U.S. Program in Heavy-Ion Nuclear Physics:

Scientific Opportunities and Resource Requirements

Report of the
NSAC Subcommittee Review of Heavy-Ion Nuclear Physics

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Section I. Overview of the Report

I.A Introduction

A major component of the U.S. program in Nuclear Physics addresses fundamental issues related to the role of partons, quarks and gluons in the character of the nuclear force, the properties of nuclear matter at both normal and high energy density, and the origins of the universe as it evolved after the big bang. These investigations lead to experimental tests of the theory of quantum chromo-dynamics (QCD), the mechanisms of quark confinement and chiral symmetry, the search for new forms of matter such as the quark-gluon plasma, and confirmation at modern accelerators of the QCD phase transition in the early universe.

The 2002 Long Range Plan (LRP) developed by the Nuclear Science Advisory Committee (NSAC) provided a set of recommendations for exploiting opportunities for research in these areas. Significant progress has been made in identifying and exploring the properties of a new form of dense matter generated in relativistic heavy-ion collisions at the Relativistic Heavy Ion Collider (RHIC) and in describing these in the context of QCD. Furthermore, instrumentation has been developed at RHIC to permit investigation the spin structure of the nucleon through polarized proton-proton collisions at center-of-mass energies well above those available anywhere else in the world.

In February 2004, the Department of Energy/Office of Science (DOE) and the National Science Foundation (NSF) requested further guidance beyond the LRP, regarding the continued development of this program. The request was for an updated assessment of the scientific priorities in this field as required for a strong national research program in this scientific area. In response to this request, NSAC formed a Subcommittee to review the U.S. program in Heavy-Ion and Nucleon Structure Physics. The following report is the assessment of the scientific opportunities and resource allocations required by this program as developed by the NSAC Subcommittee, together with a set of recommendations as summarized below.

I.B Charge and Process

Briefly, the guidance requested by the funding agencies can be understood from the following sentence taken from the formal request (see letter in Appendix A):

> "What scientific opportunities should be addressed and what facility and instrumentation capabilities should be used and developed, including those supported by NSF and outside the United States, in order to maintain a strong scientific program in the coming decade?"

The Subcommittee (see Appendix B) was organized in March 2004 and consisted of five experimentalists, an accelerator physicist, and three theorists, all of whom are working in this field, and four nuclear/particle physicists working outside of this field.

The business of the Subcommittee was conducted in one three-day public meeting held June 2-4, 2004, at Brookhaven National Lab (BNL), followed by two executive meetings held at BNL

(June 5-6, 2004) and at the offices of the NSF in Washington D.C. (July 7-10, 2004). The agenda of the public meeting is included in Appendix C.

In its deliberations, the Subcommittee focused on the physics program which could develop over the next ten to fifteen years both in the U.S. and abroad, while the detailed budget analysis was restricted to FY06 to FY10. The physics areas and related facilities within the scope of the discussion included research opportunities at RHIC as driven by the Heavy-Ion program, the RHIC Spin program, and the plans to develop an electron-ion collider, together with an analysis of the heavy-ion physics research opportunities for the U.S. community at the Large Hadron Collider (LHC) and at the Gesellschaft fur Schwerionenforschung (GSI), as well as an assessment of an additional electron-ion collider concept being developed at the Thomas Jefferson National Accelerator Facility (JLab).

In its evaluation of the resource allocations appropriate for this program in FY06 to FY10, the Subcommittee considered these scenarios:

a. A constant level of effort budget based on the FY05 DOE budget request for $ 158.9M
b. Increments above a constant level of effort of 5% and 10%.

Under the constant level of effort scenario, a detailed model of resource allocations to all the components of the program was worked out. A balance was sought between exploiting the current RHIC facility and making investments to extend the future scientific reach at RHIC combined with a new program at the LHC. The impact of an incremented budget above constant level of effort and the assessment of priorities for these investments were also analyzed.

I.C. Assessment and Recommendations

In each of the physics areas identified above, the Subcommittee made an assessment of the current scientific status and the actions required for the continued health and future impact of the field. The Subcommittee makes the following five primary recommendations, which, with the specific actions discussed in the individual sections, are the primary conclusions of this report.

C.1 RHIC Heavy-Ion Program

It is the sense of the Subcommittee that important new phenomena have been discovered at RHIC, which will drive a compelling research program at this facility over at least the next ten years. With appropriate resources, RHIC will use existing and upgraded detectors and a luminosity upgrade for a series of measurements (ion+ion and p (d)+ion collisions) to fully characterize a newly discovered form of matter.

Recommendation #1:

A new and complex form of dense QCD matter has been discovered at RHIC. The unprecedented flexibility of this dedicated collider, coupled with the detector and luminosity upgrades that provide access to rare probes, will sustain RHIC's unique discovery potential. Consequently, the Subcommittee recommends full exploitation of the existing RHIC facility combined with investment in future research tools. Specifically, RHIC should run for as many weeks per year as possible, compatible with the following:

- **Investment in near-term detector upgrade projects for the two large experiments, PHENIX and STAR, to take full advantage of the existing accelerator capabilities;**
- **Investment now in accelerator and detector R&D, in preparation for RHIC II, to enable crucial measurements of this new form of dense matter using rare probes;**
- **Construction of the EBIS as quickly as possible to improve the reliability and increase the capabilities of the heavy-ion injection system and to realize the projected reduction in RHIC operating costs.**

C.2 LHC Heavy-Ion Program

The developing LHC facility at CERN offers outstanding opportunities for new discoveries in relativistic heavy-ion physics, driven by a large increase in center-of-mass energy, which generates different initial conditions and a larger kinematic reach for hard probes. The combined studies at RHIC and the LHC would provide a synergy important for global understanding of the properties and dynamics of dense QCD matter.

Recommendation #2:

The LHC will open up a new regime in relativistic heavy-ion physics with significant opportunities for new discoveries. The Subcommittee recommends that:

- **Participation at the LHC should become a new component of the U.S. Heavy-Ion program;**
- **This participation should receive comparable investment priority with each of the two near-term upgrade programs for the two large RHIC detectors.**

C.3 RHIC Spin Program

With its polarized proton capability combined with very high energy, the RHIC Spin program provides an outstanding and unique opportunity to investigate the spin structure of the proton in both the gluon and the quark-antiquark sectors. RHIC's capabilities go well beyond current and expected results at other facilities.

Recommendation #3:

Among high energy accelerators, RHIC is poised to become the premiere hadronic physics facility through the study of the spin structure of the proton with a unique polarized proton capability. In order to ensure the success of the RHIC Spin program, the Subcommittee recommends that:

- **Polarized proton-proton running remain an essential part of the RHIC program;**
- **In the near term, polarized proton-proton running time be sufficient to allow the first significant measurement of the gluon polarization;**
- **Accelerator and detector improvements proceed at a rate that allows a timely determination of the flavor dependence of the polarization of the quark-antiquark sea through W-asymmetry measurements at 500 GeV.**

C.4 Constant Level of Effort Budget

The Subcommittee finds that it is impossible to realize all the compelling scientific opportunities identified in Recommendations #1-3 within the constant level of effort budget addressed in the NSAC charge. However, within such a budget, the long-term scientific impact of the Heavy-Ion and Nucleon Spin programs can best be maintained by a balanced program that includes elements from all three recommendations. This can only be done through painful cuts. Specifically:

- RHIC running will have to be reduced substantially (up to 50 %);
- Compelling near-term RHIC detector upgrades will need to be stretched out or deferred;
- Participation in the LHC Heavy-Ion program can only be funded at a reduced level;
- PHOBOS and BRAHMS may need to be phased out earlier than envisioned in the BNL 20-year plan.

Recommendation #4:

Within a constant level of effort budget, the Subcommittee recommends that certain essential investments be made. These include:

- **Construction of the PHENIX Silicon Vertex Tracker and the STAR Time-of-Flight Barrel;**
- **Participation in the LHC Heavy-Ion program;**
- **Investment in RHIC accelerator and detector R&D;**
- **Construction of the EBIS;**
- **Support at the present level for university and national laboratory research;**
- **Provision for RHIC running time sufficient to preserve the integrity of the Heavy-Ion and Spin Physics programs.**

C.5 Incremented budget

In view of the serious cut backs in the program identified above (Section I.C.4), it is the Subcommittee's assessment that funding at a constant level of effort will seriously impact the ability of the U.S. Heavy-Ion and Nucleon Spin research programs to pursue the exciting scientific opportunities identified. The Subcommittee concludes that additional resources, at about 10% above the constant-effort level, would allow this field to exploit and realize the outstanding scientific opportunities in the Heavy-Ion and Spin Physics programs identified in this report.

Recommendation #5:

The Subcommittee concludes that additional resources above the constant level of effort would allow extraordinary opportunities to be pursued by this field. In particular, such resources would permit the field to maintain a productive run schedule at RHIC, extend the new and exciting program at the LHC, and to perform a series of critical upgrades to the RHIC detectors, greatly enhancing their capabilities.

The Subcommittee considered resource allocations under two possible budget increments in addition to the constant level of effort budget (Recommendation #4):

- **An increment of up to 5% over constant level of effort should be devoted to restoring the planned level of RHIC running time. This should permit operation of the RHIC accelerator for at least as many weeks per year as envisioned within the recent BNL 20-year plan;**
- **Additional funds beyond a 5% increment should be allocated in comparable amounts to:**
    - **RHIC detector upgrade investments to maximize the scientific potential of the RHIC facility in the era prior to the luminosity upgrade;**
    - **U.S. participation within the LHC Heavy-Ion physics program;**
    - **Support to research groups at universities and national laboratories working in relativistic heavy-ion physics.**

I.D Conclusion

The world wide community of physicists working at RHIC and making plans for future research at the LHC, have embarked on a series of experiments designed on one hand to reveal the underlying structure of matter in terms of quarks and gluons and the symmetry principles which govern their interactions and on the other hand to explore the origins of the universe as revealed in the physical processes which followed the big bang. Issues such as the confinement of quarks, the origins of their mass, and the nature of the QCD vacuum as it relates to chiral symmetry, are fundamental to our understanding of the structure of matter. In the context of the early universe, following the big bang the universe expanded and cooled in a series of phase transitions, which drove some of the most important epochs in cosmic history. It was during the QCD phase transition that the baryonic matter in the present universe condensed from a plasma-like state of quarks and gluons. Scientists believe that RHIC is currently reproducing this transition in heavy-ion collisions in the laboratory and, through lattice gauge calculations of QCD, is making the connection to the role of the underlying quarks and gluons.

The program reviewed in this report, with its two-fold emphasis on QCD matter at extremely high energy density and on the gluon and antiquark contributions to the spin structure of the nucleon, is rapidly emerging as a new and rich area of physics research. In this report, the Subcommittee has identified a set of new and compelling research opportunities at RHIC and the LHC for the U.S. program in Nuclear Physics. The immediate program has three important components: heavy-ion research at RHIC, nucleon structure research at RHIC, and a developing new heavy-ion research opportunity at the LHC facility, which will be come available in FY08-09.

In the past four years at RHIC, significant progress has been made in the identification and elucidation of a new form of QCD matter at very high energy density. Recent measurements have emphasized the importance of a broad class of new measurements at RHIC with current and upgraded capabilities, including the exploration of hard scattered partons and heavy vector mesons to probe the color screening length and the observation of forward processes related to gluon saturation.

In addition, the tools required at RHIC for studying the spin structure of the nucleon through polarized p p collisions at the highest energies are now in place, and a new research program is poised to begin. Preparations for asymmetry measurements at 200 GeV are now complete, and plans for a capability for 500 GeV operation, as required for W production asymmetry measurements, are being developed.

The Subcommittee concludes that these two lines of investigation at RHIC are well formulated and innovated attacks on some of the most fundamental questions in our understanding of the nuclear force and the origins of the universe.

In addition, the Subcommittee strongly recommends U.S. participation in a new Heavy-Ion program at the LHC, with a center-of-mass energy 30 times that of RHIC, and consequently generating a different initial state and opening a new kinematic range for probes of the matter formed. This exploration of processes at high Q^2 and very low x is an important complement to the rich program in progress at RHIC. The interplay of the different research programs at the LHC and RHIC will significantly enhance our understanding of this new form of dense QCD matter.

Furthermore, the Subcommittee found the physics arguments for the development of a future electron-ion collider facility persuasive and exciting. This facility would have the capability to significantly extend in both precisions and kinematic range, measurements of the parton structure of nuclear matter. The Subcommittee strongly encourages the further development of the physics case and the supporting technology for this project, so that it can be fully evaluated in advance of the next NSAC long-range plan.

In the judgment of this NSAC Subcommittee, the future scientific impact of the research activities highlighted in this report both at RHIC and in the future at the LHC, will be outstanding. The long-term plan for expanding the scientific reach of the U.S. nuclear physics program in QCD physics, is well formulated, and has strong motivation. It has excellent prospects for new discoveries and for developing a deeper understanding of the properties of nuclear matter and of the origins of the universe.

However, the Subcommittee is seriously concerned about the availability of resources to sustain this activity. Analysis of a constant level of effort budget (at $158.9M, FY05) indicates that the increasing costs of electricity and the new investments required to extend the scientific reach of the RHIC facility, together with the investment in the new program at the LHC, would force, over the next several years, a slow down in data taking at RHIC by as much as 50%. This would seriously impact the rate of progress in both the heavy-ion and polarized proton programs. In the judgment of the Subcommittee, the resulting loss in momentum in these programs, at a time of intense and continuing interest in these science issues by the international scientific community and in view of the investments already made in establishing the U.S. leadership in this field, should be avoided. It is the conclusion of this review that this outcome can be corrected with a funding increase of approximately 10%, which would permit full exploitation of the science opportunities in these emerging programs.

Section II. Introduction

II.A NSAC charge

A major component of the U.S. program in Nuclear Physics addresses the role of quark and gluon fields in the collisions of nucleons and nuclei. These investigations lead to experimental tests of the theory of quantum chromo-dynamics (QCD), the mechanisms of quark confinement and chiral symmetry, the search for new forms of matter such as the quark-gluon plasma, and confirmation, at heavy-ion accelerators, of the existence of the QCD phase transition in the early universe, which is believe to have followed the big bang.

Two aspects of this program involve investigation of high energy density phenomena in relativistic collisions of heavy-ions and the spin structure of the nucleon probed in polarized proton-proton collisions at relativistic energies. The 2002 Long Range Plan developed by the NSAC provided a set of recommendations for exploiting opportunities for research in these areas both within the United States and elsewhere. In the intervening years significant progress has been made in identifying and exploring the properties of a new form of dense matter generated in relativistic heavy-ion collisions at RHIC, and in describing these in the context of QCD. Furthermore, a capability has been developed at RHIC to permit investigation of the spin structure of the nucleon through polarized proton-proton collisions at center-of-mass energies well above those available anywhere else in the world.

In a letter sent to NSAC, on February 18, 2004, the Department of Energy/Office of Science and the National Science Foundation requested further guidance beyond the LRP, regarding the continued development of this field. The request was for an updated assessment of the scientific priorities in this field as required for a strong national research program in this scientific area. The essence of the guidance requested can be understood from the following paragraphs:

> “What scientific opportunities should be addressed and what facility and instrumentation capabilities should be used and developed, including those supported by NSF and outside the United States, in order to maintain a strong scientific program in the coming decade?”
>
> “What opportunities can be pursued with funding at the FY2005 Budget Request level ($158.9 M) and an assumed constant level of effort into the out years? What is the appropriate mix of facility operations, research, computer support, investments in instrumentation and accelerator capabilities, and detector and accelerator R&D that will be needed to optimally exploit these opportunities?”
>
> “What are the priorities of the scientific opportunities that could be pursued with additional funds beyond this constant level of effort?”

The NSAC accepted this charge and in a letter from NSAC Chairman Richard F. Casten to Peter D. Barnes requested that an NSAC Subcommittee be formed and an assessment made in response to the particulars of the DOE/NSF request. A written report responsive to this charge is to be provided by September 30, 2004.

The Subcommittee was formed in the spring of 2004 and the present report is the assessment made in response to the charge to NSAC. The full text of the letter from the funding agencies, with the charge to NSAC, is included in Appendix A.

II.B Process and Scope

The NSAC Subcommittee consisted of thirteen individuals including Peter D. Barnes as the chairman and the NSAC chairman, Richard F. Casten, as an ex officio member of the Subcommittee. The full membership of the Subcommittee is listed in Appendix B. Overall the Subcommittee consisted of five experimentalists, an accelerator physicist, and three theorists who are working in this field of heavy-ion and spin physics, and four nuclear/particle physicists working outside this field.

The business of the Subcommittee was conducted in a series of conferences calls, and in one three-day public meeting held June 2-4, 2004 at Brookhaven National Lab (BNL), followed by two executive meetings held at BNL (June 5-6, 2004) and at the offices of the NSF in Washington (July 7-10, 2004).

The agenda of the public meeting is included in Appendix C. This meeting included reports from the four experimental groups working at RHIC, experimental and theoretical experts in the field, BNL management, the three U.S. groups wishing to join the LHC, as well as reports on research plans at Fermilab and the GSI facility, together with a public comment session for remarks from the community. Talks presented at the public meeting can be viewed at the web site: http://nsac2004.bnl.gov/ .

In its deliberations, the Subcommittee focused on the physics program which could develop over the next ten to fifteen years, both in the U.S. and abroad, while the detailed budget analysis was restricted to FY06 to FY10.

The physics areas and related facilities included in the scope of the report are summarized in Table II.B. The research opportunities at RHIC include the Heavy-Ion program, the RHIC Spin program, and the plans to develop an electron-ion collider. In addition, heavy-ion physics research opportunities for the U.S. community at the LHC and GSI, as well as an electron-ion collider concept being developed at JLab, are evaluated in this report.

In its deliberations, the Subcommittee evaluated the possible overlap of this program with future proton-antiproton measurements at the Tevatron at Fermilab.

In its evaluation of resources available for this program, the Subcommittee considered these scenarios:

a. A constant level of effort budget based on the FY05 DOE budget request for \$ 158.9 M, for the period FY06-FY10,
b. Increments above constant level of effort of 5% and 10%.

Under the constant level of effort assumption, a detailed model of resource allocations to all the components of the program in Table II.B were considered. A balance was sought between exploiting the current RHIC facility and making investments to extend the future scientific reach at RHIC combined with a new program at the LHC. The changing operating cost of RHIC due to changes in electric power and taxes are included in this analysis. The impacts of an incremented budget and the priorities for investment in all of these activities are also analyzed.

Physics	**Facilities**		
Dense QCD Matter & Heavy-ion Collisions	RHIC	LHC	GSI
Nucleon Spin Structure	RHIC Spin		
Parton Distributions, Spin Structure & Electron- Ion Collisions	e-RHIC	JLAB ELIC	

Table II.B Scope of Subcommittee Deliberations

II.C. Organization of the Subcommittee Report

Section III of this report is directed toward the U.S. Heavy-ion Nuclear Physics program. Section III.A gives an overview of the evolution of the heavy-ion physics program in the context of recent measurements and the capabilities of RHIC and the LHC, together with an analysis of the open physics questions in this field. An assessment of the specific experimental opportunities and investments required at RHIC and at the LHC are reported in Sections III.B and III.D. Major facility upgrades to the RHIC collider are analyzed in Section III.C, together with the R&D programs required to make these construction projects viable.

The experimental opportunities and potential physics impact of the RHIC Spin program are discussed in Section IV. An analysis of the physics opportunities offered by electron-ion colliders is being formulated at RHIC and JLab. The motivation for these initiatives is evaluated in Section V., together with the supporting R&D programs needed in the near term.

A number of related topics are brought together in Section VI. The programs developing at GSI and Fermilab for heavy-ion collisions and proton-antiproton collisions, respectively, are discussed in Sections VI.A and VI.B. The Subcommittee's assessment of the computing needs of the program is reported in Section VI.C, followed in Section VI.D by a description of the participating research community. The results of the budget analysis for the different scenarios discussed above are provided in Section VII.

In each of these sections, the Subcommittee makes an assessment of the actions required for the future health and scientific impact of the field. The Subcommittee makes five primary recommendations that address the following topics:

Heavy-Ion Physics:
- Recommendation #1 The RHIC Heavy-Ion Physics program
- Recommendation #2 The U.S. LHC Heavy-Ion program

Nucleon Structure
- Recommendation #3 The RHIC Spin Physics program

Budget Scenarios:
- Recommendation #4 Program Choices for a Constant Level of Effort Budget
- Recommendation #5 Program with a 5-10% Incremented Budget

These recommendations appear at the end of each relevant Section and are summarized in Section I.

A summary of the Subcommittee's conclusions is provided in Section VIII.

Section III. Relativistic Heavy-Ion Nuclear Physics

III.A. Overview: relativistic heavy-ion nuclear physics

The temperature of the universe immediately following the Big Bang was so high that ordinary hadrons such as protons and neutrons could not form. The dominant state of matter, at an age of about 10 microseconds, consisted of unbound quarks and gluons, a state referred to as the quark-gluon plasma. As the universe cooled, the vacuum ground state became filled with a quark condensate that spontaneously broke the chiral symmetry present at high temperature, giving rise to hadron masses which are large compared to the masses of light quarks. The underlying mechanism which connects symmetry breaking, mass generation and ground state properties is thought to account for more than 95 % of the observable mass in the Universe. General arguments, substantiated by lattice QCD simulations, indicate that the properties of the ground state vary dramatically with temperature: at temperatures exceeding T_C ~170 MeV the vacuum "melts", the underlying symmetries of QCD are restored, quark masses go to their bare values, and quarks and gluons are deconfined.

The QCD matter at finite temperature, similar to other bulk materials, is expected to have a complex phase structure. The deconfined plasma is expected to exhibit unique features due to the non-Abelian nature of the strong interaction, while also showing features of conventional plasmas such as screening and collective excitations. The collision of heavy nuclei at ultra-relativistic energies presents the opportunity of studying this phase structure in controlled laboratory experiments. Experimental observables available at collider energies give insight to the degree of equilibration of the medium, to the dynamical processes that lead to dense QCD matter, and to the initial state from which this matter emerges.

The study of the physics of the quark-gluon plasma (QGP) has been identified as a scientific priority in the National Academy Reports "Connecting Quarks with the Cosmos: Eleven Science Questions for the New Century" and "Frontiers in High Energy Density Physics -The X-Games of Contemporary Science" as well as in the NSAC 2002 LRP. The 2002 LRP identified the following specific questions, all of which are addressed by the current and future heavy-ion research programs:

> "1) In relativistic heavy-ion collisions, how do the created systems evolve? Does the matter approach thermal equilibrium? What are the initial temperatures achieved?
>
> 2) Can signatures of the deconfinement phase transition be located as the hot matter produced in relativistic heavy-ion collisions cools?
>
> 3) What are the properties of the QCD vacuum and what are its connections to the masses of the hadrons? What is the origin of chiral symmetry breaking?
>
> 4) What are the properties of matter at the highest energy densities? Is the basic idea that such matter is best described using fundamental quarks and gluons correct?"

The Subcommittee was charged with identifying the future scientific opportunities in the field of Relativistic Heavy-Ion Physics together with the facilities and instrumentation that will maintain a strong U.S. scientific program in this area in the coming decade. The flagship facility of the field is RHIC at BNL, a machine dedicated to the study of high density QCD matter. As outlined below, the first discoveries at RHIC have established that high density QCD matter is produced at collider energies and that its properties can be measured by a wide range of experimental probes. In 2008 the high-energy frontier for nuclear collisions will move to the LHC at CERN. QCD matter produced at the LHC is expected to arise from significantly different initial conditions than at RHIC and may exhibit markedly different properties. The simultaneous study of the dynamical evolution of QCD matter generated from such widely differing initial conditions provides a unique and powerful set of probes of its nature.

III.A.1. State of the Art

RHIC is the world's first heavy-ion collider. It collides heavy nuclei at center-of-mass energies up to 200 GeV per nucleon pair, which represents an order of magnitude increase over previously available facilities. Table III.A.1 summarizes the delivered integrated luminosities at RHIC to date.

Year	Species	Energy (GeV/u)	Integrated luminosity
2000 (Run-1)	Au + Au	56	< 1 μb^{-1}
	Au + Au	130	20 μb^{-1}
2001/2002 (Run-2)	Au + Au	200	258 μb^{-1}
	Au + Au	20	< 1 μb^{-1}
	p↑ + p↑	200	1 pb^{-1}
2002/2003 (Run-3)	d + Au	200	73 nb^{-1}
	p↑ + p↑	200	6 pb^{-1}
2003/2004 (Run-4)	Au + Au	200	3740 μb^{-1}
	Au + Au	62	67 μb^{-1}
	p↑ + p↑	200	7 pb^{-1}

Table III.A.1 Summary of integrated luminosities delivered to all RHIC experiments to date.

The analysis of these data in combination with theoretical models leads to the assessment that the matter produced in nucleus-nucleus collisions at RHIC is very dense and shows evidence of evolution towards a thermalized system. Several findings indicate that this produced matter is a strongly coupled plasma in which color charges are not fully screened from one another:

a. Measurements of low transverse momentum inclusive spectra and azimuthal correlations indicate that different hadron species emerge from a common medium that has built up a strong transverse velocity field ("collective radial and elliptic flow"). These measurements are broadly consistent with calculations based on ideal hydrodynamics, indicating a very small mean free path in the medium and a very rapid thermalization, at a time less than 1 fm/c after initial impact. The relative population of a wide array of hadron species is statistically distributed at a temperature of about 170 MeV, suggesting that observed hadrons are generated by a system in chemical equilibrium near the deconfinement phase transition boundary.

b. Independent evidence for a small mean free path and the presence of strong equilibration processes in a dense medium comes from measurements at high transverse momentum. Both inclusive hadron yields and back-to-back dihadron correlations are strongly suppressed in central, head-on collisions of heavy nuclei when compared to p+p collisions. Such suppression effects are not observed in d+Au collisions, demonstrating that they result from final-state interactions in the medium generated by the collisions of heavy nuclei. The systematic behavior of the suppression phenomena is consistent with a picture in which high p_T partons lose a large fraction of their initial energy via strong interactions with the dense medium prior to fragmenting into correlated jets of hadrons ("jet quenching"). Perturbative QCD-based models of jet quenching require energy densities of about 15 GeV/fm^3 at a time ~0.2 fm/c after the initial collision in order to describe the measurements. This energy density exceeds that of cold nuclear matter by two orders of magnitude and is consistent with the initial density required by hydrodynamic simulations to reproduce the collective flow phenomena. It is an order of magnitude larger than the critical energy density for the deconfinement transition predicted by Lattice QCD.

These are the data that at present carry the clearest physics messages. They are supplemented by many other measurements, several of which pose challenges for the current dynamical models of heavy-ion collisions. In particular, pairs of identical hadrons at small relative pair momentum probe the space-time structure of the collision region due to quantum-statistical interference effects. Their measurements indicate that the hot dense matter is relatively short-lived, in contrast to expectations from hydrodynamic calculations that agree well with other observables. This "HBT puzzle" has not been resolved and remains the most significant disagreement of models and data at RHIC. At intermediate transverse momentum, the spectra of different baryon and meson species and their flow patterns follow simple counting rules consistent with hadronization occurring via the coalescence of flowing constituent quarks ("recombination"). However, it is not yet understood why constituent quarks - which play little role in the modeling of other aspects of heavy-ion collisions - should be the relevant dynamical degrees of freedom for hadronization, or whether other quite different dynamical pictures could also give rise to the same constituent quark counting rules. However, these findings already indicate that the medium strongly influences the hadronization mechanisms.

The interplay of RHIC experiments and theory has also resulted in progress towards understanding features of high-density QCD that lie outside the context of QCD equilibrium and near-equilibrium dynamics. In particular, QCD-based arguments suggest that saturated small-x parton distributions may determine the bulk properties of hadro-production at sufficiently high energy and may underlie the rapid equilibration. However, the scale for the onset of such saturation phenomena remains to be established by experiment. The possibility of further substantiating these theoretical expectations is presented in the following discussion.

III.A.2 Open Questions and Future Opportunities

These first data represent a significant advance in our understanding of relativistic heavy-ion collisions, towards meeting the fundamental goals laid out in the 2002 LRP. In particular, one can already state that high-density matter is created in such collisions and that the question of the approach of the medium to thermal equilibrium appears to have a positive answer. More generally, the first RHIC measurements illustrate that systematic experimentation applying a wide variety of experimental probes can be used to elucidate the properties of the produced matter. However, rather little is currently known about the properties of this state of matter and the dynamics that lead to it. Among the significant questions that future experiments and theoretical work will address, are the following:

a. What is the initial state from which the dense matter emerges?
As detailed above, RHIC measurements have established that the produced matter is very dense. However, it remains to be determined what features of the nuclear wave function and which initial dynamical processes drive the production of this high-density matter. Initial conditions can be varied experimentally by changing the collision energy and studying the rapidity dependence. Widely different initial conditions are experimentally accessible via the parallel study of a large suite of observables at RHIC and at the LHC. Further theoretical motivation for these studies comes from the QCD-based prediction that with increasing center-of-mass energy or rapidity, saturation effects in the parton distribution may play a crucial role in hadro-production processes.

b. What are the microscopic mechanisms underlying the apparently rapid onset of hydrodynamic behavior? Is the fluid indeed ideal, i.e. of small viscosity?
As indicated above, a broad class of measurements at RHIC, in particular elliptic flow, give strong support for non-viscous hydrodynamic behavior setting in at less than 1 fm/c after initial impact. However, at present there is little understanding of the processes leading to such rapid equilibration. On the theoretical side, significant conceptual developments and advances in microscopic modeling are required to substantiate the hydrodynamic interpretation of data. On the experimental side, the hydrodynamic interpretation will be subjected to important further tests by utilizing multi-strange baryons and charmed mesons and by varying the initial conditions through variation of collision energy, projectile size and nuclear deformation.

c. What are the properties of the dense QCD matter produced in nuclear collisions?
At collider energies, the detailed determination of bulk particle production correlated with the measurement of a wide range of rare processes allows for a detailed characterization of the properties of the produced matter. As discussed above, current measurements of bulk elliptic flow and jet-quenching phenomena already give first constraints on the mean free path determining the collision frequency and the time-averaged opacity of the produced matter. The main motivations for jet quenching studies are first to understand in detail how a hard out-of-equilibrium parton, as a test particle, fragments in the medium and approaches equilibrium, and second to exploit this fragmentation pattern to infer detailed properties of the matter produced in the collision. This includes the study of charm- and bottom-induced jets, the measurement of photon-tagged jets and the full characterization of the jet fragmentation. Real and virtual photons at thermal momentum scales, and fluctuation observables of soft hadrons, can potentially also address basic properties of the produced matter.

d. What are the generic properties of equilibrated QCD matter at high temperatures? Are current quark masses (partially) restored at high temperature, as expected from the restoration of chiral symmetry? Is there direct evidence for deconfinement?
Data from RHIC provide strong evidence that efficient equilibration processes occur in nucleus-nucleus collisions. However, thus far they have provided limited information about the properties of equilibrated QCD matter. There are two classes of measurements

which are within experimental reach in the coming years and which are essential for addressing the second and third fundamental question of the 2002 LRP on chiral symmetry restoration and deconfinement:

First, any test of deconfinement has to characterize the degree of color screening in the medium on different length scales. An essential experimental tool to this end is the study of medium effects on charmonium and bottonium bound states whose full hierarchy allows one to scan the relevant sub-femtometer length scales. Interpretation of these measurements also requires measurement of open charm and bottom production, as well as theoretical control over the production mechanisms.

Second, leptonic decays of resonances such as the rho and omega give access to the medium-induced changes of the resonance masses and widths in dense matter. Since resonance masses trace the size of the chiral order parameter, their measurement addresses directly the origin of chiral symmetry breaking.

e. **Can the mechanisms underlying hadronization be uncovered? What is the origin of the striking scaling with constituent quark number at intermediate p_T?**

   As discussed above, it is not yet understood why, at intermediate p_T, the transverse momentum spectra of identified particles and their elliptic flow, follow simple constituent quark counting rules. Most generally, this phenomenon promises to provide significant new insight into the dynamics of hadronization from a dense QCD medium, thus opening a novel window to the dynamical properties of produced partonic matter. To this end, it is important to extend the measurement of p_T-identified hadron spectra to more particle species over a broader transverse momentum range and to determine identified particle correlations over a wide kinematic range.

III.A.3 Physics Opportunities at RHIC and the LHC

Existing and future experiments at RHIC and at the LHC will provide a complementary, multi-pronged approach to addressing the questions outlined in the previous section. Several important aspects of these experiments are outlined below and then discussed in detail:

- Systematic study of the rapidity and energy dependence of hadron production will determine the initial state from which dense matter emerges. Upgraded forward instrumentation of the RHIC detectors will explore the kinematic regime where novel saturation effects may occur at RHIC energies. The kinematic overlap between forward rapidity at RHIC and mid-rapidity at LHC will help to isolate saturation-specific effects, while measurements at forward rapidity at LHC will extend the kinematic reach at low x by three orders of magnitude. A program of A+A and p (d)+A collisions at both colliders, together with measurements having significant coverage in rapidity and good particle identification, will elucidate those properties of the initial state which drive equilibration processes.

- RHIC data have already roughly indicated the kinematic boundaries within which equilibrium is established. Detailed understanding of the microscopic mechanisms underlying equilibration requires the study of a broad array of rare probes (multi-strange baryons, charmed mesons, heavy quark bound states, high energy partons or jets) and the extent to which they participate in the equilibration processes. The systematic study of elliptic flow and its particle species dependence at both RHIC and the LHC, including beam energy and species scans at each facility, will provide an enormous range of variation of initial conditions and probes with which to confront our understanding of equilibration processes.

- RHIC data have shown that the measurement of the hadronic fragments of jets generated in nuclear collisions provides novel and highly sensitive tools for characterizing the dense matter produced in the collision, within the framework of partonic energy loss theory. This program at RHIC is still in its infancy. The measurements are, thus far, restricted to inclusive leading hadrons and di-hadron correlations from undifferentiated light quark and gluon jets. Future studies at RHIC of heavy quark jets and jets recoiling from a direct photon will provide much more detailed insight into partonic energy loss and properties of the medium. The enormous collision energy at the LHC will provide a rich sample of hard probes in a kinematic regime, which is typically an order of magnitude broader than at RHIC (e.g. there is significant yield at the LHC for jets with E_T>200 GeV). This will make qualitatively new observables available. For instance, one can anticipate the full reconstruction of jets with reasonable energy resolution over the heavy-ion event background, enabling new ways of studying the interaction of the parton and its radiation with the medium. It will be essential that hard probes be correlated with a wide range of soft physics phenomena sensitive to the bulk properties of the medium.

- Hadron production in the intermediate p_T regime at RHIC (<10 GeV/c) exhibits unique and unexpected features, perhaps arising from partial equilibration of moderate energy partons with the medium. The studies of hadronic spectra and correlations in this regime at both RHIC and the LHC, with special emphasis on particle identification, may provide significant new insight into the dynamics of equilibration.

- The study of the dense matter produced in heavy-ion collisions aims ultimately at determining the generic properties of equilibrated QCD matter at high temperatures. Experiments at RHIC and the LHC will determine the color screening properties of QCD matter by measurement of the dissociation patterns of charmonium and bottonium bound states. For full utilization of these probes the spectroscopy of the complete families of bound states is essential, together with measurement of open charm and bottom production to provide the key benchmarks. At RHIC this requires both detector and luminosity upgrades. The measurement of the properties of vector mesons and the low-mass di-lepton continuum, currently in the planning stages at RHIC, may provide unique insight into the chiral structure of the dense matter.

Beyond the focus on the properties of hot dense QCD matter through A+A collisions together with p+A collisions used for normalization, one can address the parton structure of cold nuclear matter in p+A (and d+A) measurements. Many outstanding questions in hadron physics can be explored at RHIC which provides unique opportunities for exploring proton-nucleus collisions. The center-of-mass energy reached at RHIC in p+A collisions is roughly an order of magnitude higher than that for any existing fixed-target proton-nucleus experiments. Moreover large-acceptance collider detectors at RHIC are capable of measuring simultaneously the many particle species produced in the p+A collisions over a broad kinematic range. This could provide qualitatively new information not accessible in previous fixed-target experiments.

Thus, investigation of p (d)+A collisions will provide unique information on the partonic structure in nuclei and the propagation of partons in a cold nuclear medium. Specific physics results might include:

- The study of parton energy-loss and jet quenching in cold nuclear matter via the measurement of high-p_T single hadrons up to large p_T values.
- The study of cold nuclear matter effects on particle production in hard and semi-hard processes to higher momentum. This includes measurement of fragmentation functions of moderate energy jets in p+A collisions as well as multiple scattering for identified hadrons.
- A measurement of J/ψ (and eventually upsilon, Υ) production in the nucleus, covering a wide kinematic regime including small Bjorken-x. As a result, nuclear shadowing of gluons and the generation of dynamical parton mass at small x can be studied.
- A measurement of open-charm and –bottom production and heavy-quark propagation in a cold nucleus via the detection of high- p_T single leptons.

In addition an extensive list of physics topics at relatively low p_T can be studied with p+A collisions. The 2003 d+A run at RHIC has demonstrated the capability of colliding asymmetric species at this facility. The results from that run form an important basis for future planning to realize the full potential of the p+A program at RHIC.

In summary, both RHIC and the LHC, within their individual energy regimes and different capabilities, are poised to address the fundamental questions about QCD matter and heavy-ion collisions raised in the previous section. To realize the promise of the interplay of these two programs requires both the right instrumentation and sufficient integrated luminosity. The specific capabilities and measurements at these two facilities are discussed in the next several sections.

Section III.B RHIC: Heavy-Ion Program

In the U.S. relativistic Heavy Ion program, the flagship facility of the field is the RHIC at BNL, a machine dedicated to the study of high density QCD matter. The Subcommittee heard presentations from the four RHIC experiments and from a number of leading theorists in the field, discussing results of the first four years of RHIC running and their interpretation. Goals for the future program of RHIC were then outlined, drawing upon insights from the extraordinarily successful initial running period.

III.B.1. Findings

RHIC running to date has focused on the production of matter at the highest attainable energy densities and the initial characterization of its basic properties. The main scientific results of the program thus far are outlined in Section III.A and are very well documented in a series of white papers, now in press, prepared by the four major experimental collaborations at RHIC. They make a compelling case that equilibrated high density QCD matter is generated very early in the evolution of the nuclear collisions at RHIC. First studies of its properties suggest that it behaves as an ideal fluid (small viscosity). The matter is quite unlike a weakly interacting plasma of freely propagating quarks and gluons. Rather, the color charges may not be fully screened from one another and the coupling is strong. Most of the essential properties of this new state of matter remain as yet unexplored; it has not been shown directly that the matter is de-confined or that chiral symmetry has been restored, nor have its more detailed plasma properties been studied.

The most significant measurements to date include the collective flow pattern of pions, kaons, protons, and lambdas. The common velocity and the anisotropy in the azimuthal distribution of these particles are sensitive to pressures in the early phase of the collision. Another key result from RHIC is the direct evidence for extraordinarily high densities in the initial state indicated by the suppression of jets of hadrons from hard scattered partons probing the medium. Both the collective flows and energy loss suggest that the system is strongly coupled. Hydrodynamical descriptions of the collision evolution and lattice solutions of QCD in the non-perturbative regime lead to the same conclusion. The evidence for quark-gluon plasma formation is still circumstantial, but should be resolved by probing the dense matter with short wavelength probes, as detailed below.

Theoretical determination of quark-gluon plasma properties is very important and will require large computational resources. Extensive lattice QCD calculations at finite temperature are critical to probe the strongly coupled regime. Detailed modeling of the collision dynamics, by combining quantum evolution of the initial state, hydrodynamic description of the resulting matter and transport equations to describe the produced particles, are also needed.

III.B.2. Observations

The results of the measurements to fully characterize the new state of matter discovered at RHIC suggest a roadmap for utilization and upgrades of RHIC to explore high energy density physics at the highest energy densities achievable. This effort addresses one of the major goals laid out in the recent report "The Physics of the Universe" and discussed in Section III.A. Carrying out the measurements will require a strategic choice of run configurations to fully exploit the existing detector capabilities, short-term detector upgrades as described below, as well as more extensive detector and accelerator improvements in the future. A twenty-year plan (http://www.bnl.gov/henp/docs/20year_BNL71881.pdf) for full utilization of RHIC has been developed by the RHIC community. This includes a detailed run plan for the first five years, along with continuous expansion of the physics reach through near-term upgrades of the large detectors and the accelerator complex.

One can anticipate that in the medium term the high cross section measurements will be completed and the RHIC program will be at a point where qualitative advances in physics at the nominal (current) RHIC beam parameters would require data runs of 5-10 years duration to accumulate the needed integrated luminosity. Such a program would clearly be unsustainable. Therefore, compelling measurements of the hot, dense medium with rare short wavelength probes require a luminosity upgrade of the RHIC facility by about an order of magnitude, together with corresponding detector upgrades to utilize the enhanced luminosity. To enable this, R&D must be carried out in the near future, to address the accelerator and detector-related technical challenges of producing and utilizing the increased luminosity.

Utilization of the current suite of detectors

The parameters at the experimentalist's disposal include the collision energy and mass of the colliding nuclei to vary the initial energy density and the volume of the generated hot matter. Such studies are critical to elucidate the equation of state of the matter and the dynamics of the expansion, but good statistical precision at each beam and energy configuration requires significant running time. The RHIC Twenty Year Plan that emerged from discussions in the past year among experimentalists, accelerator physicists, and the theory community identified the next step in the RHIC program as running the current suite of experiments with different energy and nuclear mass combinations. The Subcommittee finds this short-term strategy to be sound.

Initial steps in this direction were taken in 2004 with an exploratory run with Au+Au collisions at $\sqrt{s}$ = 62 GeV per nucleon pair, but a complete set of measurements, including comparison to proton-proton collisions, remains to be done. The second column of Table III.B.1 shows a possible scenario for running through FY 2010, mostly based on the RHIC Twenty Year Plan. In FY 2010 a uranium-uranium run has been included to illustrate the extended scientific reach enabled by construction of the EBIS injector. Such a run may provide an opportunity to confirm the implications of the elliptic flow measurements made in Au-Au runs. The third column shows a possible run plan under the constant level of effort budget scenario described later in this document, designed to preserve the most urgent measurements that must be made in a timely fashion. Appropriate baseline measurements of unpolarized proton (deuteron)-nucleus scattering are included in the schedule. Note that a RHIC run with lighter ion species is by now the only task in the baseline program of BRAHMS and PHOBOS remaining to be done. This requires a limited amount of running time and could be accommodated in the beam schedule of 2005 or 2006.

The availability of running time is critical in the coming years to fully realize the promise of the facility. In both scenarios, heavy-ion running is interleaved with polarized proton running. In particular, it should be noted that polarized proton running at $\sqrt{s}$ = 500 GeV center-of-mass energy is very important to open a new window on physics at RHIC, as discussed in section IV (the RHIC Spin program). This opportunity has attracted considerable foreign resources into the RHIC program. The third column in Table III.B.1 illustrates one impact of a constant level of effort budget: the seriously curtailed running time causes a significant delay of the physics program, decreasing the impact of RHIC. In this scenario, the 500 GeV measurements would be delayed until FY10 –FY11.

However, devoting all available resources to data taking is also not the right response to budget pressures. A significant upgrade program is urgently needed to address the compelling physics questions and keep the program robust and competitive. This is a fundamental conflict in developing the RHIC program under a constant level of effort budget scenario.

<table>
<tr><th>Year</th><th>Scenario based on
20-Year Planning Study Goals</th><th>Curtailed Run Example</th></tr>
<tr><td>FY 2005</td><td>Smaller species (3nb^{-1}), pp development</td><td>Smaller species (3nb^{-1}), pp development</td></tr>
<tr><td>FY 2006</td><td>Long pp run ($\geq$150 pb^{-1})</td><td rowspan="2">Long pp run ($\geq$150 pb^{-1}) at 200 GeV, d+Au or
62 GeV Au+Au</td></tr>
<tr><td>FY 2007</td><td>Long d+Au and/or lower energy (3nb^{-1})</td></tr>
<tr><td>FY 2008</td><td>200 GeV Au+Au ($\geq$2000μb^{-1})</td><td rowspan="2">200 GeV Au+Au ($\geq$2000μb^{-1})</td></tr>
<tr><td>FY 2009</td><td>500 GeV pp ($\geq$300 pb^{-1})</td></tr>
<tr><td>FY 2010</td><td>200 GeV U+U (new option)</td><td rowspan="2">500 GeV pp ($\geq$300 pb^{-1})</td></tr>
<tr><td>FY 2011</td><td></td></tr>
</table>

Table III.B.1 Possible running scenarios for the next five years at RHIC

Short-term Detector Upgrades

Upon completion of the volume and energy density scans, further experimental progress requires upgraded detectors. Short-term upgrades utilizing the RHIC baseline luminosity are best targeted at sensitive probes with relatively large cross section. They suffer, however, from limited background rejection capabilities of the current detectors. In particular, low mass di-lepton spectra, identified hadrons at moderate to high p_T, and charm measurements are vital. These address the following compelling issues: the temperature achieved at RHIC, the extent of chiral symmetry restoration, energy loss and thermalization of heavy quarks, and the mechanism of hadronization.

Di-lepton measurements are potentially sensitive both to the temperature evolution and the symmetry properties of the matter. Theoretical calculations indicate that the underlying chiral symmetry of QCD is restored at high temperature, with light quarks becoming essentially massless. It would be a profound discovery to observe such effects experimentally and to elucidate the conditions under which chiral symmetry is partially or completely restored.

Leptonic decays of resonances such as the rho and omega, allow measurement of the medium-induced changes of the resonance masses and widths in dense matter. Since resonance masses track the size of the chiral order parameter, their measurement addresses directly the origin of chiral symmetry breaking, the third fundamental question in the 2002 LRP, (see Section III.A). This critical measurement requires upgrades of the existing detector suite to reject the large backgrounds from hadronic decays. PHENIX will accomplish this using a novel Hadron Blind Detector, while STAR will utilize a new, large Time-Of-Flight detector coupled with the TPC.

The background rejection capabilities will also allow measurement of electron-positron pairs from virtual photon radiation, which should reflect the initial temperature of the system.

Open charm yields will test theoretical predictions that heavy quark jets are not suppressed to the same extent as light quark jets. The extent to which the heavy quarks participate in the collective flow shared by the light quark species will provide an important handle on the thermalization process. Identification of intermediate momentum hadrons will allow study of the modification of jet fragmentation by the strongly coupled medium. To these ends, PHENIX requires a silicon vertex tracker (barrel and end caps) to measure displaced vertices from semi-leptonic decays of charmed mesons and an aerogel detector for additional hadron identification. STAR requires a large acceptance time-of-flight barrel, both to supply hadron rejection for di-electron measurements and to identify 95% of all mid-rapidity hadrons for a broad range of new hadronic measurements. These upgrades, along with the Hadron Blind Detector should be in place before the next long Au+Au run, which is planned to occur prior to the startup of heavy-ion running at the LHC. It does not appear possible to achieve this goal before the LHC startup in a constant level of effort budget (see Section VII. B).

Both large experiments, PHENIX and STAR, can greatly increase their physics reach by addition of detection capability in the forward region. This will allow characterization of the initial state at RHIC through extended rapidity coverage, and increased acceptance for photon-tagged jets for tomographic studies of the medium. Both STAR and PHENIX require forward calorimetry for coincidence studies. The cost of these detector upgrades is discussed in more detail in Section VII.

Opportunities with increased luminosity

Other properties critical to characterizing any plasma include the collision frequency, thermal conductivity, (color-) dielectric properties, radiation rate, radiative-absorptive coefficients and opacity. This information can be accessed experimentally by mapping the interaction of short wavelength probes, namely hard scattered quarks and gluons, with the matter. The recently completed long 200 GeV Au+Au run (run 4), provides greater momentum reach and precision for such phenomena, for instance to carry out tomographic analysis relative to the reaction plane in asymmetric (finite impact parameter) collisions. However, due to the small production cross section of key probes, the full set of essential measurements requires an order-of-magnitude increase in the collider luminosity, as well as enhanced detection and triggering capabilities for the experiments. It is crucial to make these measurements at the unique density and temperature accessed at RHIC where the coupling of the color charges appears to be strong, in contrast to the weaker coupling at the higher temperatures, which may be achieved at the LHC. These are the basis of the RHIC-II project, which includes a luminosity upgrade and related detector improvements.

There are two principal channels in which rare probes offer great benefits. Photons emerge from the collision without significant re-interaction and therefore carry information related to the temperature at the earliest and hottest stages. High momentum photons can be used to tag high momentum-transfer partonic scatterings, thus opening access to calibrated probes of the hot, dense medium. Reconstruction of the jet recoiling against a hard photon will provide the direct measurement of transport properties and definitively establish whether the coupling is indeed strong. The rather low interaction rates of electromagnetic probes, particularly at high momentum, require increased luminosity of RHIC to provide access to these clean plasma diagnostics.

Heavy flavor production is another rare process with unique abilities to probe the properties of the produced matter. The large masses of charm and bottom quarks persist in a chirally restored medium. They introduce new scales to the plasma, overcoming the scale-free nature of a plasma of only light quarks in which all lengths are proportional to the inverse temperature. Spectroscopy of bound heavy quark states is the tool of choice to probe the Debye color-screening lengths in the quark-gluon plasma. Recent investigations of the production of such bound states via coalescence and the temperature dependence of their binding have confirmed the importance of measuring these states at RHIC. Charmonium production rates are small at RHIC and bottonium rates are even smaller, and full exploitation of these crucial probes is unattainable at the current RHIC luminosity. The tremendous analyzing power of these channels argues for a significant luminosity increase to perform quantitative studies of these important signals.

Both large detectors, PHENIX and STAR, will require significant additional upgrades to take advantage of the higher luminosities. The U.S. and international physics communities have made a huge investment, of order $100M, in these detectors. This investment has paid off handsomely in the significance, high quality, and speed of the physics output to date. The partial overlap in capabilities between the experiments, allowing crosschecks that build confidence in the key results, has played an important role in RHIC's success. Continued operation of two experiments helps ensure the outstanding performance of RHIC, at the cost of a modest incremental investment in each detector. The RHIC-II detector upgrades are currently in the conceptual design stage, and require an ongoing R&D program. STAR's upgrade options, beyond the TOF Barrel, include a micro-vertex detector, data acquisition upgrade, enhanced forward tracking, and a fast and compact TPC (with GEM readout) to handle the increased luminosity. PHENIX is developing, beyond the silicon tracker, forward calorimetry, an inner fast TPC for tracking inside the magnetic field, as well as a greatly enhanced muon trigger.

It is natural to ask whether construction of a new detector, based upon insights gained in the first four years of RHIC running and when released from the physical constraints of the existing experiments, might provide greatly improved physics opportunities. The community should consider whether a new second generation detector could enhance the physics opportunities at very high luminosity, even within the expected budget constraints of the planned RHIC-II project. The Subcommittee considers this a serious issue with important consequences, and recognizes that the Electron Ion Collider will also require a new detector. The impact upon the RHIC program of a new detector for heavy-ion collisions instead of, or even in addition to, upgrading the existing detectors should be carefully evaluated. The costs and benefits of a new detector should be quantified after detailed simulation of the detector's physics potential and a thorough cost and performance review by the RHIC detector advisory committee.

III.B.3. Assessment and Recommendations

Searching for threshold effects and energy dependence of the striking new phenomena at RHIC, as well as exploring newly accessible observables, requires scanning additional collision energies and beam species. This is most efficiently and effectively accomplished by operating the facility at least 27 weeks per year, and preferably 31 weeks, to avoid start-up and shutdown end effects.

Modest near-term upgrades will allow measurements of chiral symmetry characteristics, thermal radiation, and the interaction of heavy quarks with the medium. These are vital to addressing the physics questions laid out in the 2002 LRP, which are currently limited by detector performance and background rejection. Modest incremental investments will provide crucial additional physics, taking advantage of the large investments already made in the RHIC accelerator and detector complex. Additional long runs of full energy Au+Au and d+Au collisions will be needed once these upgrades are in place.

For a complete understanding of this physics, it is essential to fully characterize the new matter produced at RHIC and to determine the nature of its coupling with small wavelength probes produced in initial hard scattering. The critical measurements will require more than an order-of-magnitude increase in the collider luminosity due to the small production cross sections, along with enhanced detection and triggering capabilities. These are the basis of the RHIC-II project. The RHIC-II detector upgrades are currently in the conceptual design stage, and require an ongoing R&D program. The luminosity upgrade is a technically challenging problem (see section III.C) and requires investment of R&D funds. It will benefit both the planned Heavy-Ion program and also be applicable toward an eventual electron-ion collider at RHIC.

Recommendation #1:

A new and complex form of dense QCD matter has been discovered at RHIC. The unprecedented flexibility of this dedicated collider, coupled with the detector and luminosity upgrades that provide access to rare probes, will sustain RHIC's unique discovery potential. Consequently, the Subcommittee recommends full exploitation of the existing RHIC facility combined with investment in future research tools. Specifically, RHIC should run for as many weeks per year as possible, compatible with the following:

- **Investment in near-term detector upgrades of the two large experiments, PHENIX and STAR, to take full advantage of the existing accelerator capabilities;**
- **Investment now in accelerator and detector R&D, in preparation for RHIC II, to enable crucial measurements of this new form of dense matter using rare probes;**
- **Construction of the EBIS as quickly as possible to improve the reliability and increase the capabilities of the heavy-ion injection system and to realize the projected reduction in RHIC operating cost.**

The accelerator and detector R&D and the EBIS project are discussed below in Section III.C.

Section III.C RHIC: Collider Upgrades

The RHIC Collider Upgrades program requires major improvements in the accelerator complex. They consist primarily of two major items, the Electron Beam Ion Source (EBIS) and the RHIC II Luminosity upgrade (average luminosity increase approaching a factor of ten) by means of electron beam cooling. The two items are presently at quite different stages of development as discussed below.

III.C.1. Findings

BNL management presented to the Subcommittee plans for two major upgrades of the RHIC facility. Although it is not part of the Subcommittee charge to undertake a detailed technical review of these proposals, one can draw on the conclusions of the Report of the Meeting of the 1st Collider-Accelerator Department (C-AD) Machine Advisory Committee (CAD-MAC), held on March 10-11 2004 and the presentations made to that committee, available at http://www.c-ad.bnl.gov/mac/. The Subcommittee has reviewed that material as far as its resources permit and concurs with the main points of the CAD-MAC report as summarized below.

EBIS

The Electron-Beam Ion Source, EBIS, together with associated pre-injectors, is proposed as a replacement for the aging Tandem Van de Graaff accelerator pre-injectors that are the present source of ions for the RHIC complex. There is a significant potential cost and downtime associated with a failure of one of the Tandem accelerator columns.

This EBIS concept for an ion source has been developed at BNL, culminating in the successful demonstration of a half-size test EBIS source. This model produced half the performance required for RHIC and this result is expected to scale straightforwardly to the full-size system.

The cost of the complete EBIS project, including the RFQ and the 2 MeV/u linac that form the remainder of the proposed new pre-injector system, is estimated at $18M (TPC $18.5M, T. Roser, BNL 6/2/2004), roughly distributed over a construction period of three years, as assumed in Section VII of this Subcommittee Report. The constant level of effort budget developed, assumes an investment by NASA (a BNL user of ion beams for radiation studies) of about $5M (not yet confirmed), a redirection of CE/AIP funds ($5.5M), with the balance of the funds coming from the RHIC operations budget.

The benefits expected from the EBIS source are:

- Increased integrated luminosity from RHIC, thanks to greater reliability and stability and reduced setup time, all contributing to reducing the dead time between stored colliding beams.
- Enhanced flexibility with rapid switching between ion species for handling the simultaneous and various needs of RHIC, the AGS and the NSRL (NASA facility).
- A broader range of ions, including noble gases and uranium, will be available.
- The elimination of two stripping stages and the very long transport beam line between the Tandems and the AGS Booster.
- Injection into the Booster achieved in fewer turns.

- A reduction in operating costs (estimated at ~ \$2M /yr); and the avoidance of an estimated \$6M investment to maintain the reliability of the tandems.

The CAD-MAC concluded that the EBIS is a "comprehensive and convincing proposal" and recommended its construction as soon as possible. They also drew attention to the many repetitive failures of the Tandems in recent years and the time and manpower required to keep them running. They expressed their confidence in the maturity of the EBIS technology.

Electron Cooling for Luminosity Upgrade

The performance of the present RHIC with heavy-ions is limited by transverse emittance growth from intra-beam scattering. The consequent growth of the beam cross-sectional area at the collision points reduces the luminosity lifetime. A beam cooling mechanism to arrest this growth and even reduce the beam sizes at the collision points is the most effective way to significantly increase integrated luminosity. Among possible cooling methods, electron cooling, an established technique practiced at several laboratories, seems the most promising, although optical stochastic cooling is also under consideration.

A short-term improvement program of microwave stochastic cooling of bunched-beam is also under way. If successful, this promises to enhance luminosity by reducing the loss of particles from the RF bucket; it is independent of, and complementary to, electron cooling.

The parameters of an electron cooling system working on bunched beams at the top energy of RHIC go far beyond any previous experience and pose substantial challenges in terms of present beam physics and accelerator technology. For example, cooling power must be increased by about 4 orders of magnitude compared to existing systems for cooling un-bunched beams at low energy. The high power electron beam mandates the use of a superconducting energy-recovery linac (ERL).

BNL has embarked on a vigorous R&D program to establish feasibility and to design an electron cooling system for RHIC. This includes

- Extensive simulation studies on electron cooling.
- Construction of a test ERL.
- Demonstration of a high precision solenoid.
- Demonstration of a suitable CW photo-cathode superconducting RF electron gun.
- Studies of the beam dynamics of magnetized transport.
- Design of a CW superconducting cavity for intense beams.

Initial studies are encouraging but the CAD-MAC drew attention to a number of concerns, including:

- Understanding of the measured emittance growth in terms of the theory of intra-beam scattering.
- Prediction of electron cooling rates and the theory of magnetized electron cooling.
- The interaction of intra-beam scattering, beam-beam effects and electron cooling.
- Magnetized electron beam transport and emittance preservation.
- Mechanical tolerances on the very long superconducting solenoid.
- Diagnostics of the electron and cooled ion beams.
- Photo-injector design and short lifetime of the CsK_2Sb photo-cathode

The CAD-MAC described the RHIC electron cooling scheme as "one of the most complex and challenging accelerator projects". They made a number of recommendations including an increase in resources for some of these studies and a proof-of-principle demonstration of the beam transport scheme. However it is not clear that a suitable facility for such a demonstration exists. In response, the C-AD provided the Subcommittee with a document outlining their responses to the CAD-MAC recommendations.

	Without electron cooling	**With electron cooling**
Au-Au Collisions		
Energy [GeV/nucleon]	100	
Emittance (95%)[(π)μm]	15–40	15–10
β-function at IP [m]	1.0	
Number of bunches	112	
Ions per bunch	1×10^{9}	$(1–0.3)\times10^{9}$
Beam-beam parameter/IP	0.0016	0.004
Peak luminosity [$cm^{-2}s^{-1}$]	32×10^{26}	90×10^{26}
Mean luminosity in store [$cm^{-2}s^{-1}$]	8×10^{26}	70×10^{26}
Polarized Protons		
Energy [GeV/nucleon]	250	
Emittance (95%)[(π)μm]	20	12
β-function at IP [m]	1.0	0.5
Number of bunches	112	
Protons per bunch	2×10^{11}	
Beam-beam parameter/IP	0.007	0.012
Mean luminosity in store [$cm^{-2}s^{-1}$]	150×10^{30}	500×10^{30}

Table III.C.1 Anticipated values of key beam parameters and luminosity gain from electron cooling (source T. Roser).

Although there has been no previous implementation of electron cooling at BNL, active collaborations with specialists in other laboratories are under way. If all the technical problems are overcome, the C-AD estimates luminosity gains as shown in Table III.C.1. The gains for polarized proton operation are more than a factor of three, while for Au-Au the gain in average luminosity might be up to a factor 9.

The present schedule for feasibility studies and R&D followed by construction foresees the electron cooling as operational in the period 2013-2015 (depending on funding profiles) for a total construction cost of about $53M (FY03). The R&D investment for the project (addressed in Section VII.B) requires another $2M /yr over the next five years.

III.C.2. Observations

EBIS

Whether or not medium- and long-term projects such as RHIC II and eRHIC are finally realized, investments already made in the RHIC complex assume that it has many years of operation ahead of it. Despite being a relatively high-cost item, the EBIS source is a prudent, cost-effective and, very likely, essential upgrade for the complex, laying a firm foundation for the future program. Continuing with the present pre-injectors carries risks for the RHIC program and could well turn out to be more expensive.

Electron Cooling for a RHIC Luminosity Upgrade

The C-AD, anticipates that feasibility of the electron cooling system will be established by the end of 2006. If funding was immediately available, design could begin in 2007, construction in 2008 with R&D continuing through 2009. It is anticipated that construction will take about five years so that initial operation might begin in the period 2013-2015, depending on funding. The feasibility study and R&D on the electron cooling systems for the RHIC Luminosity Upgrade has possible future application at an Electron-Ion Collider.

III.C.3. Assessment and Recommendations

EBIS

The Subcommittee recommends the construction of the EBIS source as an over-riding priority as soon as technically and fiscally feasible.

Electron Cooling in RHIC

In view of the physics potential of the RHIC Luminosity Upgrade (see Section III.A and III.B) and its possible future application at an Electron-Ion Collider (see Section V.B), the Subcommittee recommends the continuation of the R&D work aimed at establishing the feasibility of electron cooling in RHIC and at developing key components of the system. This review has not addressed cost and schedule issues related to the actual construction of this luminosity upgrade.

The two actions recommended above are included in Recommendation #1 as presented in Section III.B of this report.

Section III.D LHC: Heavy-Ion Program

III.D.1 Physics Impact of the LHC Heavy-Ion Program

The LHC energy of 5.5 TeV per nucleon pair for Pb+Pb collisions exceeds that of RHIC by a factor 30. This is a larger increase than that from the SPS to RHIC. As a result, significant quantitative evolution of the phenomena seen at RHIC is expected, together with the appearance of qualitatively new phenomena. Heavy-ion experiments at the LHC are expected not only to extend developments first explored at RHIC but also to discover new aspects of QCD matter at extremely high energy. There are at present two classes of questions where the extended reach of the LHC is expected to make a significant contribution to our understanding:

a. **Characterizing the initial state from which dense matter emerges**
RHIC measurements have established that the matter produced in heavy-ion collisions is very dense. The characteristic low-momentum modes of the matter emerge from a large number of partons, each carrying very small momentum fractions x in the incoming nucleus. However, the dynamics which lead from the initial state to equilibrated matter is not understood at present. Experiments at the LHC will extend the accessible kinematic range of momentum fraction x by at least three orders of magnitude, providing unprecedented opportunity to study small-x dynamics in a regime where theory expects that saturation effects may play a crucial role. It is even conceivable that the matter produced at LHC at mid-rapidity will be dominated by saturation physics – a qualitative feature which is not realized at RHIC energies, underlining the complementarity of the RHIC and LHC physics programs.

b. **Characterizing the produced dense matter with copiously produced hard probes**
RHIC measurements have established that hard processes provide novel and highly sensitive tools for characterizing the properties of the produced dense matter. The much higher collision energy at the LHC will provide a larger variety of these probes with significantly wider kinematic reach than at RHIC (typically one order of magnitude in transverse momentum) and with significantly larger abundance (cross sections for many rare processes increase by two order of magnitude). This will give access to qualitatively new observables. For instance, the much wider kinematic reach enables full reconstruction of jets with reasonable energy resolution above the heavy-ion background (there is a significant yield at the LHC for jets with $E_T > 200$ GeV). Also, there are significant yields of very hard photons ($E_T >$ 50 GeV) and Z-bosons, enabling photon-jet and Z-jet correlation studies for precise characterization of the produced matter. High production cross sections turn bottonium spectroscopy into a precision tool for characterizing the screening scale of deconfined matter: LHC experiments expect a one month run at design luminosity to measure Y, Y' and Y'' bound states with a good signal-to-background ratio. It will be important to correlate these signals with the widest possible range of soft physics phenomena sensitive to the bulk properties of the medium.

Significant changes are expected at the LHC relative to RHIC in the key parameters controlling the properties of the dense QCD matter generated in the collision, in particular higher energy density and longer lifetime. Observables at low and intermediate transverse momentum such as yields, elliptic flow, and correlations are expected to reflect these changes.

In summary, experiments at RHIC and LHC will vary over a broad range, the initial energy density and lifetime which control the properties of produced QCD matter. Utilizing similar measurements and analysis strategies as those employed at RHIC, experiments at the LHC will yield complementary information about the properties and dynamics of dense matter in a different region of density and temperature. Because of the much wider kinematic range, experiments at the LHC will extend significantly the tools for the characterization of dense matter and its dynamical generation.

III.D.2 Experiments at the LHC

Heavy-ion physics is an integral part of the planned LHC experimental program. At the time of writing, CERN management anticipates that the LHC will begin operations with p+p collisions at $\sqrt{s}$ = 14 TeV center-of-mass energy in 2007, followed by Pb Pb collisions at 5.5 TeV per nucleon pair in 2008. After normal operations are established, it is anticipated that the LHC will operate for about 8 months per year for proton running and one month/year for the Heavy-Ion program. All three large LHC detectors (ALICE, ATLAS and CMS) intend to participate in the LHC heavy-ion runs. Together, their measurement capabilities cover the broad range of observables necessary for complete investigation of high density QCD matter, from the collective hydrodynamic regime at low p_T to the hard perturbative QCD region at high p_T.

The design luminosity for Pb+Pb collisions is 1×10^{27} cm^{-2}s^{-1}, though the luminosity in the first year of running will be lower (~5×10^{25} cm^{-2}s^{-1}). Although not included in the initial LHC baseline program, collisions between identical beams of light ions and p-Pb collisions are envisaged at a later stage, with design luminosities up to ~10^{29} cm^{-2}s^{-1}. It is clear from the RHIC experience that it is important, in addition to studying A-A collision, to make p-A normalization runs at the same $\sqrt{s}$.

In the following sections, the heavy-ion measurements planned by each collaboration are discussed. It should be noted, however, that the Subcommittee did not evaluate in detail the technical capabilities and cost estimates of the three U.S.-LHC related projects which have been submitted to DOE by U.S. researchers interested in this facility. The key parameters from these projects are provided in order to help gauge the aim, scope, and cost of possible U.S. participation in the LHC Heavy-Ion program. In the context of allocating research-operating costs to groups at U.S. universities and national laboratories, it should be understood that the largest component would be derived from the redirection of current allocations from the RHIC program toward the new LHC activities. Scenarios for U.S. participation at reduced cost were not considered in the documentation and presentations to the Subcommittee.

a. **ALICE**
   The ALICE detector was designed explicitly for heavy ion measurements at the LHC, with capabilities at high multiplicity density that include good tracking performance, broad hadronic PID capabilities, good acceptance at low p_T, and substantial muon measurement coverage. ALICE will carry out an extensive and varied program of heavy-ion measurements.

ALICE utilizes the existing large L3 solenoidal magnet. The central tracking device is a Time Projection Chamber (TPC, $|\eta|<0.9$), with additional high precision tracking supplied by the inner silicon barrels. Good tracking efficiency and momentum resolution in a heavy-ion environment are achieved over a broad momentum range, from soft hadrons (p_T~0.15 GeV/c) to hard jet fragments (p_T ~100 GeV/c). Special emphasis is put on hadronic particle identification over a wide p_T range, well into the jet fragmentation region. ALICE has good electron and muon coverage, together with a highly granular but small acceptance lead-glass photon spectrometer (PHOS, granularity $\Delta\eta\Delta\phi$=0.004x0.004).

The ALICE baseline design does not include large calorimetry coverage, resulting in limited ability to trigger on jets and to reconstruct jets with good energy resolution. A proposal has been developed by the U.S. ALICE group for a large electromagnetic calorimeter (EMC) in ALICE, with a design based on the existing STAR EMC. The proposed ALICE EMC coverage is $|\eta|<0.7$, $|\Delta\phi|<120$ degrees, placed opposite in azimuth to the PHOS, with granularity $\Delta\eta\Delta\phi$=0.013x0.013. Construction of the EMC would augment ALICE's capabilities significantly, enabling jet triggering to the highest available jet E_T and improving the jet energy resolution markedly. In the context of the entire LHC Heavy-Ion program, the unique roles of an EMC in ALICE will be in the correlation of jet observables with a broad array of soft bulk phenomena and in the detailed study of jet fragmentation using identified hadrons.

The author list of the ALICE-USA proposal comprises 53 individuals, most of whom are currently active in the field of relativistic heavy-ion physics. The EMC construction project would give the ALICE-USA group a central role in ALICE, with significant impact on both the hardware and the physics. The Subcommittee has not reviewed the construction costs estimated, for equipment, at $11M. The ALICE-USA total participation costs through FY10 are estimated at $13M. Staging scenarios and physics consequences of a device with reduced acceptance were not considered in the documentation and presentation to the Subcommittee.

b. ATLAS

ATLAS is one of the two large LHC experiments designed for high luminosity p+p collisions, to search for the Higgs particle and physics beyond the standard model and to carry out precision measurements of processes within the standard model. It has a high precision inner tracking system for charged particle measurements ($|\eta|<5$); hermetic, highly granular hadronic and electromagnetic calorimetery ($|\eta|<5$); and extensive muon detection capabilities. ATLAS will measure electrons, muons, photons, and jets up to the highest available energy. While the design of ATLAS emphasizes hard probes, its inner tracking system has been shown to perform well in the heavy-ion environment for p_T >1 GeV/c. Optimization of its performance at lower p_T is still under investigation. Hadronic particle identification is limited.

The proposed heavy-ion physics program of ATLAS concentrates on partonic energy loss via jet measurements, including heavy quark jets and jets recoiling from a hard photon or Z^0, and quarkonium suppression. The extensive forward instrumentation enables measurements at low x (~10^{-5}) in p+A collisions, where gluon saturation may dominate the dynamics. There is interest in studying ultra-peripheral collisions, which requires the addition of a Zero Degree Calorimeter (ZDC).

The ATLAS heavy-ion group currently comprises about 25 scientists, of whom approximately half are from U.S. institutions and are currently active in heavy-ion physics. The U.S. group will play a leading role in the ATLAS Heavy-Ion program. For heavy-ion running the only needed hardware addition to ATLAS is the ZDC, while high-level trigger algorithms and offline tracking and jet reconstruction must be optimized for the heavy-ion environment. The total participation costs (including redirection of research operating funds) through FY08 are estimated at $6.6M, consisting mainly of manpower costs. Equipment cost for the ZDC is estimated at $500K.

c. CMS

CMS is also designed for high luminosity p+p running, with goals and capabilities similar to those of ATLAS and, as such, is focused on a search for the Higgs particle and physics beyond the standard model and is preparing to carry out precision measurements of processes within the standard model. CMS puts special emphasis on measuring muons with high precision. Highly granular hadronic and electromagnetic calorimetry will cover broad phase space ($|\eta|<5$). CMS has extensive capabilities in the very forward direction, with additional calorimetry and tracking out to η~7, corresponding to x~10^{-7} at Q^2 ~ few GeV^2. The high precision inner silicon tracker has been shown to perform well in the high multiplicity heavy-ion environment, with good efficiency at p_T ~ few hundred MeV/c and good resolution (~few percent) to the highest available p_T. Hadronic particle identification is limited.

The main goals of the CMS Heavy-Ion program address partonic energy loss via jet measurements, including heavy quark jets and jets recoiling from a hard photon or Z^0, and on quarkonium suppression (similar to ATLAS). The Heavy-Ion program has been active for several years at CMS. Simulation studies have demonstrated that CMS can measure jets and their modification in the heavy-ion environment and that muon pair mass resolution is sufficient to separate the Upsilon states. The extreme forward coverage gives CMS unique physics reach in p+A collisions, probing very low x~10^{-7}.

The U.S. CMS group presently includes about 30 individuals from U.S. institutions who work in the field of ultra-relativistic heavy-ion physics. This number is expected to grow to about 50 by the time of LHC startup, and will comprise about half of the CMS heavy-ion effort. The U.S. group has taken the lead role in the CMS heavy-ion program, carrying out extensive feasibility studies. The U.S. CMS group is proposing to facilitate the CMS Heavy-Ion program by contributing a Zero Degree Calorimeter and providing computer resources for the High Level Trigger (online trigger farm) and other aspects of the data acquisition system (DAQ). Total participation cost through FY10 is estimated to be $7.5M, of which about $3M is for capital equipment and $1.5M is for computing.

III.D.3. Assessment and Recommendations

The Subcommittee believes that the Heavy-Ion program at the LHC offers a significant new opportunity for identifying new physics phenomena. There are very strong scientific arguments for a U.S. participation in the LHC Heavy-Ion program (see Section III.A). In addition, such participation would strengthen the long-term health of the relativistic Heavy-Ion program in the U.S. by ensuring the continued active scientific and personnel exchange between the RHIC and LHC programs. The funding agencies should make every effort to enable a U.S. role of high scientific impact in this program.

The Subcommittee notes that participation by the U.S. community in the Heavy-Ion program at the LHC would be heavily leveraged by the substantial contribution ($531M), which the U.S. has made to the construction of the LHC facility and its detectors. DOE-HEP has contributed $250M to the two detectors (ATLAS and CMS) and $200M to the accelerator. The NSF has contributed $81M to ATLAS and CMS.

In summary, the LHC offers outstanding opportunities for new discoveries in relativistic heavy-ion physics, driven by a large increase in center-of-mass energy that generates different initial conditions and a larger kinematic reach for hard probes. The two different programs envisioned for RHIC and the LHC would provide a synergy important for global understanding of the properties and dynamics of dense QCD matter. The diverse measurements at RHIC with heavy-ion and proton beams provides an opportunity for systematic investigation of the properties of the dense QCD matter while the LHC program focuses on high Q^2 and low x measurements. It is important that a p+A program, which has proven so important at RHIC, be developed at the LHC.

Recommendation #2:

The LHC will open up a new regime in relativistic heavy-ion physics with significant opportunities for new discoveries. The Subcommittee recommends that:

- **Participation at the LHC should become a new component of the U.S. Heavy-Ion program;**
- **This participation should receive comparable investment priority with the near-term upgrades for each of the two large RHIC detectors.**

The Subcommittee has not attempted to formulate the optimum path among the three detectors for an effective U.S. participation in the collaborations at the LHC. In the context of Recommendation #2, the Subcommittee strongly encourages the U.S. institutions involved, to define and pursue the physics opportunities that the LHC makes possible. Since construction of the facilities at the LHC are well advanced, the Subcommittee recognizes that in order for the U.S. to have maximum impact in the LHC collaborations, it is critical to empower the U.S. participants as soon as practical.

Section IV. Nucleon Structure: RHIC Spin Program

IV.A. Introduction

While the RHIC Spin program shares common facilities with the Heavy-Ion program, the focus of the physics is quite different. Relativistic heavy-ion physics studies dense QCD matter, while spin physics aims at more completely and deeply understanding the structure of the nucleon.

The three primary objectives of the RHIC Spin program are as follows:

1. **Determination of the gluon polarization, *ΔG*, of the proton.**
   The relativistic constituent quark model predicts that the sum of the quark spins should be close to the total spin of the proton. However, detailed studies of polarized deep-inelastic scattering have shown that the spin of the quarks and anti-quarks within the proton contributes only about one-fourth of its total spin. The remainder must arise from the spin of the gluons within the nucleon or from orbital motion of the quarks and gluons. Gluons are responsible for most of the mass of the proton and carry approximately half of the momentum of the proton's constituents. Thus it is important to make a high quality measurement of ΔG over a broad rand of x. If a moderately large value of ΔG is measured, the apparent spin deficit could be attributed to the axial anomaly (Adler-Bardeen scheme). On the other hand, a small observed value of ΔG would imply large contributions from the partonic orbital angular momentum.

2. **Determination of the flavor structure of the quark polarizations.**
   This is important for understanding the role that sea quarks play in the binding of the proton, i.e., the evolution from current to constituent quarks. Spin-independent deep-inelastic scattering experiments have determined that quark-antiquark pairs (the sea) are common in the proton. There are at present two types of experiments, which have furnished information on this key issue. Muon-scattering experiments at CERN and, especially, muon-pair production in Drell-Yan scattering at Fermilab have measured a significant difference between the $\bar{u}$ and $\bar{d}$ distributions of the proton, suggesting that the $\bar{u}$ and the $\bar{d}$ are not just spectators in the proton. On the other hand, experiments at JLab and at Bates have found, at best, a very small contribution of strange quarks to the proton form factor, which suggests that strange quark pairs are limited to short-distance fluctuations. If sea quarks actively participate in the binding of the proton, they are also expected to share the polarization of the proton, and thus a determination of the flavor structure of the sea quark polarization should add an essential new piece of information on the role of sea quarks in the nucleon.

3. **Measurement of transversity.**
   Transversity, the tendency of a quark or anti-quark to be polarized parallel to a transversely polarized proton, is a leading-twist property of the nucleon. Unlike the longitudinal polarization, there is no mixing between quarks and gluons. The first moment of the transversity distribution defines the tensor charge of the proton. However, very little is known about transversity because it is chiral-odd and, hence, is not measurable with inclusive deep-inelastic scattering. Rather, transversity measurements must include a second chiral-odd process. Although there is great theoretical interest in transversity, so far very limited data have been collected. One

can expect that a good measurement from RHIC will stimulate further theoretical interest in trying to better understand and interpret this quantity as discussed below.

IV. B. Findings

The 2002 Long-Range Plan identified the goal of unraveling the spin components of the proton as "one of the most important open questions in hadronic physics". Furthermore, it noted that "the coming years afford an outstanding opportunity to tackle this question" through:

- Direct measurements of gluon polarization
- Determination of the flavor structure of the quark-antiquark polarization
- Transversity measurements

The RHIC Spin physics program anticipates using polarized proton collisions to perform measurements in all three of these areas during the coming years.

RHIC is the first-ever polarized hadron collider and the only available source of very high energy polarized protons. There has been remarkable progress at RHIC, which has produced collisions between polarized proton beams at $\sqrt{s}$ = 200 GeV beginning in Run 2, with transversely polarized protons. Beginning with Run 3, spin rotators were commissioned that allow PHENIX and STAR independently to select transverse or longitudinally polarized protons at their respective interaction regions. Recently, STAR published first results for transverse single-spin asymmetries for forward inclusive π^0 production, and PHENIX is publishing results for longitudinal double-spin asymmetries for mid-rapidity inclusive π^0 production.

Over the next several years, PHENIX and STAR plan measurements of gluon polarization through longitudinal double-spin analyzing power measurements in a broad range of channels:

- inclusive π^0 production
- inclusive jet production
- direct photon production
- photon + jet coincidences
- heavy flavor production

Both collaborations plan to proceed through a sequence of observables from the simplest to the most challenging, as the proton beam luminosity and polarization at RHIC increase. The various measurements will permit important crosschecks to be performed among channels that have very different sensitivities to systematic effects. Taken together, these measurements will determine ΔG directly as a function of Bjorken-x over the range $0.01 < x < 0.2$ and will provide additional constraints on ΔG down to $x \sim 0.001$. This broad kinematic range, facilitated by the high $\sqrt{s}$ at RHIC, far exceeds that available at any other existing facility. Overall, this program is expected to provide the most comprehensive measurement of gluon polarization for the foreseeable future.

Most theoretical calculations that attempt to explain the flavor-dependence of the anti-quark sea in the nucleon predict that the sea should also be polarized. Relatively little is known from experiment about anti-quark polarization in the nucleon. To date, this has been determined from semi-inclusive deep-inelastic scattering measurements and global fits. PHENIX and STAR both plan measurements of the longitudinal single-spin analyzing power for $W^{\pm}$ production after RHIC demonstrates the capability of colliding polarized protons at $\sqrt{s}$ = 500 GeV. This will provide far

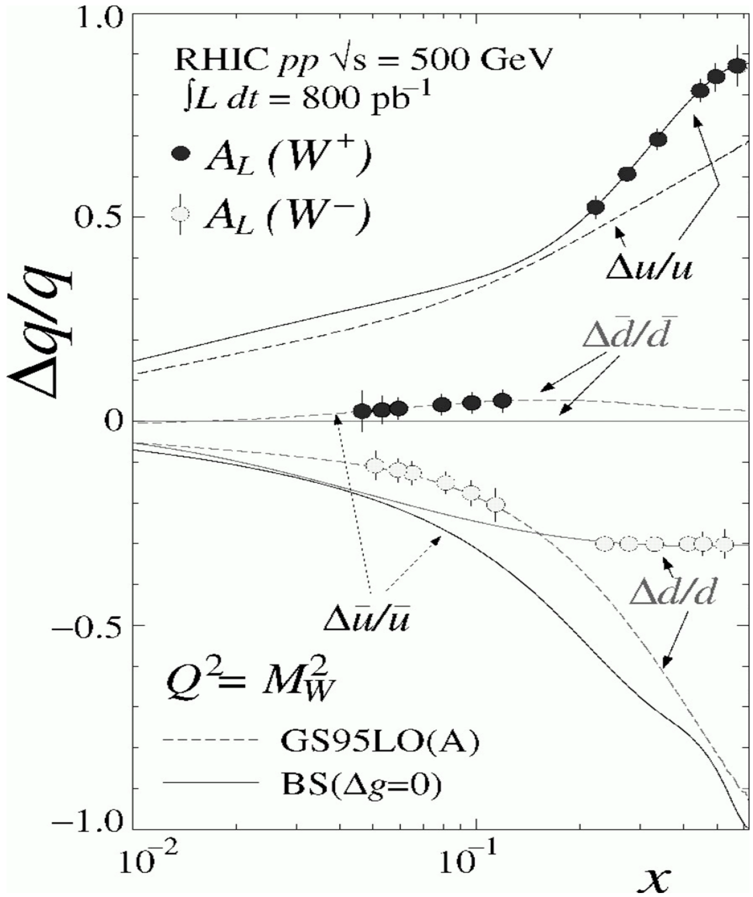

Figure IV.B.1 Expected sensitivity for the flavor-decomposed quark and antiquark polarization, overlaid on the parton densities as a function of momentum fraction, *x*. [G. Bunce et al, Annual Review of Nuclear and Particle Science, vol. 50, p 525, Dec 2000]

more detailed determinations of the polarizations of the $\bar{u}$ and $\bar{d}$ anti-quarks in the proton than has been practical to date, as well as new information about the polarization of *u* and *d* quarks. This is illustrated in Fig IV.B.1 where the expected sensitivity for quark and antiquark polarization is compared to parton densities verses *x*, as estimated for PHENIX muon data for a run of 800 pb^{-1}

Furthermore, 500 GeV operation will be important for measurement of gluon polarization at small momentum fractions, *x*.

The RHIC Spin program also includes transverse spin asymmetry measurements. PHENIX and STAR plan to utilize the Collins effect and interference-fragmentation functions as "analyzers" to explore transversity in the proton. Meanwhile, the Sivers effect, which represents the tendency for a parton to have a k_T perpendicular to the spin of a transversely polarized proton and is closely related to partonic orbital motion, can be a competing process to the Collins effect. At RHIC, the Sivers effects will be identified by measuring the $\Delta\phi$ distribution of the transverse spin asymmetry in back-to-back jet production.

IV.C. Observations

During the past few years, C-AD and the RHIC experiments have been developing the infrastructure necessary to perform high precision polarization measurements in the new environment of a polarized hadron collider. The figure of merit for double-spin analyzing power measurements is P^4L. Systematic improvements in performance throughout the RHIC complex during the past few years have led to significant improvements in both polarization and luminosity. The commissioning of the polarized gas jet target this year also means the tools are now in place to perform precision measurements of the absolute polarization of the beam at store. Current C-AD projects that address further injector and accelerator improvements will lead to additional increases in the integrated P^4L at 200 GeV. These will result in a net increase in the figure of merit by a further factor of ~140, with the proton polarization at store reaching 70% in 2007 and the average luminosity during a store reaching 6×10^{31} $cm^{-2}s^{-1}$ in 2008.

In parallel with the accelerator improvements, PHENIX and STAR have been commissioning the necessary detectors and developing the necessary local polarimetry and luminosity monitoring techniques for the gluon polarization measurements. Both experiments now have the tools in place to take advantage of the improvements in P^4L as they are delivered by C-AD over the next several years. It is anticipated that measurements of A_{LL} for inclusive π^0 and inclusive jet production will be carried out during 2005 and will provide significant new constraints on gluon polarization. They will be followed by direct photon and photon + jet coincidence measurements. The photon + jet measurements, which will provide the most detailed information on $\Delta G(x)$, will require an integrated luminosity of 150-300 pb^{-1} at 200 GeV with a polarization of 70% to reach their goal for sensitivity. Heavy flavor measurements of gluon polarization will also be carried out. However, the heavy flavor studies will require the proposed detector upgrades to identify displaced vertices in order to achieve their maximum sensitivities. Both PHENIX and STAR are ready to intersperse brief transverse spin runs amidst the dominant longitudinal spin running.

The W-asymmetry measurements will require significant further improvements in both the accelerator and the detectors. To reach the target sensitivity, an integrated luminosity of 500-800 pb^{-1} will be needed at 500 GeV with a polarization of 70%. Thus, RHIC will need to provide pp collisions at full energy, 500 GeV, with high polarization and luminosity. At present, C-AD has plans designed to reach these goals over the next several years. However, 500 GeV polarized pp running presents a new frontier for RHIC, so the plans will need to be demonstrated experimentally. Meanwhile, both experiments require detector upgrades for sensitive measurements of the W-asymmetry. PHENIX will require an upgrade to its muon trigger system to match the input bandwidth of its data acquisition system. STAR will require an upgrade to its forward tracking capabilities in front of the Endcap Electromagnetic Calorimeter to provide reliable charge-sign determination for the W decay events.

IV.D. Assessment and Recommendations

RHIC has opened a new frontier in spin physics studies as the first ever polarized hadron collider. Significant progress has been made by the BNL/C-AD in the acceleration of polarized protons. Continued improvements at 200 GeV in beam polarization and luminosity, as well as the development of a 500 GeV capability for polarized proton collisions, are required in order for the RHIC Spin program to achieve its full potential.

RHIC is poised to provide definitive measurements of gluon and flavor-separated quark and anti-quark contributions to the proton spin over the coming years. These measurements are outstanding opportunities to address fundamental questions regarding the structure of the nucleon.

The muon trigger upgrade for PHENIX and the forward tracking upgrade for STAR are required to take full advantage of the *W*-asymmetry measurements at 500 GeV.

With its polarized proton capability combined with very high energy, the RHIC Spin program provides an outstanding and unique opportunity to investigate the spin structure of the proton in both the gluon and the quark-antiquark sectors. RHIC's goals go well beyond current and expected results at other facilities.

Recommendation #3:

Among high energy accelerators, RHIC is poised to become the premiere hadronic physics facility, through the study of the spin structure of the proton with a unique polarized proton capability. In order to ensure the success of the RHIC Spin program, the Subcommittee recommends that:

- **Polarized proton-proton running remain an essential part of the RHIC program;**
- **In the near term, polarized proton-proton running time be sufficient to allow the first significant measurement of the gluon polarization;**
- **Accelerator and detector improvements proceed at a rate that allows a timely determination of the flavor dependence of the polarization of the quark-antiquark sea through W-asymmetry measurements at 500 GeV.**

Section V. Electron-Ion Colliders

V.A. Physics of the Electron-Ion Collider

The 2002 NSAC Long-Range Plan identified an Electron-Ion Collider (EIC) as a new accelerator concept with "great promise" to test with much greater precision our understanding of the quark and gluon constituents of nucleons and nuclei. EIC would provide collisions between polarized electron beams and polarized proton beams or nuclear beams at substantially higher $\sqrt{s}$ than practical at fixed-target facilities and substantially higher luminosity than achieved in previous colliders. The planned physics program at EIC is extremely broad. It includes:

- **Quark and gluon distributions in the nucleon and nuclei**: EIC will measure flavor-tagged structure functions of the proton, neutron (via d and ^{3}He beams), and nuclei through studies of semi-inclusive reactions. This will provide a detailed decomposition of the parton densities in the nucleon over a broad kinematic range into the separate contributions from up, down, and strange quarks as well as gluons. Comparisons between ep and ed scattering and eA scattering will also demonstrate how these partonic contributions change in nuclei with greater precision and over a much broader kinematic region than has been practical to date.

- **Spin structure of the nucleon**: EIC will provide information about the proton's spin-dependent structure functions at lower x than possible in any previous experiment. It will also provide information about the neutron's spin-dependent structure functions through measurements with polarized nuclear beams. The collider energy provides the lever arm, relative to fixed target energy, to precisely measure scaling violation in the spin-dependent structure functions, due to gluon polarization. Both are important and complementary measurements to the RHIC Spin measurements of gluon polarization with other probes.

- **Correlations between partons**: EIC will provide unprecedented information about the correlations between partons in nucleons and nuclei through studies of generalized parton distributions (GPD). GPDs, which will be measured in hard exclusive reactions, will provide qualitatively new information about hadron and nuclear structure because they provide direct access to partonic amplitudes.

- **Partonic matter under extreme conditions**: EIC will explore the partonic structure of nuclei to very low x, well into the regime where the gluon density is expected to saturate. Thus, it will be an ideal laboratory for precision investigations of a color glass condensate.

- **Hadronization in nucleons and nuclei**: EIC will be a precision tool to study the non-perturbative process by which an energetic quark evolves into a collection of final-state hadrons, i.e., a jet, as well as the modification of this process as the energetic quark propagates through finite nuclei. This will provide a deeper understanding of the confinement process.

All of these topics are important for our understanding of QCD and the hadronic structure of matter. Generalized parton distributions (GPDs) and the low-x structure of the large nuclei are especially interesting in that they furnish a new, and complementary, view on parton distributions and the initial state of heavy-ion collisions, respectively.

Ordinary parton distributions give the single parton (quark or gluon) densities in a nucleon or nucleus. These densities are given as a function of the longitudinal momentum fraction, x, of the nucleon's momentum carried by the parton as well a scale, Q^2, representing the scale at which the parton is probed. However, these parton densities carry no information on the coordinate-space distribution of the quarks and gluons with respect to the center of the nucleon. GPDs, because they correspond to the non-forward amplitudes, carry information on the spatial distribution of partons in the nucleon. One passes to a coordinate space distribution, for a given x and Q^2, by a simple Fourier transform of the transverse momentum dependence. Currently there are rough measurements of the transverse coordinate distribution of gluons from HERA, using vector meson production, and one can expect good measurements for valence quarks to come from the Jefferson Lab. However, the EIC will have two significant advantages compared to the current effort at fixed-target facilities: i) the higher $\sqrt{s}$ will permit measurements over a much broader kinematic region, and ii) the collider geometry is much better suited for a complete characterization of the final state fragments, which is an essential component of GPD measurements.

If the center-of-mass energy is high enough, the EIC will be an excellent facility for studying the Color Glass Condensate (CGC) through gluon saturation in the low-x wave functions of heavy nuclei. The CGC in large nuclei may determine the initial state in heavy-ion collisions, and could allow calculation from first principles of the first step in the evolution of the quark-gluon plasma from the initial non-equilibrium system. EIC measurements would complement the studies that will be performed in d(p) + A collisions at RHIC and the LHC, reaching a smaller x, and thus allowing a comparison between the electron and hadron probes and providing a precision not achievable in p + A collisions alone.

V.B. Observations

The 2002 Long-Range Plan noted "there is a strong consensus among nuclear scientists to pursue R&D over the next three years to address a number of EIC design issues." At present, this R&D focuses on two candidate designs for EIC: eRHIC at BNL and ELIC at Jefferson Lab. The current eRHIC proposal is to add an electron ring to the existing RHIC complex. The current ELIC proposal includes the construction of a proton and light ion accelerator in addition to electron and ion rings at the Jefferson Lab site. Each proposal contains attractive features. eRHIC would reach higher center-of-mass energies and would provide electron collisions with the heaviest nuclei. ELIC would achieve higher luminosity and would provide significant flexibility for detectors implemented at multiple interaction regions.

BNL and JLab provided status reports on both eRHIC and ELIC. Much of the critical R&D for these two proposals is underway at MIT and Jefferson Lab, respectively, funded through the medium-energy nuclear physics program. However, electron cooling of energetic ion beams is a central component of both proposals. The eRHIC requires electron cooling for the high-Z ion beams that will be used in many of the nuclear studies. It also may enhance eRHIC by providing a luminosity boost for the light-ion beams through pre-cooling which will reduce the beam emittance prior to acceleration. ELIC requires electron cooling to achieve the very high luminosities that are its hallmark.

As discussed in Section III.C electron cooling of energetic ion beams is a critical enabling technology for the RHIC II project. Thus, the electron cooling R&D that is underway at present within C-AD is an essential contribution to the EIC R&D effort, independent of the ultimate resolution of the two EIC options.

V.C. Assessment

The Electron-Ion Collider has the potential to be a world-leading center for hadronic physics. A substantial R&D program on electron cooling of energetic ion beams is underway in preparation for RHIC II. Electron cooling is also one of the enabling technologies for EIC. The Subcommittee regards this as another strong motivation for the electron cooling R&D program within C-AD as included in Recommendation #1.

Measurements in the RHIC Spin program and the RHIC/LHC Heavy-Ion programs, including asymmetric collision measurements, will clarify the importance of future high-precision studies of the partonic structure of nucleons and nuclei at EIC. The Subcommittee strongly encourages the further development of the scientific case for EIC in advance of the next NSAC long-range plan.

Section VI. Auxiliary Topics

VI.A GSI: Heavy-Ion Collisions at SIS300

VI.A.1. Findings

The GSI laboratory in Darmstadt, Germany, has obtained approval to construct a new 300 Tm synchrotron (SIS300) which operates in fixed target mode and will accelerate heavy-ions such as Au or U to energies of up to 35 A GeV (45 A GeV for N=Z nuclei). The relativistic heavy-ion collision program at SIS300 is one of five different physics programs using SIS300 beams, which can be explored simultaneously. The SIS300 is projected to become operational in 2013, i.e. about 5-6 years after LHC start-up and roughly at the same time as the planned RHIC luminosity upgrade. Beams will be available for a large fraction of each year for a dedicated heavy-ion collision program. The Au beams at the SIS300 will be about 25 times more intense than the Pb beams at the CERN SPS.

The maximum beam energy for the SIS300 has been designed to allow exploration of collisions at maximum net baryon density. Maximum compression of baryons is predicted by transport models, to occur at beam energies around 10 A GeV. In Pb-Pb collisions at the CERN SPS, near the lowest energies available at that machine (20-30 A GeV), evidence for non-monotonic beam energy dependences were found for a number of observables involving strange particle production. One of the goals of the SIS300 heavy-ion collision program is to explore whether these features are related to the chiral and color deconfining phase transition at high baryon density. The threshold for charm production in p+p collisions is 12 GeV. Thus the SIS300 energy range permits one to explore medium effects on charm production at high net baryon density. For example one could study, to the extent possible, the mass modification of open charm mesons due to a reduced chiral condensate or to J/Ψ suppression due to color de-confinement. Furthermore, lattice QCD calculations predict that the quark-hadron transition changes from a first order phase transition at high baryon density to a smooth but rapid crossover at low net baryon density, ending in a critical endpoint whose location in the temperature/baryon density phase diagram may be accessible at SIS300 energies. The SIS300 heavy-ion research program aims to search for and explore this critical endpoint.

To perform these studies, a new large acceptance detector, CBM, is planned. It tracks and identifies hadrons and electrons with a variety of techniques (silicon pixels/strips, RICHs and TRDs) and identifies neutral pions, photons, eta mesons and muons with an electromagnetic calorimeter. Open charm decays are directly identified through their displaced lepton production vertex. A fast trigger and high-speed data acquisition system should allow the detector to cope with an unprecedented 10 MHz heavy-ion collision rate.

VI.A.2. Observations

Heavy-Ion collisions in the beam energy region of 2 to 40 A GeV were previously studied at the Brookhaven AGS and CERN SPS, although only one long (6 week) 40 GeV run and two short (3-4 day) runs at 20 and 30 GeV were performed at the SPS. The J/psi suppression experiment, NA50, at the SPS, did not participate in the low energy runs due to low di-muon rates at such energies. None of the AGS experiments had the capability to measure di-lepton and photon spectra.

Detailed studies of rare observables such as thermal di-leptons or charmed hadrons require a dedicated research program at very high luminosity. Because of the strong beam energy dependence of charm production cross sections near threshold, charm production studies at the SIS300 energies require a capability to take data at huge collision rates (10 million events per second) using efficient triggers

While RHIC and the LHC aim to create the highest temperatures at almost vanishing net baryon density, the planned Heavy-Ion program at SIS300 complements this approach by exploring the high baryon density part of the QCD phase diagram. Many of the ideas motivating the SIS300 research program arise from the common pool of theoretical work dealing with the physics of color deconfinement and the QCD phase transition. In addition much of the planned CBM instrumentation is inspired by technology developed for RHIC and LHC experiments. The continued exchange of ideas between the RHIC/LHC and SIS300 communities will thus be an important asset to the field and contribute to the health of relativistic heavy-ion physics internationally.

VI.A.3. Assessment

At the present time it is too early to assess the extent of possible future interest by U.S. groups in participating in the CBM experiment. The physics addressed by SIS300 is fundamentally interesting, but as this program revisits a previously explored region (albeit with new tools and much higher precision), its discovery potential for fundamentally new phenomena may be perceived as smaller than that of RHIC and the LHC.

At this time the Subcommittee does not anticipate any need for financial support of GSI heavy-ion physics in the years 2006-2010. Should such a need arise at a later stage, it should be subjected to reevaluation of priorities by the funding agencies.

Section VI.B Fermilab: Proton-Antiproton Collisions

VI.B.1. Findings

The Subcommittee looked into future initiatives at the Fermilab Tevatron whose physics goals might overlap those of the Heavy-Ion programs at RHIC and the LHC. A potentially relevant initiative is GTeV ("Gluon Physics at the Tevatron"), which is currently at the pre-proposal stage. The focus of GTeV will be the study of QCD, both perturbative and non-perturbative in proton-antiproton scattering. The experiment will re-use one of the existing major detectors at the Tevatron (CDF or D0) as a central detector, augmenting it with forward (<3 degrees) tracking and calorimetry and very forward Roman Pots. The result will be a "tagged gluon collider"(gluon-gluon $\sqrt{s} \sim$ 1-100 GeV) with an experiment having complete phase space coverage. GTeV is intended to run in parallel with BTeV, beginning in 2009. A meeting at Fermilab was held in late May 2004 to form a collaboration to generate a proposal.

GTeV plans to address a broad range of physics topics. Forward tracking and calorimetry enable measurements of the gluon density of the proton down to $x\sim10^{-4}$ at moderate Q^2 via di-jets, J/Psi, and other channels. The combination of Roman Pots and full phase space coverage allows isolation and study of gluon jets. Central exclusive production via diffractive scattering permits study of the glue-ball spectrum and the production of exotic hadrons. Additional measurements are related to multi-pomeron physics (Mueller-Navelet jets), Standard Model Higgs production (central exclusive X_c and X_b production), and searches for physics beyond the Standard Model.

VI.B.2. Observations

The GTeV physics program potentially has several areas of overlap with the RHIC and LHC Heavy-Ion programs:

a. The measurement of the gluon density of the proton down to $x\sim10^{-4}$ has perhaps the most direct overlap with the central goals of the RHIC and LHC Heavy-Ion programs, in the context of saturation physics. However, such measurements are difficult and planning for them is still in the conceptual stage. The experimentally accessible and interpretable Q^2 range has not been clearly identified, thus the actual relevance of these measurements to saturation physics of the proton is not yet clear.

b. The application of diffractive interactions to the study of the Pomeron and of central exclusive production of exotic states overlaps substantially with the RHIC "ultra-peripheral collisions" program for A+A collisions, which is a well-established area of activity at RHIC. A limited number of RHIC experimentalists work in this area, principally within the STAR collaboration, together with a small community of theorists. Efforts in this area will continue at RHIC at about the same level in the future. The situation is rather similar at the LHC: for the LHC heavy-ion community this physics is expected to remain secondary to their main areas of interest.

c. There has been interest in the past in diffractive p-p physics at RHIC: the pp2pp experiment, now terminated, studied the spin structure of the Pomeron. Several of the STAR and PHENIX upgrades are designed to extend their capabilities for studying forward particle production in p+p and p+A collisions, overlapping significantly with some of the physics goals of GTeV (saturation, multi-Pomeron physics). This area is under active development and may play a significant future role in the RHIC physics program.

VI.B.3. Assessment

The GTeV project has some limited overlap with the RHIC and LHC Heavy-Ion physics programs. The experiment is still at the conceptual design stage and it is unclear whether its capabilities will attract participation by the U.S. High Energy Heavy-Ion community. There is at present no request to DOE/NP for support to participate in the development of the GTeV proposal. The Nuclear Physics community should continue to monitor the GTeV project, periodically reassessing its impact on the Heavy-Ion program.

Section VI.C. Computing

The U.S. Heavy-Ion research program involves three broad areas of computing: computing in support of experimentation at RHIC and the LHC, Lattice Gauge Theory calculations, and dynamic modeling of high energy nuclear collisions.

VI.C.1. Computing for RHIC Experiments

VI.C.1.a. Findings

The RHIC experiments generate very large data rates and enormous integrated datasets, currently among the largest samples of scientific data being analyzed. Timely production of physics results requires cutting edge computing technology as well as large storage and processing capacity. During the construction phase of RHIC a computing model was developed in which the raw data are recorded at a large centralized facility, namely the RHIC Computing Facility (RCF) located at BNL, and in addition the first pass data reduction (DST production) is performed. Higher level physics analysis is carried out both at the RCF and at remote facilities, while simulations are primarily the responsibility of the remote facilities.

This computing model was implemented and has proven to be highly successful. The RCF now comprises about 2300 CPUs (1350 kSPECint2000), over 4 PB (petabyte) of mass storage with an access bandwidth of 1.2 GB/sec, and about 400 TB (terabyte) of disk storage. During the 2004 RHIC run the RCF recorded 475 TB of raw data at an aggregate recording rate of up to 250 MB/sec. Its capacities match or exceed those of Fermilab and other large HENP computing facilities. The efficient operation of the RCF has permitted very rapid turnaround from data recording to physics results, bringing significant credit to the entire RHIC program. The remote facilities also play an important role in physics production, though at a lower level of direct investment.

The dataset recorded in the 2004 run is an order of magnitude larger than all previously recorded datasets. The two large experiments (PHENIX and STAR) estimate that one pass to reconstruct the raw data to create data summary tapes for the 2004 dataset, will take approximately one calendar year.

The annual operating budget of the RCF is over $5M, supporting 20 FTEs. The annual capital investment in the RCF is $2M, which allows replacement of about 25% of the hardware each year. Continuous capital investment of this magnitude is needed both to replace obsolete equipment that has become expensive and difficult to maintain, and to enable the growth in the capacity of the facility to keep pace with the growing demands of the experiments.

While the remote (non-RCF) facilities play a crucial role in the analysis of RHIC data, they are (with one exception) not directly supported by DOE/NP, instead being supported by local institutional or governmental funds. The sole exception is the PDSF/NERSC facility at LBNL, which in recent years has been supported by DOE/NP at an annual level of $200K to supplement local institutional and group support.

Future planning for the RCF is carried out in close collaboration between RCF management and the computing leaders of the experiments. In conjunction with this Subcommittee Review, that group reassessed the long-term projections for the RCF, taking into account the expectations of the experiments for future RHIC running scenarios. The team concluded from the reassessment that the current level of investment in the RCF is appropriate into the long-term future (about $5M annual operations, $2M annual capital equipment). A shortfall in computing capacity is expected in FY05-06 due to the large dataset recorded in the 2004 run. A one-time supplement of $1.6M in FY05 has been requested to cover this shortfall. Return to the funding baseline in future years is projected to result in capacity beyond that required by the experiments, though the uncertainties in such projections are large.

These uncertainties include the uncertainties in the future growth of computing performance at given cost, as well as the uncertainties in future recorded data volumes and processing requirements. Both large experiments, PHENIX and STAR, are upgrading their DAQ systems to compress data further and record more events per unit bandwidth than at present, thereby incrementing the demands on offline processing. Rough data enrichment factors have been included in the projections to account for these developments.

VI.C.1.b. Observations

The time it takes to process a large dataset is a critical issue. In a real sense the 2004 dataset is the first full-scale test of the RCF. While one-year turnaround for DST production is acceptable, two years would not be. The facility therefore appears to have limited margin for error in reprocessing a dataset if a serious problem emerges. However, it is unclear how to increase this margin. The experts from the experiments and RCF expressed the view that further investment in hardware would not fully solve the problem. There are also important human factors to consider, in particular an expanded role for professional staff to increase the efficiency and throughput of the facility. This issue bears watching but it does not at present provide a compelling reason to alter the level of support for the RCF into the medium-term future.

VI.C.1.c. Assessment

The projections, from RCF management and from the experimental teams, for RCF requirements through the end of the decade are credible. The timely production of physics results is judged to be of very high priority within the entire RHIC program. The appropriate investment must be made in computing facilities to ensure that outcome.

The current annual level of funding for the RCF ($5M operations, $2M capital equipment) is appropriate to support the current level of RHIC operations into the long term.

The projections predict a shortfall in computing capacity in '05-06, resulting in a one-time supplemental capital equipment request of $1.6M. In the interest of timely production of significant new physics results from the large 200 GeV Au+Au dataset from the 2004 run, the Subcommittee supports funding this request.

The projections nominally predict an excess of capacity in the out years. Bearing in mind the uncertainty in such projections and the already long expected turn-around time for physics results from the large datasets now being recorded, the Subcommittee does not see a clear basis for altering the existing funding profile in the medium-term future. This issue should be monitored, however, with adjustments made as more information becomes available.

The remote (non-RCF) facilities being used for RHIC data analysis have proven to be an effective way to leverage additional funds for the RHIC scientific program. Such efforts should be encouraged, with a modest targeted investment of DOE/NP funds where necessary to support the operation and growth of critical remote facilities. The Subcommittee also noted the significant contribution to RHIC data analysis from non-U.S. computing facilities, especially within the PHENIX collaboration.

VI.C.2. Computing Support for LHC Experiments

Computing in support of experimentation at the LHC will develop into an essential component of a successful U.S. program at the CERN-LHC detectors. The Subcommittee strongly supports participation in this program. As DOE/NSF research proposals for joining the LHC detector collaborations undergo technical review, it is crucial to evaluate the capability and resources required for the collection and analysis of data. The resources required for this activity depend on how the U.S. participation in the LHC Heavy-Ion program evolves in detail and have not been further analyzed in this review and report.

VI.C.3. Lattice Gauge Theory

Lattice Gauge Theory has played an essential role in the study of hot QCD matter. Most of what is known theoretically about the phase structure of such matter has emerged from Lattice Gauge Theory. Present discussions concerning the nature of the Quark-Gluon Plasma and the extent to which it may be either a strongly or a weakly interacting medium are receiving critical input from lattice calculations.

Current lattice calculations fix the energy density and pressure of the de-confined phase with an accuracy of about 20% and are providing first studies of the coupling of heavy quarks with a hot, dense, deconfined medium. New, dedicated machines such as QCDOC will have a capacity of about 10 TFlops, an order of magnitude improvement over existing facilities. They will enable calculations with physical quark masses to determine the QGP equation of state to within a few percent, extend the calculations to non-zero baryon chemical potential, and identify the critical end point of the chiral phase transition. New lattice measurements of the heavy quark spectral functions at finite temperature will play a critical role in extracting screening lengths from quarkonium measurements in heavy-ion collisions at RHIC. Lattice calculations accessible with a 10 Tflop machine will provide crucial guidance on the modification of hadron properties in dense matter and provide critical baseline information on QCD expectations for the thermal emission rates of real and virtual photons, which will be invaluable for inferring the medium temperature from experimentally measured photon spectra.

The NSAC report "A Vision for Nuclear Theory" from the NSAC Subcommittee, which reviewed the theory component of the Nuclear Physics program, gave strong support to lattice gauge theory and calculations.

The Subcommittee recognizes the fundamental contributions which lattice theory has made to heavy-ion physics in the past. It expects this relationship to continue and concludes that the availability of modern large-scale computing facilities for Lattice QCD simulations will continue to be an essential component for the success of the U.S. Heavy-Ion program.

VI.C.4. Dynamic Modeling of RHIC Collisions

Lattice Gauge Theory enables studies of finite temperature QCD in a static, equilibrated medium of infinite extent. In contrast, relativistic nuclear collisions generate QCD matter in a dynamic rapidly evolving environment. The connection of experimental observations to the fundamental underlying properties of QCD requires theoretical modeling of the full dynamical evolution of the QCD matter generated in nuclear collisions, from the initial impact to final freeze out.

Dynamical modeling of relativistic nuclear collisions currently uses a patchwork of different approaches for different time intervals in the evolution of the system. These include classical Yang-Mills theory, hydrodynamics, and partonic and hadronic cascade methods. Among the issues addressed by such calculations are the following:

- How does the coherent initial nuclear wave function evolve into an incoherent system of quarks and gluons with low virtuality?
- How is thermalization achieved, and on what time scale?
- What are the transport coefficients of the medium? What limits can be placed on its viscosity?
- What are the limits of hydrodynamic behavior?
- What are the microscopic mechanisms of hadronization?
- What is the influence of hadronic re-scattering on experimental observables?

Progress towards answering these questions in many cases requires significant conceptual development. In addition, such non-linear problems, by their nature, can only be fully solved by numerical methods, and this branch of theory is therefore very computationally intensive.

In its public meeting, the Subcommittee heard a discussion of the computing requirements of this branch of theory. Modest CPU farms of about 10 processors, which are easily available to many research groups, are able to address some of the issues presented. However a number of calculations that are essential for interpreting the experimental data, require computing resources, which lie well beyond the reach of small CPU farms (for example three-dimensional hydrodynamic calculations).

Future progress in the experimental study of hot QCD matter relies crucially on the availability of such calculations. These are not standardized Monte Carlo calculations that can simply be run by experimentalists as a component of the data analysis. Rather, significant phenomenological calculations require both theoretical expertise and deep understanding of the data, and will emerge from close collaboration between theory and experiment. This in turn requires a robust community of phenomenologically oriented theorists, together with sufficient computational resources to allow them to carry out numerically intensive calculations in a timely fashion.

The robustness of the theory community in this area has recently been analyzed by the NSAC Subcommittee on Nuclear Theory in its report “A Vision for Nuclear Theory”, and is addressed in Section VI.D. In order to amass the necessary hardware for these types of calculations, a number of different approaches, beyond increasing the capacity of local clusters, are possible. The theory community should investigate economies of scale that may result from collaboration with the existing large computing centers used for experimental data analysis at RCF, NERSC, and elsewhere, together with funding available from other sources such as SciDAC (http://www.osti.gov/scidac/henp/index.html).

Section VI.D Research Community

This section addresses the scientific community actively involved in the Heavy-Ion Nuclear Physics efforts in the U.S. This includes the international community of experimentalists and theorists working at RHIC, and members of U.S. institutions who have expressed interest in working at the LHC.

VI.D.1. RHIC User Community

The current author lists of the four RHIC experiments comprise about 1100 collaborators from 22 countries. Table VI.D.1 tabulates the total number of institutions and authors, as well as the number of U.S. institutions and the number of authors affiliated with them. The data are drawn from author lists of recent publications. It should be noted that this list includes researchers involved in both the RHIC Heavy-Ion and Spin programs.

	All		**U.S. Only**	
	# Institutions	**# Authors (approx)**	**# Institutions**	**# Authors (approx)**
BRAHMS	12	50	5	20
PHENIX	57	460	17	150
PHOBOS	8	60	6	55
STAR	51	500	23	195
Total	128	1070	51	420

Table VI.D.1 Distribution of physicists among the RHIC experiments.

A more detailed profile of the community is available from data supplied by the RHIC/AGS Users Group. Of its 900 members who are RHIC experimentalists, ~40% are faculty or permanent staff, and ~40% are students or postdocs. About 30% of the Users Group membership has U.S. citizenship (RHIC/AGS User Group, S. V. Greene, BNL 6/04/04).

Through the end of 2003, 45 Ph.D. theses have been awarded based on experimental work carried out at RHIC, of which 36 were awarded in 2002 and 2003. The annual number of RHIC-related theses is expected to increase in the coming years. Five DOE Outstanding Junior Investigator awards, or their equivalent, have been granted to RHIC experimentalists during the period 2000-2004.

The impact of the participation of RHIC U.S. experimentalists at the developing program at the LHC is unclear at this time but at some level will reduce the number of participants in the RHIC program. This is consistent with the plan of RHIC management to bring the two small experiments (BHRAMS and PHOBOS) to completion in the next few years. Because of the very short running period of the LHC Pb beams (about one month) one can anticipate that a number of teams will participate in both the RHIC and LHC heavy ion runs. Regarding protons, the polarized proton measurements are unique to RHIC. In the judgment of the Subcommittee, there will be strong communities of researchers to drive both the PHENIX and STAR programs at RHIC and a new program at the LHC.

VI.D.2. U.S. Heavy-Ion User Community at the LHC

The size of the U.S. community proposing U.S. participation in the LHC Heavy-Ion program is roughly estimated in Table VI.D.2. This is a tabulation of the number of authors on each of current proposals for U.S.-LHC participation, together with an estimate of how many authors are either presently active in a RHIC experiment or have been in the past. These estimates of U.S. personnel interested in these detectors are only crude estimates since the number of U.S.-supported participants in each experiment is not firmly established yet and could change substantially in the next few years.

	Number of Proposal Authors At U.S. Institutions	**Estimated Number of Authors Currently or Formerly Active at RHIC**
ALICE	53	~40
ATLAS	12	~10
CMS	30	~22
Total	95	~72

Table VI.D.2 Estimate of the current number of U.S. research physicists based on proposals to join the LHC program.

VI.D.3. Theory Community

Approximately 24% of the DOE Nuclear Theory budget supports efforts in Hot Nuclear Matter, divided about evenly between university and National Laboratory groups. These funds support 22 senior theorists, 14 postdocs, and about 20 students at universities, as well as 5 staff members and about 7 postdocs at National Laboratories. In addition to research groups at universities and national labs, there are two centers that strongly support RHIC-related theory: the Riken-BNL Research Center (RBRC) and the Institute for Nuclear Theory (INT) at the University of Washington. During the period 2000-2004, five DOE OJI awards were granted to theorists working on hot and dense nuclear matter.

The RBRC is dedicated to theoretical and experimental study of strong interactions, including spin physics, Lattice QCD, and high-energy heavy-ion physics. It was established in 1997 and is funded by the Riken Institute in Japan. RBRC has no permanent staff; rather, it funds temporary positions for Research fellows (5 years) and Research Associates (2-3 years). The Fellows program is intended to seed academic positions. Fellowships are held in conjunction with an academic appointment at a university or National Laboratory in the U.S and Japan. There are currently 16 RBRC Fellows, comprising 11 theorists and five experimentalists. The Fellowship program has been very successful: 10 former and current RBRC Fellows have been appointed to permanent tenured positions in the U.S. and Europe. RBRC also hosts a computing facility dedicated to Lattice QCD calculations: a 0.6 TFlop machine has been operating since 1998, and the 10 TFlop QCDOC machine will begin operation in late 2004. In addition, RBRC has sponsored a wide variety of workshops on strong interaction physics and has published 63 workshop proceedings volumes to date.

The INT has a broad scope that covers all aspects of nuclear physics theory but it has a long history of support for RHIC-related theory. At present it has one Senior Fellow and one postdoc working on topics related to heavy-ion physics. Since 1990 it has sponsored five three-month programs specifically on heavy-ion physics and three on closely related subjects, together with nine RHIC/INT topical workshops.

While a significant fraction of the overall nuclear theory effort in the U.S. now addresses, in one way or the other, high density QCD and the properties of hot and cold nuclear matter, the Subcommittee heard testimony from several leaders in the field that there is a worrisome shortage of theorists working on dynamic modeling of relativistic heavy-ion collisions and RHIC phenomenology. This particular brand of theory is required to connect experimental observations to fundamental properties of QCD matter, and such calculations play an essential role in the interpretation of data. In its recent report "A Vision for Nuclear Theory" the NSAC Subcommittee on Nuclear Theory recommended significant growth of the Nuclear Theory effort in the U.S. but also pointed out that this requires increased funding beyond a constant level of effort theory budget. Our Subcommittee perceives a particular need for action in the field of RHIC- and LHC-related heavy-ion phenomenology and dynamic modeling where a bottleneck has developed after a number of excellent young researchers left the field due to lack of long-term positions.

Lattice QCD, dynamic modeling of heavy-ion collisions and strong theoretical support of heavy-ion phenomenology are key components of a successful relativistic Heavy-Ion program. Specific recommendations addressing how to allocate funds to such activities are outside the charge given to our Subcommittee; instead, the reader is referred to the recommendations of the recent report from the NSAC Subcommittee on Nuclear Theory.

Section VII. Budget Scenarios and Issues

In the charge from the DOE and NSF to NSAC (see Appendix A), there was an explicit request for analysis of the resources required by this field. This request was formulated as follows:

> "What opportunities can be pursued with funding at the FY 2005 Budget Request level ($158.9 million) and an assumed constant level of effort into the out years? What is the appropriate mix of facility operations, research, computer support, investments in instrumentation and accelerator capabilities, and detector and accelerator R&D that will be needed to optimally exploit these opportunities?
>
> What are the priorities of the scientific opportunities that could be pursued with additional funds beyond this constant level of effort?"

In section VII of this report, we summarize the elements of the program and the goals, both ongoing and new, which will drive the long-term health and future scientific impact of this field, and provide an investment strategy to meet these goals.

VII. A. Elements of the Program

The following discussion highlights the major components of the program and the relative priority for investment in each area.

At this point in time, the RHIC facility is beginning its fifth year of operation with its full complement of four primary detector systems, data acquisition systems, and computer support from the RCF. In recent years the luminosity and data collection rates at RHIC have steadily increased, including an impressive integrated luminosity of 3740 μb^{-1} in the Au-Au section of run 4. With the current offline computer capabilities, this is about the limit of how much data that can be processed in one year. The Subcommittee also notes that both the accelerator facility and the detector systems deployed in this period were designed ten to fifteen years ago to meet the needs of the physics program anticipated at that time. With the new insights into the physics phenomena explored in the recent running periods, it is time to embark on an upgrade investment program which can increase the scientific reach of RHIC and provide for stable operations in the years to come.

It is the judgment of this Subcommittee that in planning the physics program for the next decade at RHIC, it is essential to make investments in new detector and facility technologies, which respond to the new scientific opportunities identified. This strategy must be pursued even at the risk of making short-term reductions in the number of weeks of operation. For the long term, increasing the scientific reach of the RHIC detectors, increasing the luminosity of the RHIC collider, together with the development of a Heavy-Ion program at the LHC, are essential elements, which could sustain this component of the Nuclear Physics program for at least the next fifteen years. The scientific opportunities and investment strategies discussed earlier in this report are summarized briefly below where the discussion focuses on changes in the program relative to the FY05 budget request:

VII.A.1. RHIC Operations

The original NSAC vision for RHIC operation (1996) envisioned a full utilization scenario of 37 weeks of operation. In the face of current budget realities, BNL management and the RHIC community have developed a Twenty-Year Plan (2003), which identified 32 weeks of cryo-operation as a healthy program in heavy-ion and proton physics. Furthermore this plan made clear that the constant level of effort budgets (FY2004) being discussed in the Twenty-year plan, only permit 27 cryo-weeks of operation (about 23 weeks of physics production), as referenced in Recommendation #5 of this report. The FY05 budget request (now before congress) was developed around 31 cryo weeks, although recent pressures on the operations budget have pushed this downward. Starting in FY06, increases in electric power costs will become a major issue. The latter, for which contract negotiations are currently in progress, is particularly troublesome. By way of illustration, an increase of current power rates from $55/Mwatt hour to $85/Mwatt hour (not yet established) would require an additional $4.1M for a 31 cryo-weeks.

In the view of the Subcommittee, the need to make investments now, in detector and facility upgrades is an acceptable trade against the number of heavy-ion running weeks for the near term. On the other hand, the proton program has been tooling up and is now ready for production running. Clearly, the productivity of both the heavy-ion and polarized proton programs would be seriously impacted by sustained cuts in the RHIC running time.

VII.A.2. RHIC Detector Upgrades

The research community has been evaluating upgrades to the PHENIX and STAR detectors and made presentations to the Subcommittee. Four initiatives have been highlighted and have strong justification:

- PHENIX Silicon Vertex Tracker (full system)
- STAR MRPC TOF Barrel and Micro-Vertex Detector
- PHENIX Muon Trigger and Nose Cone Calorimeter Upgrade
- STAR Forward Tracking Detector Upgrade

The Subcommittee finds all four upgrade strategies compelling. They would enhance the physics reach of the two experiments dramatically, both at the current RHIC luminosity and after the implementation of the luminosity upgrade (discussed below). Their individual costs vary, but the full set of initiatives listed above would require more than $50 M. It will be extremely difficult to implement all of them in a timely manner within the overall RHIC base budget. The Subcommittee assigns higher priority to the full PHENIX Silicon Vertex Tracker and the STAR MRPC TOF Barrel, because they are sufficiently advanced to provide, if funds were available, a major impact prior to a long 200 GeV Au+Au run, possibly in FY09. On the other hand, under a constant level of effort budget, they couldn't be completed prior to FY11-12.

VII.A.3. LHC Participation

A number of U.S. research physicists (currently about 100 names, many active at RHIC) have proposed joining collaborations centered around three detectors under construction at the LHC, for participation in the 5.5 TeV Heavy-Ion program. This will require both redirecting research

operation funds from the current RHIC based heavy-ion research program to this activity, and new funds to support computer costs, construction of detector components, collaboration operations fees at CERN, and travel costs. One project being discussed is U.S. construction of a large EM calorimeter for ALICE at an equipment cost of more than $10M.
The Subcommittee very strongly supports US participation in the LHC program as one of its primary recommendations. The scale of the investment of new funds should be at the level of one of the two new detector upgrade equipment programs at RHIC.

VII.A.4. RHIC Facility Upgrades

The facility upgrade program has two major components: a. the EBIS and b. the Luminosity upgrade.

a. The EBIS project involves construction of a state of the art injector facility at RHIC to replace the aging tandem Van de Graaff accelerators now in operation. The new facility, which will extend the technical capabilities, reduce personnel, and increase reliability, is estimated to cost $18.5M (TPC). It is expected that NASA (a user of the AGS facility) will contribute about $5M. The remaining funds must come from the current RHIC operating budget over an expected three-year construction period. Over the following years, this investment will be recovered through reduced personnel costs.

The Subcommittee concludes that this is a timely and wise investment and should be implemented as soon as possible (FY06-FY08).

b. The requirement for further increases in the luminosity at RHIC are being driven by the need to investigate rare processes, which cannot now be explored in a reasonable running time (see section III.B). A technique involving electron beam cooling of the heavy-ion beams is now being studied and reviewed at BNL (see Section III.C). If successful, this promises a gain by a factor of ten over the current luminosity. The immediate need is to sustain an R&D program through FY09 although design and initial construction of the luminosity upgrade facility could begin earlier.

The Subcommittee recognizes that this project has both high scientific impact and high technical risk and recommends investing in the R&D program, which could enable this important project.

VII.A.5. Computing Support

The computing needs of the research community and RHIC are analyzed in Section VI.C.
In the judgment of the Subcommittee, the RCF has a well-developed and balanced investment strategy for the coming years, strongly coordinated with the needs of the RHIC research community. No changes in this strategy are recommended.

VII.A.6. Research Operations at Universities and National Laboratories

There is a very strong research community that has grown up around the heavy-ion and proton programs at RHIC. In FY05, the investment in research operations in the U.S. was $ 12.8M at

Universities and $ 16.8M at National Laboratories (Total $29.6 M). There are about 900 members of the RHIC user community.

The Subcommittee notes that this community has been very productive over the past several years with over 100 papers published and 45 theses completed based on the new RHIC data. The Subcommittee finds that the detector and facility investment issues are most critical at this time and recommends that this research support remain at a constant level of effort. A strong and effective theory effort is an essential component of this research program. In view of the recent report from the NSAC Subcommittee on Nuclear Theory, this Subcommittee has not attempted to further analyze the resource requirements in that sector.

VII.B. Recommendations Under a Constant Level of Effort Budget Scenario, FY06-FY10.

The FY 2005 Budget Request includes 31 weeks of RHIC accelerator operations although this includes no funds dedicated to upgrades to the RHIC detectors or construction of the EBIS, nor does it include any funds in support of the Heavy-Ion physics program at the LHC. Allocating funds for these initiatives within a constant-effort scenario will necessarily require cuts in other existing fund allocations. Furthermore, the RHIC management is expecting a significant increase in the cost of electricity in the coming year. The exact magnitude of the increase is still uncertain. However, it is clear that the cost of each week of accelerator operations will be substantially higher in FY 2006 and beyond, than it has been in previous years.

Thus, the Subcommittee finds that it is impossible to satisfy Recommendations #1-#3 fully, under a constant-effort scenario. While painful compromises must be made under this scenario, the Subcommittee believes that certain critical items must survive.

The Subcommittee recommends that, even under a constant level of effort budget scenario:

1. Funds must be allocated for investments in near-term upgrades for the PHENIX and STAR detectors to enable essential new measurements that could be performed at the existing beam luminosity and to maintain RHIC as a forefront facility of heavy-ion research well into the future. The Subcommittee analyzed several compelling upgrades proposed for the PHENIX and STAR detectors that would already be extremely valuable if they were in place today. However, under a constant-effort budget, it will be necessary to stretch out the upgrade program significantly. The constant level of effort budget anticipates that a total of approximately $4M per year can be made available to the PHENIX and STAR collaborations for detector upgrades, $2M for each experiment. At this rate of investment, the ability to implement the full PHENIX Silicon Vertex Detector system and the STAR MRPC Time-of-Flight Barrel prior to the next high-statistics RHIC 200 GeV Au+Au run is at risk and may force a delay in the scheduling of those important measurements.

   Other crucial major detector upgrades, such as the PHENIX Muon trigger/Forward calorimeter upgrade and the STAR Forward Tracking Detector upgrade, would also provide essential information about the dense matter that is created at RHIC and W production physics in 500 GeV operation, that is unavailable with the current suite of detectors. But these other major detector upgrades will need to wait for funds to become available when the first two projects are completed (after FY2011 in this constant level of effort budget scenario).

2. Funds must be allocated to support U.S. participation in the LHC Heavy-Ion program. This participation must be initiated as soon as possible in order for the U.S. to have a maximum impact on the first years of LHC heavy-ion running. The Subcommittee heard proposals from three groups that wish to join the three major LHC experiments, as discussed above and in Sect. III.D. The Subcommittee found these requests to be very strongly motivated. The constant level of effort budget includes an incremental allocation of approximately $2M per year to heavy-ion research at the LHC. The majority of the operating costs for participation at the LHC will need to be obtained from redirection of existing research funds by the various groups. Nevertheless, the funding available under a constant level of effort scenario will necessitate significant stretch-outs and/or re-scoping of the existing proposals.

3. The EBIS should be completed as soon as practical to avoid significant maintenance expenditures on the aging Tandem injectors and to take advantage of the substantial reduction in operating costs that the EBIS will accrue. It is anticipated that NASA will contribute approximately $5M toward the total estimated expense of $18.5M. A significant amount of the remaining cost may be obtained by redirecting RHIC AIP funds. However, the rest of the costs will need to come from the general RHIC Heavy-Ion operations budget.

4. The FY 2005 Budget Request includes $29.6M to support university and national laboratory research. The Subcommittee recommends that this funding level continue during the period FY 2006-2010 under a constant level of effort scenario.

5. The FY 2005 budget also includes a total of $2M for detector R&D by the PHENIX and STAR collaborations and $2M for accelerator R&D by C-AD. The Subcommittee concludes that it is essential for R&D efforts to continue at approximately the current levels, both for additional detector upgrades that will provide qualitatively new information regarding the dense matter created at RHIC, and toward the development of an electron beam cooling capability of high-energy heavy-ion beams, which is the critical enabling technology to realize the RHIC II luminosity upgrade. In view of the need for ongoing R&D to validate the electron beam cooler project, plans for the construction of this facility were not evaluated in this review.

6. Under a constant-effort scenario, it will be necessary to reduce RHIC operations and support costs to provide the funds for the new initiatives that the Subcommittee concludes must be made. This results in a significant reduction in RHIC running time. While there are uncertainties regarding the magnitude of future electricity costs at RHIC, it is reasonable to expect that the constant-effort budget will only support an average of approximately half as many weeks of RHIC running time in the near term as included in the FY 2005 Budget Request.

The running time will increase again after the EBIS is completed, but may only recover to about two-thirds of the FY 2005 total. This will require runs to be merged across fiscal year boundaries to minimize the overhead costs associated with accelerator turn-on and turn-off. There is also a possibility that the PHOBOS and BRAHMS experiments will need to be phased out earlier than envisioned in the recent BNL 20-year plan.

In summary, the Subcommittee finds that it is impossible to realize all the compelling scientific opportunities identified in Recommendations #1-3 within a constant level of effort budget. However, within such a budget, a balanced program that includes elements from all three recommendations can best maintain the long-term scientific impact of the heavy-ion and proton spin programs. As stated above, this can only be done through painful cuts, namely:

- RHIC weeks of operation will have to be reduced substantially.
- Compelling RHIC detector upgrades will need to be stretched out or deferred.
- Participation in the LHC Heavy-Ion program can only be funded at a very limited level.
- PHOBOS and BRAHMS may need to be phased out earlier than envisioned in the BNL 20-year plan.

Recommendation #4:

Within a constant level of effort budget, the Subcommittee recommends that certain essential investments be made. These include:

- **Construction of the PHENIX Silicon Vertex Tracker and the STAR Time-of-Flight Barrel.**
- **Participation in the LHC Heavy-Ion program.**
- **RHIC accelerator and detector R&D.**
- **Construction of the EBIS.**
- **Support at the present level for university and national laboratory research.**
- **RHIC running time sufficient to preserve the integrity of the Heavy-Ion and spin physics programs.**

VII.C. Recommendations Under an Incremented Budget Scenario.

Figure VII.C.1 illustrates the distribution of the constant level of effort budget components, required year by year. The Subcommittee notes that while the constant level of effort budget it developed, maximizes the scientific impact of the Heavy-Ion and Spin program within the constraint, this budget will nonetheless have a serious negative impact on the Heavy-Ion and Spin physics programs.

The first recommendation in the 2002 Long-Range Plan stated that: "Recent investments by the United States in new and upgraded facilities have positioned the nation to continue its world leadership role in nuclear science. The highest priority of the nuclear science community is to exploit the extraordinary opportunities for scientific discoveries made possible by these investments." Clearly, reducing the annual operating period of RHIC to only one-half to two-thirds of what has been identified as optimal, falls far short of full exploitation of the scientific opportunities provided by RHIC.

The corresponding stretch-out of the RHIC scientific program will also jeopardize meeting several of the performance milestones that have been set for the programs in High Temperature and High Density Matter and in Hadronic Physics. Specifically, it will be extremely difficult if not impossible to provide sufficient polarized p+p running at 500 GeV to perform the beam development and data-taking necessary to complete the W-asymmetry measurements prior to FY13. The various other performance milestones will require extended runs for p+p, d+Au, lower-energy Au+Au, and full-energy Au+Au collisions during the period FY06-FY10. Not all of the milestones in these areas can be met. As Table III.B.1 illustrates, under the reduced running times dictated by the constant level of effort budget, it will be impossible to explore all of these systems in sufficient detail. Thus, the allocation of beam time will determine which milestones are met and which are not.

One of the great strengths of RHIC as a dedicated heavy-ion collider, is its ability to perform systematic studies of the behavior of dense matter as a function of colliding species and $\sqrt{s}$. The reduced running time within the constant-effort budget necessarily will sacrifice a substantial fraction of this systematic characterization of the high energy density matter. The reduced running time also will clearly limit the research opportunities for students and post-doctoral research associates who represent the lifeblood of the field.

RHIC running time is not the only serious limitation within the constant level of effort budget. While the Subcommittee anticipates that a few small RHIC detector upgrades (PHENIX Aerogel, PHENIX Hadron-Blind Detector, STAR DAQ Upgrade) can be constructed within the base budgets of the respective collaborations, other critical major detector upgrades must necessarily be postponed for lack of funds. Failure to construct these additional new detector elements in a timely manner will require that major planned RHIC runs will have to be delayed or that measurements must be repeated once new upgrades are available. This represents an inefficient use of the limited resources that are available.

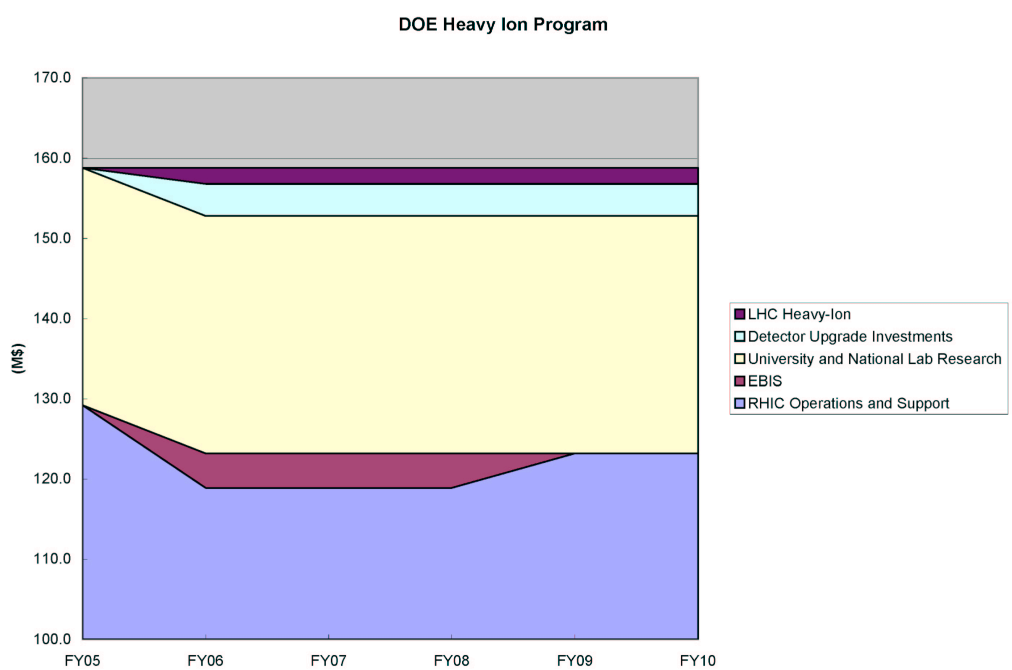

Figure VII.C.1: Constant Level of Effort Budget (FY05 $) over the period FY 2006-2010 under Recommendation #4.

The RHIC Spin physics program is on the threshold of making its first definitive measurements of the gluon polarization in the proton. It is also poised to explore $\Delta G/G$ with a number of complementary channels as the polarized proton performance of RHIC improves over the coming years, culminating in a direct measurement of the Bjorken x dependence of the gluon polarization over a broad momentum range. The reduced running time in the constant level of effort budget will seriously compromise the ability of the RHIC Spin program to obtain the integrated luminosity required to perform the full suite of gluon polarization measurements. A great strength of the program, the ability to study gluon polarization in several different channels that have different systematic effects, will be substantially diminished. Furthermore, the $W^{\pm}$ asymmetry measurements of the flavor-separated anti-quark distributions (500 GeV operation) will be pushed further into the future, both because of the limited number of running weeks and because of the delay of the relevant detector upgrades.

The high discovery potential which is a feature of the LHC Heavy-Ion program, motivates a major commitment by the United States Heavy-Ion physics community in this facility. However, the constant level of effort budget necessarily includes only very limited funds to support the U.S. participation in the Heavy-Ion physics program at the LHC.

The constant-effort budget maintains a constant research support level at universities and national laboratories, in spite of the outstanding new opportunities that will be made available by the new detector capabilities at RHIC and the new physics program at the LHC.

In view of the serious reductions in the program identified above (Section VII.B, Constant Level of Effort Budget), it is the Subcommittee's assessment that funding at a constant level of effort level will seriously impact the ability of the U.S. Heavy-Ion and Spin research programs to pursue the exciting scientific opportunities identified. The Subcommittee concludes that additional resources, at about 10% above the constant-effort level, would allow this field to exploit and realize the outstanding scientific opportunities in heavy-ion and spin physics identified in this report.

Recommendation #5:

The Subcommittee concludes that additional resources above the constant level of effort would allow extraordinary opportunities to be pursued by this field. In particular, such resources would permit the field to maintain a productive run schedule at RHIC, extend the new and exciting program at the LHC, and to perform a series of critical upgrades to the RHIC detectors, greatly enhancing their capabilities.

The Subcommittee considered resource allocations under two possible budget increments in addition to the constant level of effort budget (Recommendation #4):

- **An increment of up to 5% over constant level of effort should be devoted to restoring the planned level of RHIC running time. This should permit operation of the RHIC accelerator for at least as many weeks per year as envisioned within the recent BNL 20-year plan;**
- **Additional funds beyond a 5% increment should be allocated in comparable amounts to:**

- **RHIC detector upgrade investments to maximize the scientific potential of the RHIC facility in the era prior to the luminosity upgrade;**
- **U.S. participation within the LHC Heavy-Ion physics program;**
- **Support to research groups at Universities and National Laboratories working in relativistic heavy-ion physics.**

Section VIII. Summary

This report provides the background, analysis, and conclusions of the NSAC Subcommittee Review of the U.S. Nuclear Physics program in Heavy-Ion and Nucleon Spin Physics.

The Subcommittee was formed in March 2004, in response to a request to NSAC from the DOE and the NSF, for an update and further guidance beyond the NSAC 2002 Long Range Plan. This request was motivated in part by the important new physics results, which have recently been obtained at RHIC, and the increasing visibility of new research opportunities developing at RHIC and in Europe. The Subcommittee held a public meeting on June 2-4, followed by two executive meetings on June 5-6 and July 7-10.

This report addresses the physics opportunities which will develop over the next ten to fifteen years, the expanding set of research tools required by the field, and an analysis of what could be accomplished in this field within a constant level of effort budget (based on the FY2005 request at $ 158.9 M) and an incremented budget, in the period FY06-FY10,

The Subcommittee addressed three physics initiatives: relativistic Heavy-Ion physics and the exploration of high-density QCD matter based on measurements at RHIC, the LHC, and GSI, investigation of the spin structure of the nucleon using very high center-of-mass energy polarized proton-proton collisions; a program that is unique to RHIC, and the physics opportunities which would obtain from electron ion collider facilities being evaluated at RHIC and JLab. Subjects related to non-relativistic heavy-ion physics were not addressed in this report.

In the heavy-ion sector, it is the sense of the Subcommittee that important new phenomena have been discovered at RHIC, which will drive a unique and compelling research program over at least the next ten years at RHIC. RHIC will use existing and upgraded detectors for a series of measurements to fully characterize this new form of matter, especially using hard probes. The heavy-ion physics program beginning at the LHC in 2008, will become the new heavy-ion high-energy frontier and has high discovery potential as a result of a factor of 30 increase in the center-of-mass energy relative to RHIC. The Subcommittee believes that the interplay of these two different programs and the different capabilities at RHIC and the LHC, will bring the most clarity to the understanding of this new physics phenomena. The Subcommittee strongly supports a continuation of a vigorous program at RHIC and the development of U.S. participation in the Heavy-Ion program at the LHC.

The physics program and the tools for exploring the spin structure of the nucleon, using the polarized proton beams at RHIC, have been developing over the past four runs. Of particular interest are the role of both gluons and quark-antiquark pairs in contributing to the spin of the nucleon. The former can be measured in several channels at 200 GeV; this program is about to begin. The quark-antiquark contribution can be studied through measurement of asymmetries in W boson production and requires 500 GeV operation of RHIC, as planned. Both measurements are unique to RHIC. The Subcommittee strongly supports exploitation of this emerging nucleon spin program at RHIC in the very near future.

The 2002 NSAC Long-Range Plan identified an Electron-Ion Collider (EIC) as a new accelerator concept with great promise to extend our understanding of the quark and gluon constituents of nucleons and nuclei. EIC would provide collisions between polarized electron beams and polarized proton beams or nuclear beams at substantially higher $\sqrt{s}$ than practical at fixed-target facilities and substantially higher luminosity than achieved in previous colliders. The planned physics program at the EIC is extremely broad.

In the judgment of the Subcommittee, the Electron-Ion Collider has the potential to be a world-leading center for hadronic physics and strongly encourages the further development of the scientific case for the EIC, in advance of the next NSAC long-range plan.

In the assessment of the Subcommittee, the essential elements required for exploiting the evolving physics program at RHIC are 1) investments in a series of detector upgrades to PHENIX and STAR to extend the physics reach of the program, 2) a replacement of the aging injector system at RHIC by the EBIS system, and 3) investment in R&D to prepare for both future detector upgrades and for development of a new high luminosity capability using electron beam cooling of heavy-ion beams. These actions, together with development of a strong U.S. participation in the LHC program, are required in order to provide for the long-term health and scientific impact of the U.S. Heavy-Ion program.

The cost of investments to support this program was carefully analyzed by the Subcommittee in the context of two overriding goals. It is the Subcommittee's judgment that in addition to maintaining a strong running schedule at RHIC, it is important to make investments both in extending the scientific reach of RHIC and to developing U.S. participation at the LHC Heavy-Ion program. Two budget scenarios were evaluated: allocations within a constant level of effort budget (at the FY2005 request level) and the impact of an incremented budget. Because of rising operating costs at RHIC, the constant level of effort budget will severely impact the rate of investment in detector upgrades and in the LHC program, and will force a drastic reduction at RHIC in the number of weeks of operation per year. The Subcommittee found that at the 5-10% increment level, a well-balanced program could be implemented for both the near and the long term.

The analysis of the Subcommittee and the formulation of the above actions, are embedded in a set of five recommendations, presented in this report, which constituted the conclusions of the Subcommittee deliberations.

It is the conviction of the Subcommittee that the scientific impact of the U.S. Heavy-Ion program has been dramatic in recent years and will continue to grow over the next decade. The combined measurements at RHIC and the LHC in this period have great promise for revealing the fundamental physics underlying the role of quarks and gluons in nucleons, nuclei, and the QCD phase transition in the early universe, together with new insight into the spin structure of the nucleon.

Appendix A. Charge to NSAC and to the Subcommittee

U.S. Department of Energy
and the
National Science Foundation

February 18, 2004

Professor Richard F. Casten
Chairman
DOE/NSF Nuclear Science Advisory Committee
Wright Nuclear Structure Laboratory
Yale University
New Haven, CT 06520

Dear Professor Casten:

The recent 2002 Long Range Plan (LRP) developed by the Nuclear Science Advisory Committee (NSAC) provided a set of recommendations for exploiting opportunities for research both within the United States and elsewhere. Further guidance is requested from the NSAC by the Department of Energy (DOE) at this time beyond these recommendations in the LRP in the area of Heavy-Ion nuclear physics. Effective use of RHIC and investments in new capabilities and initiatives at RHIC and elsewhere were identified as the means to exploit the potential scientific opportunities of this program. The limitations on the implementation of this guidance, imposed by projected funding, make it timely for an updated assessment of the scientific priorities in this area, especially in light of new results obtained at RHIC. It is important that the available resources are directed to optimize DOE efforts, in coordination with the Nuclear Physics program at the National Science Foundation (NSF), for a strong national research program in this scientific area in the coming decade.

The NSAC is asked to examine current and proposed U.S. efforts in Heavy-Ion nuclear physics and identify what scientific opportunities should be pursued, in the context of U.S. and international capabilities and available resources, to ensure an optimized national research program. In your examination of these facilities and research activities, please respond to the following questions:

> What scientific opportunities should be addressed and what facility and instrumentation capabilities should be used and developed, including those supported by NSF and outside the United States, in order to maintain a strong scientific program in the coming decade?
>
> What opportunities can be pursued with funding at the FY 2005 Budget Request level ($158.9 million) and an assumed constant level of effort into the out years? What is the appropriate mix of facility operations, research, computer support, investments in instrumentation and accelerator capabilities, and detector and accelerator R&D that will be needed to optimally exploit these opportunities?
> What are the priorities of the scientific opportunities that could be pursued with additional funds beyond this constant level of effort?

Your perspective should primarily focus on the 5-year period FY 2006-2010. The impacts and benefits of pursuing these prioritized activities, as well as the impact of not being able to pursue an activity, should be clearly articulated. The resulting plans should be consistent with a set of research milestones recently established for the Heavy-Ion subprogram and validated by NSAC, unless it can be demonstrated that new information would suggest that these milestones should be amended. We request that an interim report be submitted by July 31, 2004, and a written report responsive to this charge be provided by September 30, 2004.

Thank you very much in advance for your efforts in addressing this important issue.

Sincerely,

Raymond L. Orbach
Director
Office of Science

Michael S. Turner
Assistant Director
Directorate for Mathematical
and Physical Sciences

cc:
Bradley D. Keister, NSF

NSAC charge to the Subcommittee:

30 June 2004
To: pdbarnes@lanl.gov
From: "Richard F. Casten" <rick@riviera.physics.yale.edu>
Subject: Charge to Heavy-Ion NSAC Sub-Committee
Cc: rick@riviera.physics.yale.edu,
Mary Anne Schulz maryanne@mirage.physics.yale.edu

Peter D. Barnes
Physics Division
Los Alamos National Laboratory

Dear Peter,

As you know, Ray Orbach, Director of the Office of Science at DOE, and Michael Turner, Assistant Director for the Directorate of Mathematical and Physical Sciences at the NSF, have charged NSAC to examine current and proposed U.S. efforts in heavy-ion nuclear physics, and to identify scientific opportunities to optimize the national research program in this area. The review requests guidance beyond the recommendations of the 2002 Long Range Plan, especially in light of the current and projected funding and the new results from the RHIC program. The review should focus on DOE efforts but take into account both NSF activity in this area as well as the international situation. The charge asks for guidance, under two funding scenarios, as to the scientific opportunities that should be addressed and the facility and instrumentation capabilities needed for this research. Clearly, an important part of the charge deals with defining the best allocation of resources to facility operations, instrumentation and facility developments, related R&D, research activities, and computer infrastructure and support. The charge asks for a focus on the period FY 2006-2010 but, of course, considerations of prospects and opportunities beyond this time period will play a role in any set of recommendations developed.

I am writing to formally ask you to serve as the Chair of an NSAC sub-committee to consider this charge and to report back to NSAC. The work of this sub-committee is extremely important since the Long Range Plan gives strong support to research in this area, which is at a critical juncture. The detailed wording of the charge, which I have previously forwarded to you, gives further instructions. The deadline for a preliminary report is July 31 or thereabouts and the final report is due in September 2004.

There will be an NSAC Meeting in the Washington, D.C. area on Aug 2, 2004. I ask you to provide a report on the activities and procedures of the sub-committee, and its principal recommendations, at that time.

I realize that this task imposes a significant extra burden on you, and I would like to express my deep appreciation to you that you have agreed to take on this responsibility. I will be available to help you in any way I can.
Best regards,

Rick Casten
Chair, NSAC

Appendix B. Membership DOE/NSF NSAC Subcommittee Heavy-Ion Nuclear Physics

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Appendix C. NSAC Subcommittee Review of Heavy-Ion Physics

Agenda - Public Meeting
Brookhaven National Laboratory
June 2 – 6, 2004

8:30 am Wednesday, June 2

I. Opening Remarks

A.	Welcome	Praveen Chaudhari
B.	Charge to NSAC and Subcommittee	Dennis Kovar/Brad Keister
C.	NSAC HI Review: Motivation and Process	Peter D. Barnes

II. Physics Opportunities with Heavy-Ion Reactions

A. Recent Progress at RHIC

9:15	STAR Collaboration assessment	Raimond Snellings [15]
9:35	PHOBOS Collaboration assessment	Wit Busza [10]
9:50	PHENIX Collaboration assessment	Yasuyuki Akiba [15]
10:10	BRAHMS Collaboration assessment	Flemming Videbaek [10]

10:25 Coffee

B. Opportunities for the Future (part 1)

10:55	Evolution of Physics-goals	Miklos Gyulassy[20]
11:35	Evolution of Physics-goals	Jean Paul Blaizot [20]
12:15	Next ten years of physics at RHIC	Bill Zajc [25]

1:00 Lunch

2:00	The Physics Opportunity at the LHC	Bolek Wyslouch [15]

III. Experimental Programs

A. RHIC

2:30	BNL Long term plan for RHIC	Sam Aronson [25]
3:15	RHIC Luminosity Upgrade	Thomas Roser [25]

(Electron Cooler & EBIS Source)

4:00 Coffee

Unpolarized Collisions

4:30	a. STAR- Future Program	Tim Hallman[25]
5:15	TOF Barrel Upgrade	Richard Majka[15]
5:45	Silicon MicroVertex Detector	Howard Wieman [15]

6:15 END Wednesday

6:30 Reception

8:30 am Thursday, June 3

III. Experimental Programs (continued)

A. RHIC Experimental Programs

Unpolarized Collisions (continued)

8:30	b.	PHENIX- Future Program	Axel Drees [25]
9:15		Silicon Vertex Tracker	Craig Ogilvie [15
9:40		Nose Cone Cal/W boson trig.	Ken Barish [15]
10:05	c.	Forward Physics at RHIC	Les Bland [20]

10:40 Coffee

	d.	New Detectors	
11:10		New General Purpose Detector	Thomas Ullrich [20]

B. Opportunities for the Future (part 2)

11:45	Evolution of Physics-goals	Dima Kharzeev [20]
12:25	Evolution of RHIC Physics	Ed Shuryak[20]

1:05 Lunch

2:00	Evolution of Physics-goals	Berndt Mueller [20]
2:40	Lattice QCD for HI physics	Frithjof Karsch [20]

C. GSI

3:20	HI Physics Opportunity at GSI	Bengt Friman [20]
3:55	Heavy-Ion Physics and Experiments at FAIR@GSI	Peter Braun-Munzinger [20]

4:30 Coffee

D. RHIC SPIN

4:50	Physics Overview	Werner Vogelsang [20]
5:25	Experimental Issues/upgrades	Matthias Perdekamp [20]
6:00	Machine Goals	Mei Bai [15]

6:25 END Thursday

***8:30* am Friday, June 4**

IV. Other Facilities

A. ELECTRON-ION COLLIDER

8:30	Overview-Electron Ion Collisions	Raju Venugopalan [20]
9:05	Realization at e- RHIC	Richard Milner [20]
9:40	Detector Issues for e-RHIC	Abhay Deshpande [15]
10:05	Realization at e-LIC	Rolf Ent [20]

10:40 Coffee

B. LHC

11:00	Physics Overview	Keijo Kajantie [20]
11:35	ALICE	Thomas Cormier [15]
12:05	ATLAS	Helio Takai [15]
12:35	CMS	Russell Betts [15]

1:05 Lunch

C. Fermilab

2:00	Gluon physics at the Tevatron	Mike Albrow [20]

V. Physics – Computational Issues

2:35	Dynamic Modeling of RHIC collisions	Steffen Bass [10]
2:55	Data processing requirements	Bruce Gibbard [10]

3:15 Coffee

VI. The HI Physics Community

3:45	The RHIC User Community	Westfall [10]
4:00	Comments and Discussion from the Floor [60]	

VII. Long Range View

5:00	Theory Outlook	Larry McLerran [20]
5:30	BNL Outlook	Tom Kirk [20]

Final Questions from the Subcommittee

6:15 END Friday

End of Public Sessions

Subcommittee Executive Sessions:

Saturday, June 5	8:00 AM to 7:00 PM
Sunday, June 6	8:00 AM to 1:00 PM