DOE/ER/40764-3

THEORY OF ULTRA DENSE MATTER AND THE DYNAMICS OF HIGH ENERGY INTERACTIONS INVOLVING NUCLEI

Progress Report
for Period December 15, 1993 - December 14, 1994

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Abstract

This report summarizes the progress made during the second year of the three year DOE agreement DE-FG02-93ER40764 on theoretical nuclear physics research performed at the Columbia University and presents a detailed budget adjustment for the third year period December 15,1994 to December 14, 1995. Sections 1.1 to 1.8 highlight the technical progress made on the following general areas:

1. Multiple scattering and radiative processes in QCD
2. The quark-gluon plasma transition in nuclear matter,
3. QCD transport theory and dissipative mechanism in dense matter
4. Phenomenological models of high energy interactions involving nuclei
5. Signatures of quark-gluon plasma formation in A+A
6. Neurocomputation theory

Section 2 contains a bibliography of published papers and invited conference papers. Section 3 lists the Columbia nuclear theory members for the December 15, 1994 to December 14, 1995 period. Finally, the budget adjustment requesting $319,830 for the third year relative to the original $320,000 is presented in section 6. Copies of the research papers accompany this report.

FUNDING SUPPORT (FY93-FY95) DOE/ER/F-4620.1:

	FY93	FY94	FY95
DOE/Nuclear Physics	$300,000	$300,000	$319,830 (adjusted)

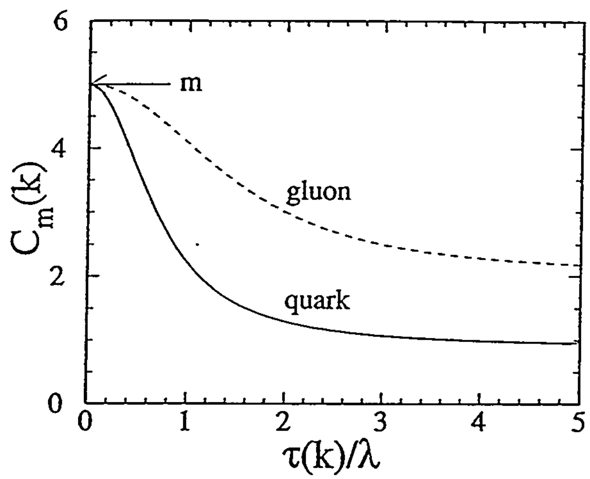
1 Technical Progress

1.1 Non Abelian LPM Effect and Radiative Energy Loss

X.N. Wang, M. Gyulassy, M. Plümer

The work begun in refs. 1,2 last year on the problem of QCD multiple collision theory and the nonabelian generalization of the Landau-Pomeronchuck effect was extended this year to clarify questions of gauge invariance and include radiation from spin 1/2 partons. This work is aimed to provide a theoretical foundation for the development of parton cascade models needed to predicting the evolution of the quark-gluon plasma produced at RHIC and higher energies. In ref. 3, we considered in detail the problem of induced gluon radiation from a spin 1/2 quark suffering two elastic scatterings to provide insight on the applicability of the effective potential model used in Ref. 1. We show why radiation from the target partons is negligible although such amplitudes are necessary to insure gauge invariance. On the other hand, gauge invariance constrains all gluon propagators to be regulated by the same screening mass in the potential model. The QCD radiation interference pattern, $C_m(k)$, modulating the Bethe-Heitler formula as a function of the number of soft collisions, m, is shown to be expressible as a function of an effective formation time that depends on the color representation of the jet parton. This is illustrated in the figure below. We also derived a new formula for the average gluon radiative energy loss dE/dz that interpolates smoothly between the factorization and Bethe-Heitler limits as a function of a dimensionless ratio depending on the incident parton energy E, the screening scale and the mean free path.

Figure caption: The induced gluon radiation formation factor $C_m(k)$, $m = 5$, as a function of $\tau(k)/\lambda = 2\cosh(y)/k_\perp\lambda$ for quarks (solid) and gluons (dashed).

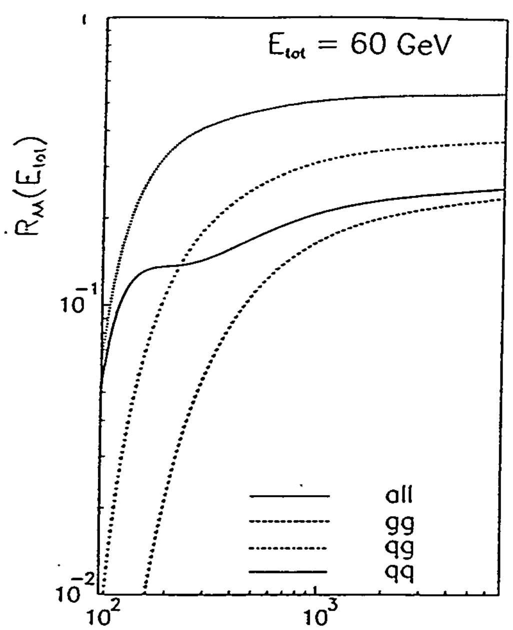


1.2 Jet Quenching Systematics in A+A

M. Plümer, X.N. Wang, M. Gyulassy

As a follow up study of the phenomenological implications of the radiative energy loss calculated in refs. 1-3, we are presently calculating the dijet and monojet quenching rates as a function of the atomic number and center of mass energy range. As proposed in Ref.4 the systematics of jet yields provides information on the stopping power of high energy quarks and gluons, dE/dz, in dense matter. The stopping power in turn is controlled by the color screening scale. Our aim of Ref. 5 is to develop further the suggestion Ref. 4 that a rapid change of that scale near the phase transition point could lead to a systematic energy and A dependence of jet quenching in nuclear collisions that could serve as a signature of QGP formation. We found two interesting new effects that could be measured at RHIC. First as shown in the Figure below due to the form of the nuclear structure functions jets with typical transverse momenta 20-30 GeV are mainly quarks at the low end of RHIC while they are mostly gluons at the high end. Because the predicted energy loss is proportional to the second Casimir, gluons are expected to have a larger energy loss than quarks by a factor 9/4. This combined with the energy dependence of the jet yields leads to an interesting cross over in the RHIC energy range of the jet quenching factor. Observation of this effect would confirm the validity of a perturbative treatment of energy loss mechanisms in the quark gluon plasma. The second effect we found was that the A dependence could reveal if the screening scale varies rapidly near the critical temperature as suggested by lattice data. Furthermore, we showed that monojet rates are also sensitive to variation in μ but at higher energies than RHIC.

Figure caption: The suppression factor of dijets with total transverse energy 60 Gev in central collisions as a function of center of mass energy $2E_{cm}$. the dashed curves give separate suppression factors for qq, qg and gg jets resp.



1.3 QCD Transport Theory and Dissipative Color Currents

A. Selikhov, M. Gyulassy

A major result of our work last year was the discovery of a new transport process in nonabelian plasmas which we call color diffusion in refs (6,7). We found the surprising result that the color relaxation time scale vanishes in the semi-classical limit, where the magnetic screening mass vanishes. This implies that the color conductivity of a QCD plasma vanishes classically and that a dense perturbative parton system remains in an insulator state contrary to all previous expectations. This year we developed a more detailed theoretical treatment of the problem in ref. 8.

Previously, we derived QCD Fokker-Planck equations treating color on a quantum footing. We now derived the analogous Fokker-Planck equations starting from the Heinz transport equations where color is treated as a classical continuous internal variable. We found the surprising result that while color relaxation rates are identical in the two approaches, the momentum relaxation rates differ due to color factors. Our main new result is that the induced non-equilibrium color current including spatial color diffusion can be expressed as $\vec{j}^a = \sigma_c \vec{E}^a - D_c^q \vec{\nabla}\rho_q^a - D_c^g \vec{\nabla}\rho_g^a$ where the color conductivity coefficient including both momentum space relaxation and color diffusion is given by $\sigma_c = \frac{m_E^2}{3}\{\frac{N_f}{N_f+N}\tau_c^q + \frac{N}{N_f+N}\tau_c^g\}$ with $m_E^2 = 2g^2T^2(N_f+N)/\pi^2$ corresponding to the square of the color electric Debye mass for N_f quark flavors and N colors in the Maxwellian limit neglecting quantum statics. The spatial color diffusion coefficients are given by $D_c^i = \frac{1}{3}\tau_c^i$ and the color relaxation times are found to be

$$\begin{aligned} \frac{1}{\tau_c^q} &\approx C_A\alpha_s T\log(m_E/m_M) + (4C_F - C_A)\alpha_s^2 T\log(3T/m_E) \ , \\ \frac{1}{\tau_c^g} &\approx C_A\alpha_s T\log(m_E/m_M) + (4C_A - C_A)\alpha_s^2 T\log(3T/m_E) \ . \end{aligned} \quad (1)$$

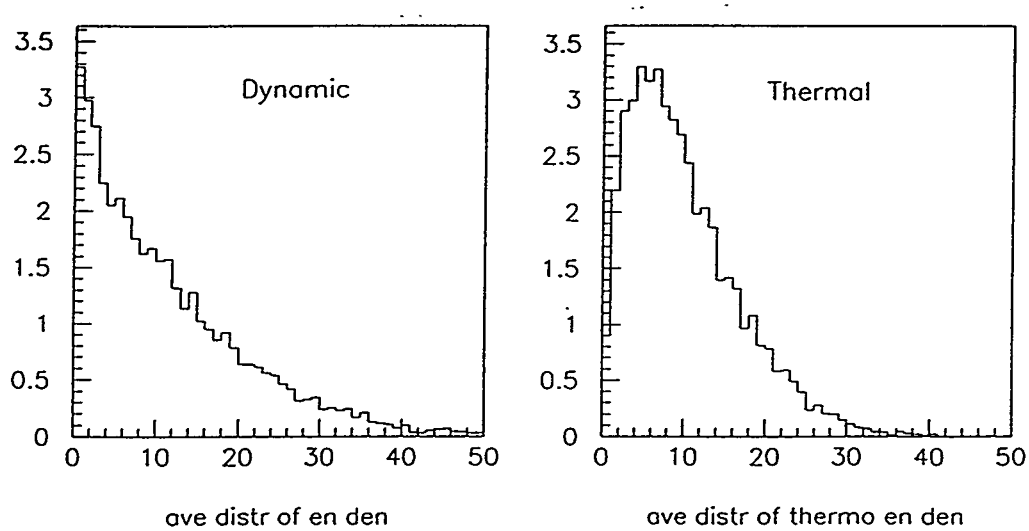
From (1) it is clear that color diffusion dominates perturbatively by a factor $\sim 1/\alpha_s$ over the contribution from momentum relaxation. However, the dependence on the unknown non-perturbative magnetic mass, $m_M \sim O(g^2T)$, in t_c emphasizes the novelty of color dissipation in quark-gluon plasmas.

1.4 Turbulent Initial Mini Jet Conditions

M. Gyulassy, D. Heumann

Based on the HIJING event generator ref.9, the spectrum of energy density fluctuations were calculated for RHIC energies and compared to thermal expectations. As shown in the Figure we discovered that on a transverse scale of 1 fm and times before 1 fm/c the fluctuations due to minijet production dynamics at RHIC energies are far greater and distributed more asymmetrically than thermal fluctuation in corresponding finite volumes. In thermal equilibrium a plasma with mean energy density $\epsilon = KT^4$ has fluctuations in a finite volume V given by $\Delta\epsilon/\epsilon = 2/(KT^3V)^{1/2} \approx 0.5$ for $T = 300$ MeV and $V = 1$ fm^3. The dynamical fluctuations computed are however $\Delta\epsilon/\epsilon \approx 1$. The greatly enhanced fluctuations are due to Glauber multiple collision geometry and result from the fact that the mini jet cross section at RHIC is only 10 mb. We are currently working on the observable consequences of such non-thermal fluctuations. We expect that high pT probes such as open charm, dilepton pairs, and direct photons will be most sensitive to these fluctuations. If these expectations are born out, then the interpretation of RHIC data on such hard observables will require revision since they will then not probe the average thermal properties of the plasma but the instead the dynamical mechanism of minijet production which is a fundamental problem in its own right. Thermal properties can only be studied by long wavelength probes for which dynamical fluctuations are suppressed. Results were presented at 3 international conferences. Publication in preparation.

Figure Caption: The distribution of energy densities, $dN/d\epsilon$, versus ϵ in GevV/fm^3 at time 0.5 fm/c. The transverse area scale is 1 fm^2. Left figure is the dynamical fluctuations computed via HIJING. Right is the expected thermal fluctuations.

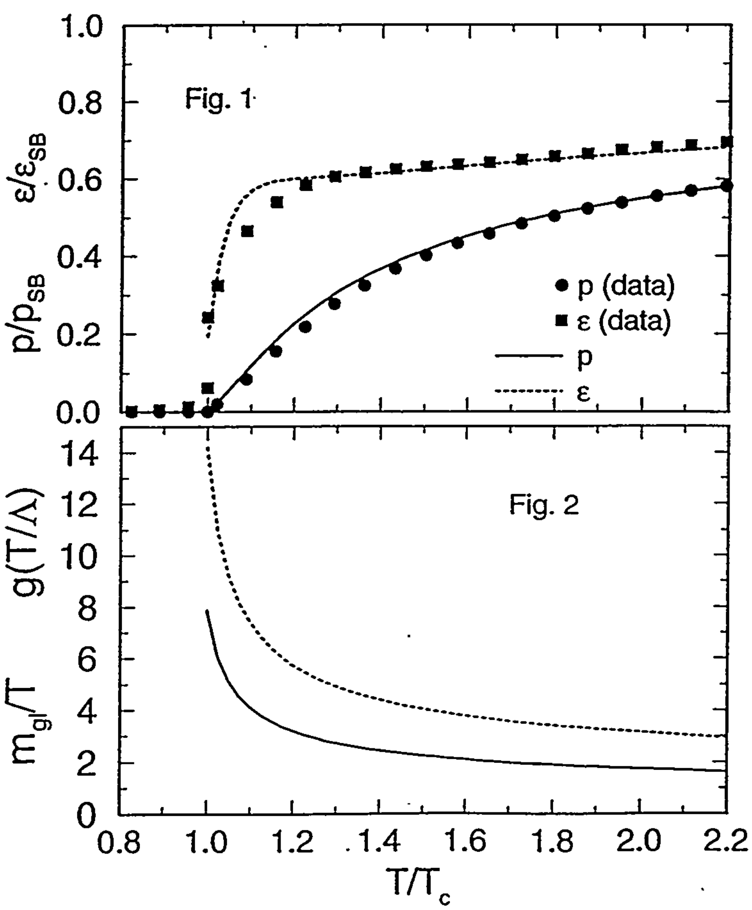


1.5 Thermodynamics of pure SU(3) gauge theory with massive gluons

Dirk H. Rischke* and Miklos Gyulassy
Physics Dept., Columbia University, New York NY 10027, U.S.A.

Thermodynamic functions for the pure SU(3) gauge theory [1] are compared to those of a gas consisting of gluons with mass $m_{gl}(T) = \alpha g(T/\Lambda)T$ [2], where $g(T/\Lambda)$ is the one-loop running coupling constant at scale $M \equiv T/\Lambda$. The QCD scale parameter Λ, as well as the constant of proportionality α, is used as a fit parameter to adjust energy and pressure of the massive gluon model to the lattice data. As shown in Fig. 1, this model is able to describe the behaviour of lattice data (circles and squares) above the deconfinement transition temperature T_c in a reasonable manner. However, the resulting "effective" running coupling constant $g(T/\Lambda)$ and, consequently, the "thermal" gluon mass $m_{gl}(T)$ are rather high (Fig. 2) and indicate the presence of strongly non-perturbative phenomena [3].

[1] J. Engels, J. Fingberg, F. Karsch, D. Miller, M. Weber, Phys. Lett. B 252 (1990) 625.
[2] W. Greiner, D.H. Rischke, Columbia University preprint CU–TP–648 (to appear in Phys. Rep.)
D.H. Rischke, Columbia University preprint CU–TP–649 (to appear in Nucl. Phys. A)
[3] D.H. Rischke, J. Schaffner, M.I. Gorenstein, A. Schäfer, H. Stöcker, W. Greiner, Z. Phys. C 56 (1992) 325



*Partially supported by the Alexander von Humboldt–Stiftung under the Feodor–Lynen program.

1.6 Perturbative versus Lattice QCD Energy Density Correlators at High Temperatures†

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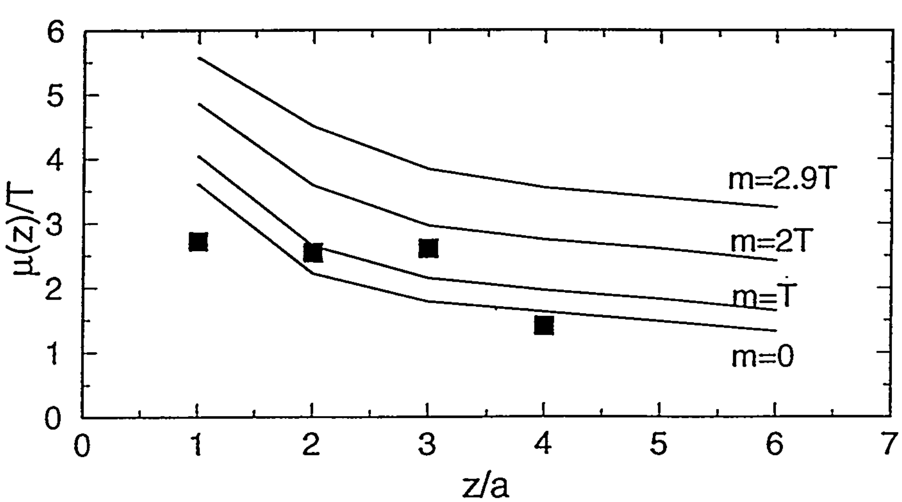
Correlators of magnetic and electric field energy density are investigated for $SU(N_c)$ gauge theory at high temperatures T [1]. At separations $z \leq 2/T$ the correlators are dominated by a power–law behavior even for finite gluon screening masses m. This continuum behavior is well approximated on current $(1/aT \times [L/a]^3 = 4 \times 16^3)$–lattices in the perturbative limit and leads to a considerable overestimate of screening masses deduced from fitting the lattice correlators with the conventional form $\cosh[2\mu(z)(z - L/2)]$, i.e., in general the measured (local) screening mass $\mu(z) \gg m$. The use of extended sources and sinks to enhance the signal improves the situation for screening masses $m \gg T$ but leads to a largely uncontrolled error for masses less than T. This can be seen in the figure where we show $\mu(z)/T$ for various values of the actual screening mass m (lines). While the (minimum) error is of the order of 20% for $m \sim 3T$, the local masses fail completely to reproduce a vanishing actual screening mass $m = 0$. Also shown are magnetic screening masses deduced from recent lattice QCD data on spatial plaquette–plaquette correlators [2] (squares). We are lead to the conclusion that either the actual screening mass in these calculations is by about a factor of 3 smaller or, given the sensitivity of the local masses to the form of the extended source and sink [1], that it cannot be reliably determined at all. However, it is entirely possible that $\mu(z)$ is not even proportional to the gluon screening mass: either discretization effects could invalidate the simple relationship between the plaquette and the energy density, or the energy density correlator is dominated by a bound gluon state instead of independent exchange of screened gluons.

[1] D.H. Rischke, M. Gyulassy, Columbia University preprint CU–TP–639 (submitted to Nucl. Phys. B)
[2] B. Grossmann, S. Gupta, U.M. Heller, F. Karsch, Nucl. Phys. B417 (1994) 289.



†This work was supported by the Director, Office of Energy Research, Division of Nuclear Physics of the Office of High Energy and Nuclear Physics of the U.S. Department of Energy under Contract No. DE-FG-02-93ER-40764.
‡Partially supported by the Alexander von Humboldt–Stiftung under the Feodor–Lynen program.

1.7 Finite signal transmission times and synaptic memory in neural networks

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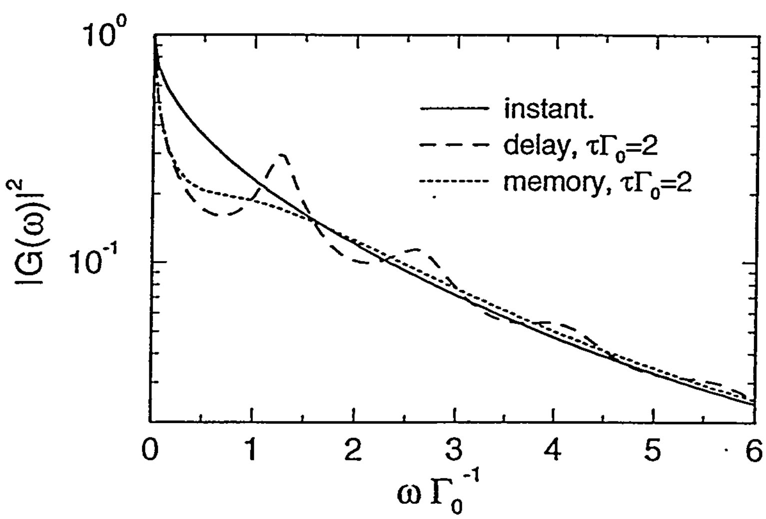
The influence of delayed synaptic signal transmission and memorizing prior synaptic activity on the static and dynamical properties of attractor neural networks [1] is studied [2]. For a system of N neurons, which are characterized by their state $\sigma_i(t)$ at time t and which interact via the (in general asymmetric) synaptic coupling strengths J_{ij}, the generalized synaptic output $w_j(t)$ of neuron j entering the postsynaptic potential of neuron i, $h_i(t) = \sum_{j \neq i} J_{ij}\, w_j(t)$, reads [3]

$$w_j(t) = \int_{-\infty}^{t} \mathrm{d}t'\; f(t-t')\; \sigma_j(t')\;, \tag{1}$$

where f is the so-called memory function. Choosing $f(x) = \delta(x)$, we recover the well-studied case of instantaneous signal transfer [4]. The choice $f(x) = \delta(x - \tau)$ corresponds to delayed signal transmission with delay time τ, for $f(x) = \tau^{-1} e^{-x/\tau}$ the past is exponentially forgotten on the time scale τ. The postsynaptic potential $h_i(t)$ enters the (Langevin) equation of motion for $\sigma_i(t)$ which is solved in the mean-field approximation via a functional integral approach [4]. An exact analytical expression for the (Fourier-transformed) single-neuron response function $G(\omega)$ is obtained in the framework of a spherical model. As shown in the figure, we find a significant reduction of the system's random response and a considerable enhancement of the response to stimuli with frequencies proportional to the inverse delay or memory time scale.

[1] D.J. Amit, "Modelling Brain Function – The World of Attractor Neural Networks" (Cambridge University Press, Cambridge, 1989)
[2] U. Krüger, W. Martienssen, D.H. Rischke, Columbia University preprint CU-TP-644 (submitted to Phys. Rev. E)
[3] H. Sompolinsky, I. Kanter, Phys. Rev. Lett. 57 (1986) 2861
[4] A. Crisanti, H. Sompolinsky: Phys. Rev. A36 (1987) 4922

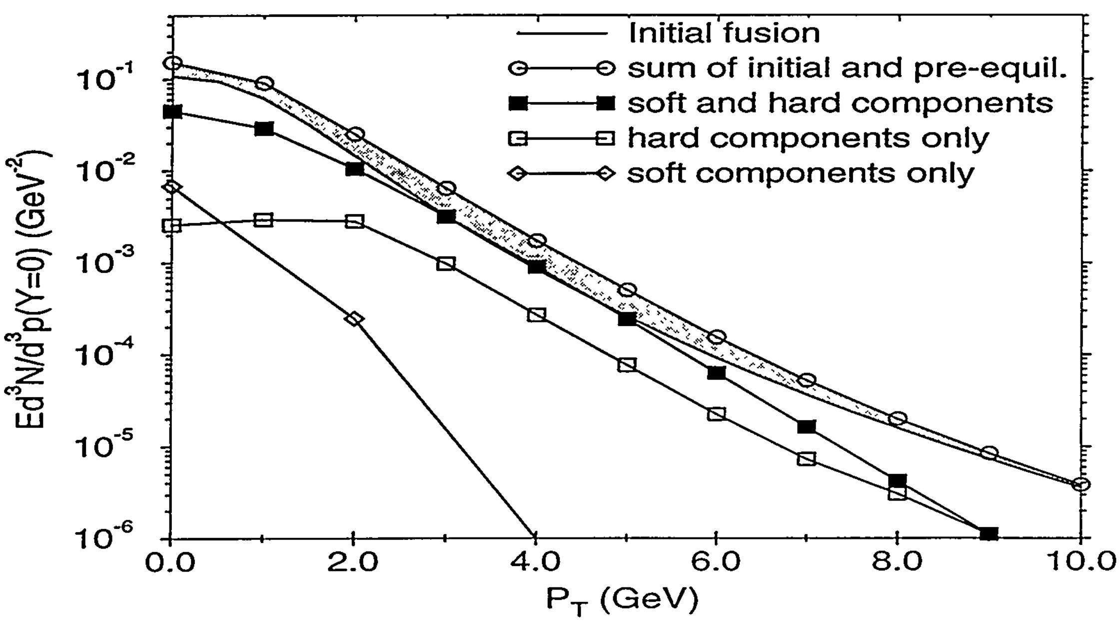


*Partially supported by the Alexander von Humboldt-Stiftung under the Feodor-Lynen program.

1.8 Open Charm as a Probe of Pre-Equilibrium Dynamics in Nuclear Collisions

Ziwei Lin and Miklos Gyulassy

One of our motivation comes from two recent studies [1,2] of open charm which predict widely different rates in nuclear collisions. The copious charm production in [2] is found to be mainly due to an overestimation of the intrinsic charm contribution. The pre-equilibrium contribution to open charm production in nuclear collisions at $\sqrt{s} = 200$ AGeV is calculated and shown to be sensitive to the early time evolution of the initial mini-jet gluon plasma. The role of charm as a probe of the formation zone physics and correlations between momentum and space-time coordinates is emphasized. Three different models for the space-time and momentum correlations are studied and the influence on the charm yield is shown to be significant. For the ideal Bjorken-correlated case, where $\eta = y$, the pre-equilibrium charm production is negligible compared with the yield due to initial gluon fusion. For the opposite extreme fireball case, corresponding to uncorrelated y and η [1], the pre-equilibrium charm production is comparable with the initial charm production. In order to investigate the effect of more realistic correlations that may exist in the initial mini-jet plasma, we introduced a minimal correlation model taking into account the uncertainty principle and finite formation times. The minimal correlation with finite geometrical spread enhances the initial fusion rate by a factor ~ 2 in the moderate $p_\perp \sim 2-6$ GeV range. That is dominated by fusion of "semi-hard" $p_\perp > 2$ GeV mini-jet gluons and secondary "soft" $p_\perp < 2$ GeV gluons from initial and final state radiation. The "intrinsic" charm flavor excitation process is negligible in the mid-rapidity domain[3,4].



[1]B. Müller and X. N. Wang, *Phys. Rev. Lett. 68 (1992) 2437.*
[2]K. Geiger, *Phys. Rev. D 48 (1993) 4129.*
[3]R. Vogt, S. J. Brodsky and P. Hoyer, *Nucl. Phys. B 383 (1992) 643.*
[4]S. J. Brodsky, P. Hoyer, A. H. Mueller and W. K. Tang, *Nucl. Phys. B 369 (1992) 519.*

2 Bibliography

2.1 Refereed Papers

1. Multiple Collisions and Induced Gluon Bremsstrahlung in QCD, M.Gyulassy and X.N. Wang, Nucl. Phys. B420 (1994) 583-614

2. Non-Abelian Bremsstrahlung in a Quark-Gluon Plasma, Alexei V. Selikhov, Phys.Rev.C49 (1994) 1726

3. The LPM Effect in QCD and Radiative Energy Loss in a Quark Gluon Plasma, X.N. Wang, M. Gyulassy, M. Plümer, CU-TP-650 (1994), submitted to PRC

4. M. Gyulassy and M. Plümer, Phys. Lett. B **243**, 432 (1990); Nucl. Phys. A **538**, 37c (1992); X.-N. Wang and M. Gyulassy, Phys. Rev. Lett. **68**, 1480 (1992).

5. Systematics of Jet Quenching in $A + A$ Michael Plümer, Xin-Nian Wang, and Miklos Gyulassy, in preparation

6. Color Diffusion and Conductivity in a Quak-Gluon Plasma, A. Selikhov and M. Gyulassy, CU-TP-598, Phys.Lett.B316 (1993) 373

7. QCD Fokker-Planck Equations with Color Diffusion A. Selikhov and M. Gyulassy, CU-TP-610 , Phys.Rev.C49 (1994) 1726.

8. Dissipative Color Currents in Quark-Gluon Plasmas A. V. Selikhov and M. Gyulassy, CU-TP-637 (1994), submitted to Nucl.Phys.B.

9. X.N. Wang and M. Gyulassy PRD 44 (91) 3501; PRD 45 (92) 844; PLB 276 (92) 285; PLB 282 (92) 466; PRL 68 (92) 1480.

10. Open Charm as a Probe of Pre-Equilibrium Dynamics in Nuclear Collisions, Ziwei Lin and Miklos Gyulassy, CU-TP-638 (1994), submitted to PRC

11. Perturbative versus Lattice QCD Energy Density Correlators at High Temperature Dirk H. Rischke and Miklos Gyulassy, CU-TP-639 (1994), submitted to Nucl. Phys. B.

12. Neural Filters for Jet Analysis, Dawei W. Dong and Miklos Gyulassy, Phys.Rev. E47 (1993) 2913.

13. Finite Signal transmission Times and Synaptic Memory in Neural Networks, U. Krüger, W. Martienssen, D.H. Rischke, CU-TP-644 (1994), submiteed to PRE.

2.2 Invited Talks

1. Signatures of Quark-Gluon Plasmas, M. Gyulassy, European Research Conference on Physics of High Energy Heavy Ion Collisions, Helsinki, Finnland, June 17-22 1994

2. "What is the structure of the quark–gluon plasma near the critical temperature ?", D.H. Rischke, Proc. of the Int. Conf. on "Nucleus–Nucleus Collisions V", Taormina, Sicily, Italy, May 30 – June 4, 1994, Columbia University preprint CU–TP–649 (to appear in Nucl. Phys. A)

3. "The structure of the quark–gluon plasma around the deconfinement transition", W. Greiner, D.H. Rischke, Proc. of the Belyaev–Feast, Philadelphia, U.S.A., May 1994, Columbia University preprint CU–TP–648 (to appear in Phys. Rep.)

4. Turbulent Initial Conditions in AA, M. Gyulassy, Budapest Workshop on High Energy Heavy Ion Physics, Budapest, Hungary, August 25-28, 1994.

5. Beyond the Hot Glue Scenario, M. Gyulassy, PHENIX Collaboration Meeting, BNL, August 29-31,1994

6. Open Charm Production, Z. Lin, PHENIX Collaboration Meeting, BNL, August 29-31,1994

7. Nonabelian LPM effect and radiative transport, M. Gyulassy, ECT Workshop on Parton Production and Transport, October 2-14, Treton, Italy

8. Chaos Concepts in Nuclear Physics, D. Rischke, Workshop of the SFB 185 (Nonlinear Dynamics), Riezlern, Kleinwalsertal, Austria, Sept. 17-23 1994

3 Columbia Nuclear Theory Members 12/15/94-12/14/95

The PI supervises the following personnel under this contract:

1. Dr. Dirk Rischke, post-doctoral Feodore Lynnen Humboldt Fellow from University Frankfurt, supported partially ($1700/mo.) from this DOE grant

2. Dr. Asayuki Asakawa, postdoctoral fellow from Lawrence Berkeley lab, full support ($ 3000/mo) under DOE grant

3. Ziwei Lin, graduate student, started June 1, 1993 under my thesis supervision, ($1216/mo before July 1, 1995, $1258 after)

4. Bin Zhang, graduate student, started June 1, 1994 under my supervision, salary as above

5. 3rd graduate student, expected from June 1,1995

4 Long Term Visitors

1. Tamas Csorgo, KFKI Budapest, Jan. 1, 1994- June 30, 1994, partially supported by the Hungarian National Science Fund (OTKA) from World Bank loans, to work on Non-ideal effects in pion interferometric probes of nuclear collisions.

2. V. Topor Pop, Bucharest, Nov. 1, 1994 - Jan 30, 1995, to work on baryon stopping power at SPS energies.

3. Alexei Selikhov, Kurchatov Institute, May 1, 1995 to July 2, 1995, to continue collaborative work on QCD transport theory

Budget removed.