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Final Report

The Theory of Relativistic Heavy Ion Collisions

DE-FG02-93ER40768

1/1/93 - 12/31/99

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Final Report on DOE Program The Theory of Relativistic Heavy Ion Collisions

March 24, 2000

Abstract

The program existed during 1993-1999 as Stony Brook-Brookhaven Nuclear Theory Groups collaboration, aimed at preparing both groups to re-orient themselves toward studies of heavy ion collisions and dense hadronic matter. The program supported mostly postdocs and students. It became obsolete when heavy ion research rose into the major topic of research of both groups. Major contributions to the field included (i) prediction of mostly gluonic initial conditions at RHIC with the maximal $T \approx 400 \text{ MeV}$; (ii) instanton-based theory of chiral symmetry breaking in vacuum and its restoration at $T_c \approx 160 \text{ MeV}$; (iii) prediction of new mechanism of color superconductivity in high density hadronic matter; (iv) detailed studies of heavy ion data from Brookhaven AGS and CERN SPS using hadronic event generators ARC and RQMD; (v) hydrodynamical description of flow phenomena at AGS/SPS and prediction of new explosion pattern expected at RHIC (the "nutcracker").

1 History of the program

The program described below had started on January 1, 1993, and was terminated as a separate grant January 1, 1999 (with some remaining funds used during 1999).

It was originally a joint venture, initiated by two Nuclear Theory Groups, at Brookhaven and Stony Brook, with Edward Shuryak as PI and Carl Dover and Andrew Jackson as co-PIs. Its primary goals were to perform research in areas such as: properties of highly excited hadronic matter, its production in nuclear collisions at high energies, and direct description of available experimental data.

Although by 1993 both groups were engaged in a wide variety of projects in related areas, it was considered important to pool efforts and resources through the establishment of a permanent existing collaboration, in order to assist the analysis of on-going experiments at the AGS and, more importantly, to develop a core of young people capable to carry on similar research at (then just approved) RHIC project. Throughout the duration of the program, funds were used primarily in support of postdoctoral positions and graduate students.

In parallel with this (DOE funded) program, Stony Brook group have obtained some support for research from the University administration as well. The so called Center

for Nuclear Theory was established as an Organized Research Unit, with Shuryak as Director and G. E. Brown, A. D. Jackson and J. Verbaarschot as initial faculty members, partially assigned to this Center. (Of course, other people in Brookhaven and Stony Brook also participated in related work: see below.) Among the long term research faculty supported by this Center (on University funds) were V. Koch and H. Sorge, both heavy ion phenomenologists who contributed a lot into understanding of the AGS and SPS data.

The program has succeeded to create much stronger interaction between Brookhaven and Stony Brook Nuclear Theory groups. During 1994-1996, there existed monthly Brookhaven-Stony Brook nuclear theory meetings, with alternating locations. These meetings take half a day and include 3-5 talks, usually with a common theme. Later the Columbia group (lead by M. Gyulassy) joined and have participated in the so called Triangle Nuclear Theory meeting. As these three institutions enjoyed a considerable concentration of exciting people and physics, the meeting attracting a lot of people from other places, both as speakers and participants. The style of these meetings allowed for discussion of the issues in considerable detail. Our sense is that at the time they were very helpful, especially for junior members and students, who could acquire a better sense of general direction of the field, and what other people around are doing.

As time went by, activities at Stony Brook and Brookhaven in the direction of this grant – theory of highly excited matter and nuclear collisions – gradually became the central topic of research of both groups. Opening of RIKEN/BNL Center in Brookhaven in 1997, and growing strength of Brookhaven Nuclear Theory group in the last year have made this smaller-scale joint grant obsolete. It is important to note that although the joint grant was terminated, the collaboration between Stony Brook and Brookhaven is actually becoming more intense. E. Shuryak, as a “senior visitor” at RIKEN/BNL Center spends there about a day a week, participating in many related seminars. He and Thomas Schaefer had organized a workshop “QCD Phase Transitions” there, in November 98. RIKEN/BNL Center is currently funding half of a bridge faculty line at Stony Brook, at which Thomas Schaefer (previously fellow of Princeton IAS) was appointed, since January 2000.

Naturally, it is impossible to discuss all works done during this rather extended period: below we mention the major achievements and also some “representative” ones for different areas. We organized the report along the topics of research rather than timing: whenever possible we commented about the internal logic of the development and major milestones on the way.

2 The Non-perturbative QCD

2.1 QCD Vacuum and Hadrons

Although these topics are not the major direction of the program, we start the report with these most fundamental issues, the basis of all hadronic physics. Understanding of vacuum/hadron properties goes hand-in-hand with similar phenomena in a macroscopic approach, in dense hadronic matter.

The particular direction pursued by the Stony Brook group was studies of tunneling phenomena in the QCD vacuum, described semi-classically by instantons. It can be considered as modern version of Nambu-Jona-Lasinio (NJL) model, which anticipated a need for strong short-range quark-anti-quark attraction long before QCD was born.

During the early 90's a sequence of works by Shuryak, Verbaarschot, Zahed and T.Schafer have demonstrated that instantons are indeed the major element in vacuum/hadronic structure, responsible for breaking of chiral symmetry and making all quarks effectively massive "constituent quarks". This fact alone shows that they are responsible for most of the nucleon's (and thus nuclei's) mass.

Development of a self-consistent model, called Interacting Instanton Liquid Model (IILM) and its numerical solution have allowed to include *all orders* in t' Hooft interaction. It allowed to calculate systematically many correlation functions, and opened a possibility to calculate many hadronic masses, coupling constants and form-factors. It was shown that the model actually reproduces well pions and nucleons, the major building blocks of nuclear physics. Shuryak and A.Blots have also calculated some form-factors, from the pion one to that of the "constituent quark". One very important prediction of this approach is existence of compact spin-0 isospin-0 diquark clusters inside the nucleons (which was long suspected on the basis of some phenomenological considerations).

Fundamental review paper describing progress in the field during the last decade was completed by T. Schäfer and E. Shuryak [97]. Although it appeared in April 98 issue of Rev.Mod.Phys., it already has about 250 references, according to SLAC database. The dominance of instanton-induced effects, long advocated by Stony Brook group, has lately attracted attention of many other theorists, from lattice practitioners, to phenomenologists studying hadronic form-factors, to people studying QCD phase transitions.

The most direct tests of these ideas are provided on the lattice numerically, because in this way one can find instantons explicitly, and correlate their presence with such physical observables as quark condensate or light quark propagators.. Among such groups very important set of results has been obtained by the MIT group lead by John Negele:, those have confirmed many of the IILM predictions from the first principles, on the lattice. The most important were studies of the lowest Dirac operator eigenvalues/modes. Their fundamental role in light quark physics can be compared to the role of Bloch wave functions in metals, in studies of their conductivity. As those are basically a superposition of atomic wave function for valence electrons, those in the QCD vacuum were demonstrated to be superpositions of instanton zero modes.

In the last few years instanton-based physics has grown tremendously, now including the domain of supersymmetric gauge theories. The celebrated solution by N.Seiberg and E.Witten for the effective action describing lowest excitations in $N=2$ supersymmetric QCD was shown to be just a perturbative logarithm, plus a series in the instanton-generated diagrams. Further instanton-based results have explained the underlying reason for the so called "Maldacena conjecture", *exact* correspondence between some *classical* field theory in 5-d anti-De Sitter space and *quantum* $N=4$ supersymmetric gauge theory. As shown by M.Mattis from Los Alamos (and his collaborators from UK) this 5-d space is nothing else but the coordinates of the instantons. It indicates that instanton physics is important or even dominant well beyond the QCD domain, where it was first phenomenologically established.

Another surprising similarity between the QCD and its supersymmetric relatives was found by L. Randall (MIT, now Princeton), R. Rattazzi (CERN) and E. Shuryak [136]. In $N=2$ supersymmetric $SU(2)$ the instanton corrections are known to all orders from the Seiberg-Witten solution: and one knows exact ratio between the scale Λ_{QCD} at which the perturbatively evolved coupling blows up, and a scale where the same happens with the “non perturbatively evolved” couplings. Remarkably similar behavior, up to some numerical coincidences, have been found in QCD and the supersymmetric $N=2$ Seiberg-Witten model.

2.2 Chiral Random Matrix Models

Originally a spin-off of the instanton-based works, the so called **chiral random matrix theory** was proposed by Shuryak and Verbaarschot. Now this direction, developed by J.Verbaarschot, A.Jackson and I.Zahed with collaborators, is an independent active branch of non-perturbative QCD. It too has got strong support from lattice calculations, explaining in surprising details some of the results of these large-scale simulations. It accurately describes properties of the lowest quark Dirac eigenvalues, and also put on much more firm ground the understanding of the so called finite-volume corrections, being imposed on lattice data in order to extract physical parameters of QCD such as the chiral condensate, see e.g. [144].

3 The Phases of QCD

3.1 Phase Transition at high temperatures and non-perturbative Quark-gluon plasma

This fundamental direction is the very center of RHIC-related physics: its aim is understanding of the transition between hadronic phase and the quark-gluon plasma (QGP). A number of approaches have been proposed to understand phenomena which happen at the critical temperature $T_c \approx 160 MeV$, such as (i) deconfinement and (ii) chiral symmetry restoration. The most direct is, of course, again lattice numerical simulations, obtaining results from first principles of QCD.

Although the former phenomenon remains an open problem, the latter – disappearance of quark condensate – has been understood in significant details. The main breakthrough happened in 95-96, when several works by Schaefer, Shuryak and Velkovsky [58,56] have found the microscopic mechanism driving it. It happens to be a rearrangement of instanton ensemble, from random liquid to a set of correlated pairs, the so called *instanton-antiinstanton molecules*. Without this rearrangement it was unclear why quark condensate vanishes above T_c , rather than simply decreasing to some small value. Not only this instanton-induced dynamics explains restoration of chiral symmetry, but it also reproduces lattice numerical data to many significant details.

One important consequence of these works is predicted survival of those molecules and strong non-perturbative interactions at $T = (1 - 3)T_c$. This is exactly the range of temperatures which are expected to occur at RHIC: with some luck we may find

manifestations of these effects experimentally. Among those are possible survival of *some* hadrons such as pions and sigma mesons as bound states in QGP above T_c , where of course they are no longer light Goldstone modes but just resonances.

Another observation (which is more theoretical but important in principle) is that chiral restoration driven by molecule formation is becoming much stronger in QCD with larger number of light quarks N_f . It was found that already for $N_f = 4$ the temperature of transition to QGP is very low, and for $N_f = 5$ there were no observable quark condensate even at $T=0$. The first part of this prediction has been verified by Columbia-RIKEN/BNL group, who has studied $N_f = 4$ QCD and indeed found a very small quark condensate. It means that the boundary of "the world as we know it" in the N_f direction may be much closer than we thought.

3.2 A QCD tricritical point?

New idea has been put forward by M.Stephanov (then Stony Brook, not the nuclear group but ITP), K.Rajagopal (MIT) and Shuryak [126], who suggested that there may be a real 2-nd order phase transition point, if one moves from zero to non-zero density along the critical line. This suggestions created significant interest both among CERN experimentalists and in theory community (e.g. F.Wilczek wrote a letter about this paper to journal Nature and mentioned it in Physics Today, explaining it to wider audience and making some new points).

If this point exists, it can be located by a number of methods, discussed in the second paper of the same authors [168]. Those event-by-event signatures which are characteristic of freeze-out in the vicinity of the critical point will exhibit non-monotonic dependence on control parameters. The reason why fluctuations are relevant here is because this point should show critical opalescence. It is methodically similar to the well known multi-fragmentation phenomenon associated with the endpoint of the nuclear liquid-gas transition.

The event-by-event fluctuations have been treated from the thermodynamical point of view by Shuryak in earlier work [102], later semi-quantitative description of the NA49 data on fluctuations in mean p_t and pion multiplicity.

3.3 New Color Superconducting phases of high density QCD

This new development is booming during the last 2 years. It was triggered by the first applications of the instanton approach to the finite baryon density case. Two groups, the Stony Brook group (R.Rapp, T.Schafer E. Shuryak and M.Velkovsky) [135] and Princeton group (M.Alford, K.Rajagopal and F.Wilczek) have simultaneously noticed that instantons produce not only $\bar{q}q$ but also qq attraction, and therefore can generate very robust set of Color Superconducting phases, with gaps of the order of 100 MeV. This is about two orders of magnitude larger than it was previously considered possible. This created excitement in a rather dormant field: In a year several conferences have concentrated on this issue, and about 100 papers is already written about it.

Large magnitude of the gap is actually is not that surprising, taking into account that it originates from basically the same interaction which in vacuum creates a gap of about

400 MeV, the constituent quark mass. Note also that the Cooper pairs in this case are direct continuation (in the quark matter) of the “scalar diquarks”, which we have studied before in vacuum. It was found then [5] that their binding is the primary reason why the nucleon is lighter than the Δ isobar. Re-summation of diagrams a-la BCS rather than numerical simulations allows one to get around the famous complex-valued fermion determinant related to chemical potential¹.

Two qualitatively different phases of Color superconductivity were found, which follow each other as density grows. First, the chiral symmetry is restored and instead the color gauge group SU(3) becomes broken to SU(2), by the colored qq condensate selecting a direction in color space. Then, at higher densities, the strange quarks become paired too and color became locked with flavor: remarkably enough, chiral symmetry becomes broken again! Some progress toward understanding of dense nuclear matter inside the neutron stars was also made, although many issues remain unresolved.

4 Dynamics of Nuclear Collisions

4.1 Initial conditions at RHIC: equilibration of quark-gluon plasma

In preparation for large-scale experiments at RHIC and LHC, the most obvious questions are the temperatures and densities which are likely to be reached. Significant progress has been made during the last three years, and it is now widely accepted that the so called ‘hot glue scenario’² is likely to happen. This means that dynamics are no longer dominated by ‘soft’ hadronic physics but rather by ‘semi-hard’ processes which involve partons in the ‘few’ GeV range.

Thus, perturbative QCD becomes the natural tool. Several groups have made detailed studies of partonic cascades and have confirmed that the gluon equilibration time is quite short (*i.e.*, 0.3 to 0.5 fm/c) which leads to high initial temperatures of 400-600 MeV at RHIC. (This is about twice the temperatures assumed previously.) The experimental consequences are very exciting, and their discussion will continue for some time. For example, this scenario predicts *enhanced charm production*. Studies of dilepton observability in PHENIX were made by Shuryak, who has pointed out that contrary to earlier claims, a correlated production charm pairs are not a prohibitive background because they are very likely to be stopped in matter due to significant stopping dE/dx . As a result, large-mass dileptons may become observable.

Most works on partonic cascades considered only the lowest-order processes, elastic scattering or the radiation of a single *soft* gluon. Studies made at Stony Brook by Li Xiong and E.Shuryak was aimed instead at the multi-gluon processes of the type $gg \rightarrow ng$, which were shown to play an important role in multiplication of gluons and their eventual thermalization. Another important point made in these works is the idea of self-screening of parton cascades, with Debye mass growing in time after collision moment, till no further gluon/quark radiation becomes possible. The mass estimated in this way is about 1 GeV

¹That is why lattice QCD has severe technical problems at non-zero baryon density, so that the results obtained in this direction are so far very limited.

²E. Shuryak, Phys.Rev.Lett. 68 (1992) 3270.

or so at RHIC, and about 3 GeV at LHC.

4.2 Hydrodynamics: going through the phase transition

There were made some efforts to join two types of cascades, partonic and hadronic ones, in order to describe matter throughout the whole evolution of excited system in heavy ion collisions. However all cascade event generators, both partonic and hadronic ones, leave as an unanswered problem how they can reproduce the Equation of State (EoS) which we know from lattice calculation. The so called Bag term (or effect) which makes matter very soft at $T \approx T_c$ was not yet successfully included in any of them. Because this is one of the key phenomena we are after at the RHIC project, models which can successfully incorporate such EoS are badly needed.

In order to do practical calculations which include realistic EoS after partonic equilibration is reached, we have preferred to move to macroscopic hydrodynamical description, and only later, in the hadronic phase, we freeze-out matter elements by switching to a hadronic cascade (RQMD).

There were two basic steps in developing such a model for RHIC. First a hydro-based project was completed by (Stony Brook student) Chi Ming Hung and Shuryak [116]: this model, called hydro-kinetic model (HKM), concentrated on the explanation of the available AGS/SPS data and making new predictions in this energy domain. It incorporated three basic elements of the macroscopic approach – (i) thermodynamics of hadronic matter, (ii) hydrodynamics of its expansion, and (iii) realistic hadronic kinetics at the freeze out. Many elements of the model have in fact been worked out by others, some are new, but we think they are taken together for the first time. Essential point is that freeze-out conditions used are very different from the simple isotherms used before, being also different for different secondaries. The conditions were based on kinetic calculations of the rates of major scattering processes.

Also, these freeze-out conditions are significantly different for light and heavy ions, and this explains the A-dependence of the flow: the heaviest systems not only produce the hottest matter at the beginning, but they also lead to the coolest gas at its end. Because dense hadronic matter near the QCD phase transition is very soft (pressure p is much smaller than the energy density), most of the acceleration happens at late stages of the collisions, when relativistic pions provide most of the pressure. Comparison of HKM results with cascade-based event generator RQMD has been made in significant details: we found that the EOS of both models, as well as the resulting flows, are in fact rather good agreement.

The second project has been performed by D. Teaney (Stony Brook student) and Shuryak [159], who have developed new hydro code for RHIC energies. While calculations for central collisions have confirm results obtained earlier by D. Rischke and M. Guylassy, those for *non – central* ones have shown remarkably different picture. The results were very unexpected and unusual: matter motion happened to be very EoS-dependent, with the “realistic EoS producing for non-central two denser shells of matter, which became physically separated by the freeze-out, in the direction of the impact parameter. At medium impact parameter there remains also a small central part - a “nut”. The whole scenario was named the “nutcracker”.

This scenario does not take place without the so-called "QGP push" at early time. The calculations have been confirmed by at least two groups, M.Gyulassy et al (Columbia) and U.Heinz et al (CERN), after we have reported them at some meetings. Among its observable consequences are generation of higher (4 and 6-th) moments in azimuthal angle, very specific behavior of the HBT radii etc.

4.3 Transport models

Two major models have been used over these years, in Brookhaven and Stony Brook.

Brookhaven group, S.Kahana, Y. Pang and T.Schlagel, has developed purely hadronic event generator ARC. It was successfully used at low energies, 1-10 GeV/N, covering Bevalac/AGS energy domain.

One ARC-related project (performed primarily by D. Kahana) was related to directed flow, for energies ranging from BEVALAC energies (where this phenomenon was studied in detail) to AGS ones. It was related with the latest data from the TPC detector EOS. A surprisingly good description of the directed transverse momentum, generated for protons in Au+Au collisions, between $p=1$ and 2 GeV/c, results from the pure cascade. One interesting physics point made in this work is that transition from repulsive two-body forces at lower end to absorptive cross section at high end can be modeled classically, as a different mixture of "attractive" and "repulsive" classical trajectories.

Significant other work on *directed* flow was done using ARC event generator by D.Kahana, Y. Pang (Columbia University, BNL) and Shuryak. Transverse energy 'flow' and event asymmetries reported by the E877(814) collaborations for Au+Au were found to be in reasonable agreement with ARC predictions for the proton flow, which reaches the maximum in-plane momentum about 120 MeV/c.

Alternative approach with potential use at SPS energies is realized in the well known RQMD code, developed by H.Sorge. Its basic physics is, beyond the hadronic cascade, the Lund-model description of production and decay of color strings. Among early applications of the model was calculation of strangeness enhancement: it was eventually concluded that the original Lund-type model leads to insufficient strangeness enhancement, and modification in for of "color ropes" (strings with more than one flux quantum) were incorporated into the model.

Widely used by experimentalists over a decade, the RQMD code was compatible with many observables, including such details as radial and directed flow. Among specific points made by Sorge lately were observation that Ω^- show significantly reduced radial flow, because it decouples early. Another important point was his observation that the elliptic flow develops early, and therefore better suited for triggering the initial QGP push.

In 1999 H.Sorge has invented modification of the scattering algorithm (with positive or negative time delay) which can tune the Equation of State (EOS) at will without changes of the cross sections. He tried to imitate the "softness" of the QCD phase transition in this (still hadronic) code. (Unfortunately his decision to quit physics has not allowed completion of this interesting idea.)

Cluster production at AGS energies was studied by Mattiello et al. using RQMD. A phase space coalescence description based on the Wigner-function method for cluster formation is used, leading to spectra of nuclear clusters d,t and He. Transverse expansion

leads to a strong shoulder-arm shape and different inverse slope parameters in the transverse spectra of nuclear clusters deviating markedly from thermal distributions. A clear "bounce-off" event shape is seen: the averaged transverse flow velocities in the reaction plane are for clusters larger than for protons. The cluster yields –particularly at low p_t at mid-rapidities– and the in-plane (anti)flow of clusters and pions change if suitably strong baryon potential interactions are included. This allows to study the transient pressure at high density via the event shape analysis of nucleons, nucleon clusters and other hadrons.

5 Other phenomena in high energy heavy ion collisions

5.1 Dileptons

Dileptons are one of the primary ways to get information about initial conditions, lost in hadronic observables due to re-scattering.

The experiments of the CERES collaboration carried out at CERN show an excess of dileptons, thought to be emitted from the ρ -meson while still in the fireball of the colliding nuclei. Mass spectrum of these dileptons in ion collisions is very different from what was expected from free hadronic collisions (basically $\pi\pi \rightarrow \text{dileptons}$) and from what was observed with p-A collisions: there is no visible peak at the rho mass, and there appears much larger continuum below it. Other groups, especially NA50 muon experiment, also reported excess of dileptons, reaching masses as large as 2 GeV.

The possibility that these excess dileptons arise from the decrease in ρ -meson mass predicted by Brown/Rho scaling naturally excited one component of our group. Rapp and Wambach, on the other hand, in a series of papers maintained that an explanation of the CERES dileptons could be achieved within the framework of standard many-body theory. In their case the width of the ρ -meson increased with density, and they believed that the ρ -meson "broadened" into chiral restoration.

One more possible description is partonic: one may imagine that hadrons are gradually substituted by freely moving quarks in the "mixed phase" present for long time at CERN SPS. This direction was discussed by Rapp and Shuryak [146], who have shown that simple partonic rates are in fact able to describe both data, CERES and NA50 ones. They have investigated the significance of thermal dilepton radiation in the intermediate-mass region in heavy-ion reactions at CERN-SpS energies. Within a thermal fireball model for the space-time evolution, the radiation from hot matter is found to dominate over hard 'background' processes (Drell-Yan and open charm) up to invariant masses of about 2 GeV, with a rather moderate fraction emerging from early stages with temperatures $T \simeq 175 - 200$ MeV associated with deconfined matter. Further including a schematic acceptance for the NA50 experiment we find good agreement with the observed enhancement in the region $1.5 \text{ GeV} < M_{\mu\mu} < 3 \text{ GeV}$. In particular, there is no need to invoke any anomalous open charm enhancement.

We believe that these scenarios are competitive in describing present experiments, the results of which lie between predictions of these models.

5.2 J/ψ suppression and related topics

This issue was not central for our work: and still over the years several interesting works have been made which are worth mentioning in this report.

Sorge, Shuryak and Zahed argued that a decrease of the chiral scalar meson mass is responsible for re-creation of Ψ' from J/Ψ in ultra-relativistic nucleus-nucleus collisions. This causes the charmonium yields to freeze out at temperatures close to the chiral symmetry restoration temperature T_c . As a result Ψ'/Ψ may serve as a thermometer for T_c itself. Results in a detailed reaction model support the conjecture. They show good agreement with recent data of NA38 and NA50 for J/Ψ and Ψ' production in S on U and Pb on Pb collisions.

E.Shuryak and D.Teaney suggested that the new regime of J/ψ suppression in Pb-Pb collisions found by the NA50 experiment at CERN may be the result of non-trivial space-time evolution due to specific behavior of the Equation of State (EOS) near the QCD phase transition.

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