A THEORY UPGRADE FOR RHIC:
Towards a Quantitative Understanding of Relativistic Heavy Ion Collision Dynamics and Quark-Gluon Plasma Properties

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Preamble

Theoretical nuclear physics research, in general, pursues different objectives which contribute in various ways to scientific progress. On the one hand, theorists develop new concepts that form the basis of future experimental programs. On the other side, a healthy, broadly diversified theory community that maintains an active dialogue with the experimental program is an essential component of the overall nuclear science effort. Both sides of this base program in nuclear theory must be adequately supported to fulfill its critical role.

In addition to this fundamental role of nuclear theory in general, the ultimate success of an experimental research program sometimes requires the timely completion of a theoretical research agenda, often including the development of specialized computational tools, that is specifically targeted at the science program of an operating facility. In such cases theoretical research is of an enabling nature, comparable to the construction and upgrades of facilities and instruments which enable experimental research. Such targeted theoretical research programs are of limited duration and have clearly defined objectives and deliverables. Our White Paper describes a theoretical research and development program of this enabling kind, targeted at the development of validated tools for the extraction of quantitative physics from the data taken at the Relativistic Heavy Ion Collider.

The costs of experimental facilities and instrumentation upgrades are kept separate from the funds of the experimental research program. We believe that the same principle should apply to enabling, closely targeted theoretical research as it is described in this White Paper. The program outlined below forms a part of the scientific infrastructure required for the successful completion of the RHIC science program, and this nature should be reflected in its mode of support. In particular, it should not be funded in competition with the base research program in nuclear theory, but as a part of the overall RHIC science program, which includes facility operations and upgrades. With this in mind, we have called the initiative described below "A Theory Upgrade for RHIC".

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I. The Challenge

The RHIC facility provides a unique environment for studying QCD bulk matter at temperatures and densities that surpass the limits where hadrons can exist as individual entities, bringing quark-gluon degrees of freedom into prominence. Theoretically, this transition is associated with color deconfinement and the melting of the quark-antiquark condensate which encodes the spontaneous chiral symmetry breaking properties of QCD. Analysis of the first few years of RHIC data has provided a qualitative understanding of matter above the transition temperature. First, the matter is found to thermalize rapidly and evolve like a low viscosity (”nearly perfect”) liquid, as evidenced by the surprisingly strong elliptic flow. Second, it is opaque to color charges as evidenced by strong jet quenching, suggesting a strongly coupled medium. Third, large domains in parameter space for the equation of state have been excluded by comparison with single-particle spectra and correlation measurements: while the equation of state obtained from Lattice QCD is compatible with the data, equations of state with a large latent heat or those that are very stiff have been excluded.

The great challenge for the RHIC community now is to progress from qualitative statements to rigorous quantitative conclusions. The experiments approach this challenge in a two-pronged way, both involving major new investments: At RHIC-II, upgraded detectors and beam luminosity will permit the careful study of sensitive hard and rare probes of the medium. These will make it possible to address specific questions about the thermodynamic and transport properties of the matter produced in the nuclear collisions. At the LHC, QCD matter will be studied at even higher energy densities, and with hard probes that extend far beyond the kinematic range accessible at RHIC. The data from these facilities will provide a solid foundation for a rigorous theoretical effort aimed at developing definitive insights about the nature and properties of QCD matter at the highest energy densities, i. e. the quark-gluon plasma.

The main obstacle on our path to achieving this goal is the inherently complex and highly dynamical nature of relativistic heavy-ion collisions. Since experimental observations are confined to measuring the asymptotic momenta of outgoing particles, quantitative conclusions require sophisticated modeling and thorough comparison of such models with data. The complexity of the modeling derives from the fact that reactions traverse two orders of magnitude of energy density and three phases, each with different underlying degrees of freedom: a pre-equilibrated phase characterized by the presence of strong color fields, an approximately thermalized partonic phase and, finally, an increasingly viscous hadronic phase. Experiments provide three classes of observables: spectra, correlations and fluctuations, and jets. Each class encompasses a host of hadronic and electromagnetic species which provide observational access to different stages of the collision. None of them, taken alone, yields complete and unambiguous information about any of these stages, but taken together they are expected to fully constrain the dynamics of the collision and to allow quantitative extraction of key properties of the created quark-gluon matter.

Doing so will require a full account of the rapid dynamical evolution of the collision fireball, using sophisticated models which correctly describe all aspects and stages of its three-dimensional expansion. For example, just as has been true for the analysis of the final decoupling stage of the fireball with Hanbury Brown-Twiss interferometry, the full power of jet tomography, i.e. the use of jet quenching and parton energy loss as a tomographic probe of the density and transport properties of the dense fireball medium, can only be exploited if the dynamical evolution of the bulk matter to be probed is quantitatively accounted for. Similar arguments apply to all other observables. Therefore, a successful quantitative interpretation of the heavy-ion data will not be possible without extensive and sophisticated modeling, using a costly iterative procedure which directly interfaces the experimental data analysis with the theoretical modeling effort in order to pin down all model parameters.

Without such an effort, the RHIC physics program cannot be successfully completed, and the synergies from the parallel LHC heavy-ion programs cannot be adequately brought to bear on the physics program of RHIC. Fortunately, most of the theoretical framework required for modeling QCD matter produced in relativistic heavy-ion collisions and the dynamics of medium probes has been developed during the past 10–15 years. The time is now right to focus resources on the development of the completion of the software and infrastructure needed to bring these theoretical insights to bear on the wealth of experimental data from RHIC (and soon, the LHC). In view of the time scale of the progressing experimental effort, which will provide us with data from substantially upgraded detectors as well as from collisions at much higher energies, the necessary tools for a comprehensive and quantitative determination of the properties of the medium produced in relativistic heavy-ion collisions must developed with utmost urgency. This will require intimate collaboration between all segments of the RHIC theory community, as well as between theory and experiment. The described effort mandates significant additional investment not only in theoretical resources, but also a focused effort on the part of the experimental community (due to the need for constructing interfaces between models and data and applying the models to quantitative data analysis).

The two established theoretical milestones[2] in the DOE performance measures for the RHIC program address limited aspects of the above challenge. In spite of tight funding, significant progress has been and is being made by the nuclear theory community to reach these milestones in a timely fashion. They stop well short, however, of the ultimate goals of the RHIC program (as, for example, outlined in the RHIC II White Paper "Future Science at the Relativistic Heavy Ion Collider") which include the quantitative determination of quark-gluon plasma transport coefficients and its equation of state from RHIC data. While the experimental effort to collect the necessary data is well under way, there is at present no programmatic focus from the theory side on accomplishing these ambitious goals. Earlier recommendations by NSAC and other committees to significantly increase funding for nuclear theory, in particular in the areas relevant to the scientific programs of major national facilities (in this case RHIC), have not been systematically implemented. This lack of a programmatic

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[2] 2009: "Perform realistic three-dimensional numerical simulations to describe the medium and the conditions required by the collective flow at RHIC.";

2010: "Complete realistic calculations of jet production in a high density medium for comparison with experiment."

focus jeopardizes the whole RHIC science program, whose ultimate success depends on the availability of validated tools for extracting medium properties from the data. On the positive side, the requirements for a comprehensive modeling and data interpretation program are now well understood, permitting a well targeted effort to be established. Such an effort, which is outlined below, must be implemented urgently and with high priority to achieve the science goals of RHIC in a timely manner.

As the algorithmic implementations required for this quantitative modeling effort become available for use by the broader RHIC physics community, computational resources which by far exceed those presently available to RHIC theorists will be needed to perform the necessary calculations. The funding agencies will have to ensure the availability of adequate computer and storage resources for this effort through access to large-scale computing facilities at national laboratories, including the (possibly upgraded) RHIC Computing Facility.

II. A Roadmap for Addressing the Challenge

Over the last twenty years, a sophisticated array of modeling tools have been developed by the nuclear theory community, covering the entire range of RHIC data. However, each of these tools addresses only a sub-class of RHIC observables. Furthermore, for each stage of the collision there exist competing approaches. Selection of the best approach cannot always be done on purely theoretical grounds, and to do so on a phenomenological basis requires their integration into a comprehensive dynamical framework that covers all collision stages. What is needed is a modular framework that allows the division of the problem into smaller projects to which anybody in the international theory community can contribute, in a standardized way that allows subsequent integration into a complete dynamical model. This will require standardization and quality control of communication and documentation, with particular effort invested into the testing of interfaces between implementations of different transport models, such as hydrodynamic and Boltzmann descriptions, and the computation of medium probes, such as parton energy loss in an evolving medium. The modeling environment must be professionally maintained and documented.

Specific tasks needed for the creation of a comprehensive dynamical approach towards modeling RHIC data include:

- descriptions of energy and baryon number stopping as initial conditions for the dynamical evolution;
- nonperturbative evolution of classical color fields with Color Glass Condensate initial conditions, including space-time evolution of plasma instabilities;
- dynamical models for the initial thermalization stage based on classical or quantum kinetic theory, including the interaction of colored particles with strong color fields;
- (2+1)- and (3+1)-dimensional viscous relativistic hydrodynamics to describe the dynamical expansion of an approximately thermalized quark-gluon fluid;

- Boltzmann models for the evolution of the late hadronic stage, including mean fields;
- jet production and quenching, and parton energy loss in a dynamically evolving background, including back reaction of the medium to the lost energy;
- three-dimensional jet tomography at all rapidities;
- modification of jet fragmentation functions by a dynamically evolving medium;
- the solution of rate equations for strangeness and heavy flavor production and for chemical equilibration among quarks and gluons in a dynamically evolving locally thermalized medium;
- the modeling of hadron production at intermediate transverse momenta by quark recombination from an expanding partonic medium;
- production and propagation of heavy quarkonia, including dissociation and recombination in the evolving medium, as well as energy loss of heavy quarks;
- emission of electromagnetic radiation (photons and dileptons) from a dynamically evolving medium, either by using the temperature and flow history of the dynamical models above, or by including photon production rates into the kinetic codes;
- afterburners to compute correlation and fluctuation spectra and for performing two- and three-particle interferometry from the output of the dynamical models.

Developing such a modular tool set is only the first part of addressing the challenge. The second part consists of comparing the numerical results with experimental data. This is not a one-dimensional procedure because each component of the dynamical model contains parameters which are either not reliably calculable directly from QCD or for which one wants to verify that QCD theory indeed provides accurate predictions while alternative options can be excluded. Approximately two dozen such parameters describe features of bulk matter, such as the color saturation scale, the equation of state, transport coefficients and relaxation rates, thermal and chemical reaction rates, as well as the initial geometry and the stopping of energy and baryon number. In addition, each probe is sensitive to probe-specific parameters, such as the energy loss coefficient for light partons, diffusion coefficients for heavy quarks, broadening and mass shifts for lepton pairs, and so on. For a given set of parameters, the data/model comparison then becomes an optimization problem that must be solved systematically. Techniques to avoid false minima corresponding to unphysical parameter values can and must be implemented.

Similar strategies have been applied to other highly complex physical systems, often related to important engineering applications. For many of these problems, the parameter set is much larger than the one encountered here. The unique numerical difficulty of performing such an analysis on RHIC data derives from the fact that a single complete run for a fixed parameter set might require tens of hours of CPU time. The search through parameter space is thus highly CPU intensive, requiring millions of CPU hours on advanced processors. The availability of large computer clusters for parallel computation will therefore be essential.

Experimental cooperation will be key to the success of the project. The optimization procedure requires an intimate understanding of statistical and systematic errors in the multi-dimensional data set and their correlations. As the results of the comparison are uncovered, experimental and theoretical collaboration is needed to decide what additional experimental analysis or measurements would best further constrain the error matrix. Furthermore, the experimental RHIC community's long experience and expertise with large-scale computing and programming projects will be an invaluable resource.

III. Required Resources

To successfully address the challenge, a targeted program should be established that is aimed at achieving the above goals, supported by a clear programmatic focus within the funding agencies. Developing, organizing, validating, maintaining, and documenting the model library will require the dedicated effort of a cadre of theoretical and experimental physicists, with broad input from both subcommunities. This might be accomplished by the creation of a (virtual) center, with a limited lifetime of about 5 years, whose unique mission would be to accomplish the goals laid out here. In addition to developing and maintaining codes, improving and extending theoretical methods for the calculation of dense matter probes, as well as coordinating the whole modeling and data interpretation effort, the center would be responsible for running workshops to assist the greater community in contributing to and making use of the modeling infrastructure. All of this can be done by physicists with appropriate expertise, with nuclear theorists playing the crucial role during the development phase. In our estimate it requires full-time commitment by $\mathcal{O}(10)$ properly trained scientists for the duration of the project, and a corresponding significant amount of targeted resources from the funding agencies *outside the scope of the base theory program.* After this 5-year development period, further maintenance and operation should become part of the experimental program within its data analysis effort, with continuing improvements provided by the theory community as part of the base nuclear theory program.