum of one of the detected hadrons, keeping the other fixed. This technique may allow one to probe the soft collective behaviour of the gluonic sector. If there are bound states in this sector, soft gluons radiated from a hard jet may excite resonances in such states. This will lead to the modification of the gluon dispersion relation and may lead to the production of Cherenkov like conical pattens around hard jets. Already, there exists experimental evidence for the presence of such patterns.

In this direction, we intend to incorporate Cherenkov radiation within the medium modified fragmentation formalism outlined above. This is achieved by endowing the radiated gluon with a medium dependent dispersion relation. A first attempt in this direction, which ignored any modification to the polarization of the emitted gluon, concluded that the energy loss is greatly enhanced. This will be extended by a complete derivation of the next-to-leading twist modification from space-like propagating gluons.

A related topic is that of three particle correlations. It has been pointed out that the conical patterns seen in two particle correlations may be due to deflected jets. A possible means to disentangle a genuine conical pattern of gluon Cherenkov radiation around a hard jet from that of a jet deflected by scattering centers in the medium is to look at three-particle correlations, of a leading particle in one direction and two associated particles in the opposite direction. The aim here is the development of a three particle correlation that is measurable by both the STAR and PHENIX experiments and is sensitive to genuine conical pattern of Cherenkov-like radiation. The fully developed, consistent medium modification formalism for two- and three-particle correlations that can turn on and turn off the Cherenkov effect will be allow us to address both the phenomenology of a deflected jet and Cherenkov radiation within a single formalism.

We want to further study the implications of the possible excitation of collective modes of the hot and dense nuclear medium. Two-particle correlation measurements by STAR and PHENIX indicate that energy lost by a hard parton traversing the medium (jet quenching) is redistributed in a non-trivial manner. Instead of directly coupling into the energy-momentum density of the medium, a recent phenomenological analysis has shown that the data are compatible with the assumption that a sonic shock wave is excited. There are, however, a number of important point left to be clarified: First, in order to reproduce the data, the assumption has to be made that this coupling to the sound mode is rather efficient. A more microscopic approach leading to constraints for a source term for a hydrodynamical calculation is needed. Second, both the PHENIX and the STAR collaboration have shown that three-particle correlations must be investigated to confirm a cone structure.

Since PHENIX and STAR presently use different techniques to obtain the three-particle correlations and reach different conclusions about the existence of Mach shocks in the medium, a solid theoretical understanding of three-particle correlations and the expectations with regard to their strength is highly desireable. As a first step in this direction, it is essential to obtain the distortion of the transverse momentum spectra of hadrons as a function of angle in the presence of Mach shocks on an event-by-event basis. This information can then be used for a Monte-Carlo simulation of three-particle correlations. Finally, alternative scenarios to the Mach cone interpretation of two-particle correlations have been suggested (Cherenkov radiation, jet bending, etc.). It clearly is important to compare these mechanisms with the data within the same level of detailed phenomenological study.

3.3 Heavy Quark Production

The production and transport of heavy flavors, i.e. charm or bottom quarks, create important probes of the properties of the hot, dense medium created in relativistic nuclear collisions. Measurements of hadrons containing heavy quarks will be among the most exciting results of RHIC Run-4 and Run-5 and will add important pieces of information to the emergent picture. Heavy quark-antiquark pairs are initially produced in hard parton interactions, which are calculable in pQCD. The PCM is therefore well suited for the study heavy flavor production. While much theoretical progress has been made on mechanisms for charmonium absorption, there have been few detailed comprehensive studies from heavy-quark production to J/Ψ formation and dissociation beyond simplified calculations utilizing Glauber model geometries.

We are planning to study the production and transport of heavy quarks in the early phase of the heavy ion reaction at RHIC. Currently the PCM only includes leading order pQCD matrix elements for the interaction of massless partons. For our investigation we shall include the proper matrix elements for the production and scattering of massive partons. Once these matrix elements have been implemented, our investigation will focus on the following questions: (1) What are the time scales relevant for heavy-flavor production? (2) How does the production and rescattering of heavy quarks depend on the formation time in light parton interactions? (3) How often do heavy quarks rescatter – can they thermalize?

3.4 Electromagnetic Probes

Recent NA60 high precision dimuon measurements are a test of theoretical models of changes of the in-medium current-current correlator. We intend to study these implications in a dynamical evolution model of 158 AGeV In-In collisions with different approaches addressing the question of the in-medium changes of the correlator. Especially interesting will be constraints on scenarios predicting a shift of the ρ-mass, such as the Brown-Rho scaling scenario. First studies using a naive mass scaling neglected changes of the in-medium width which have to be included to be consistent with the QCD sum rules and exaggerated the drop of the absolute value of the quark condensate with temperature. A more careful study to determine which dropping mass scenarios are excluded by the data is needed.

An additional question which one wants to address is to what extent the leading order density and temperature changes of the correlator are sufficient to account for in-medium effects. Of special interest are in this respect also constraints on in-medium modifications of the ϕ-meson The cocktail ϕ contribution has been already subtracted in the NA60 data, therefore, possible changes of the ϕ have to be identified taking this subtraction into account. The question also arises if the NA60 data can be used to discriminate between temperature and baryon density induced in-medium modifications. In our earlier work it was shown that non-perturbative finite-T broadening effects on the ρ-meson can lead to substantially higher in-medium width than predicted by perturbative calculations. The question whether these effects can be of importance to explain the NA60 data will be addressed.

3.5 Probing Quark-Gluon Plasma Structure

The success of the fluid dynamical approach has led to the claim that the plasma formed at RHIC is a strongly coupled liquid. Shuryak and Zahed recently argued that the plasma is composed of a myriad of colored bound states. It was demonstrated, however, that such a picture cannot be entirely true on the basis of the ratios of flavour susceptibilities measured off the lattice. The coefficient in question, the ratio C_{BS} of the correlation between baryon number and strangeness to the variance in the strangeness, has been found to be almost 50% higher in lattice QCD simulations than the prediction of the bound state model. This demonstrated that the model as originally proposed cannot contain the correct physics.

Observables of this nature represents powerful tools as they can be measured both on the lattice, in models, and also in RHIC experiments. They thus allow for clean comparisons between all such approaches. We make use of the fact that all the ratios of the flavor off-diagonal susceptibilities (C_{BS}, C_{QS} etc.) in QCD are related to each other by the Gell-Mann–Okubo formula. Another observation guiding our study is that the derivatives of the off-diagonal susceptibilities with respect to the baryon chemical potential place severe constraints on the existence of bound states of quarks above T_c. Studies such as those outlined above will, hopefully, help to reveal a simple picture of the matter above T_c. Our preliminary results indicate that the quark sector of such matter behaves like a medium of quasiparticles with the quantum numbers of quarks, not diquarks or quark-antiquark bound states. Efforts are also underway to decipher the nature of the gluonic sector.

Regardless of the nature of the gluon sector, one may now proceed with the contruction of models which may represent the dynamics of the matter formed. In this direction, we will explore such possibilities in the framework of a Nambu–Jona-Lasinio model, which allows for quasi-particle quark degrees of freedom. The gluon sector will be modeled by an effective potential based on the Polyakov loop. Such a model has been shown to contain a chiral condensate below T_c and thus should allow for an unbroken plot of the off-diagonal susceptibilities on both sides of the phase transition.

3.6 "Holistic" Model of Heavy Ion Collisions

In our collaboration with the Minnesota group we will complete the development of our model of the pre-equilibrium phase, which is based on a combination of energy deposition via coherent color fields and via semihard perturbative scattering. We will study the predictions of our model for the initial conditions of the hydrodynamic evolution of the equilibrated matter. For example, our model predicts that a non-negligible amount of transverse (and elliptical) flow is generated by coherent fields before equilibrium is reached. We will carefully explore the dependence of the predictions on our model parameters.

In the next step, we will use these results as starting point for the three-dimensional relativistic hydrodynamical calculation of the bulk of the produced matter. We will also study the interaction of the (semi-)hard parton component with the equilibrated matter and thus explore the space-time dynamics of jet quenching and dynamical correlations between the hard and the soft component generated by final-state interactions.

3.7 Decoherence and Entropy Generation

We intend to improve our estimate of the decoherence time of the initial gluon distribution of colliding nucei by evaluating the full nonlinear trace $\mathrm{Tr}(\mathcal{D}\ln\mathcal{D})$ of the density matrix $\mathcal{D}$. This calculation will be more difficult than the one we recently completed, and we expect that it will confirm our estimate that the initial-state gluon distribution decoheres on a time scale of $1/Q_s$. In addition, we intend to evaluate various expectation values of the time dependent gluon density matrix, in order to obtain estimates of the energy density and pressure of the gluon distribution during the decoherence phase. One expectation value of special interest is the light-cone correlator of the gluonic energy-momentum tensor, which enters into the calculation of parton energy loss in the medium. This research will be carried out in collaboration with colleagues in Regensburg (Germany).

3.8 Personnel

The following personnel has been or will be supported by this grant:

S.A. Bass	Summer (1 month)
N. Demir	Graduate student: 6/1/05 – 8/31/05
A. Majumder	Postdoc (50%): 10/1/06 – 8/31/07 (?)
B. Mueller	Summer (2 months)
B. Neufeld	Graduate student: 6/1/06 – 8/31/06
C. Nonaka	Postdoc (50%): 3/15/05 – 8/31/05
T. Renk	Postdoc (partial): 3/15/05 – 9/30/05
J. Ruppert	Postdoc (partial): 3/14/05 – 12/31/06

3.9 Work Matrix

The following table describes how the research projects of our group are divided between this grant (GG) and the OJI grant supporting research by S A. Bass, his student and 50% of our research associate.

task	Müller	Bass	Ruppert	Majumder	Demir	Neufeld
Parton Recombination:						
two-particle correlations	GG	GG		GG		
Collision Dynamics:						
Parton Cascade Model	GG	GG				
3D-Hydro plus micro		OJI				
decoherence & entropy generation	GG					
holistic model heavy-ion collisions	GG	GG				
QGP properties:						
jet-medium interactions: Mach cones	GG		GG	GG		
jet-medium interactions: soft/hard		OJI		OJI		
in-medium hadron properties			GG			GG
quark-gluon plasma structure				GG		
heavy quark diffusion	GG	OJI				
evolution of transport coefficients		OJI			OJI	