Review of the Extension Request for the RIKEN-BNL Research Center and RHIC Spin Physics Program

October 10-12, 2005

Brookhaven National Laboratory

The Scientific Review Committee met at Brookhaven National Laboratory on October 10-12, 2005 to conduct the annual review of the scientific program of the RIKEN Brookhaven Research Center (RBRC) and to review and comment on the 5-year Extension Request for RIKEN support of the RBRC, the RHIC spin physics program, and computing. This report is focussed on the Extension Request and addresses the progress and the future prospects for the program.

The Scientific Review Committee consists of Jean-Paul Blaizot, Makoto Kobayashi, Akira Masaike, Jack Sandweiss, Charles Prescott (Chair), and Stephen Sharpe (not present at this meeting). The Committee was augmented this year with two distinguished scientists, Kozi Nakai and Akira Ukawa. The Committee membership is listed in the appendix to this report, with members' addresses and affiliations.

The Committee heard presentations on the RBRC Proposal for a 5 Year Extension on October 12 by Nick Samios, Hideto En'yo, Larry McLerran, Norman Christ, and Thomas Roser. In the following sections we summarize the important elements of the program. The Committee's comments and recommendations are in the last section.

I. An Overview - Past Progress and Future Expectations

The RIKEN Brookhaven Research Center was established in the mid 1990s starting with an implementing agreement between the Science and Technology Agency of Japan and the Department of Energy of the United States. This was followed by a Memorandum of Understanding (MOU) signed by RIKEN and Brookhaven National Laboratory collaborating on a spin physics program at RHIC. Construction of spin manipulation components and some PHENIX detector components ensued. T. D Lee assumed the position of Director in 1997. Term appointments in RBRC commenced in 1997. A theory group was first to be formed, followed shortly by some experimental appointments. A University Fellows (tenure track) program was soon added to augment the academic nature of the RBRC. The RBRC MOU was renewed in 2002.

The growth in the RBRC Fellows and post-doc positions has leveled off, reaching a steady state number around 25 full time equivalents. The RBRC is augmented by long term residents and visitors from RIKEN.

The RBRC entered the QCD lattice computation field in 1997 with a collaborative effort with RIKEN and Columbia University. They commissioned the 0.6 teraflop QCDSP machine, designed especially for and dedicated to lattice gauge theory calculations. The QCDSP became operational in 1998. The collaboration of theorists from RBRC, Columbia and BNL exploited QCDSP to develop the so-called domain-wall fermion simulation of lattice QCD. This novel approach ensures chiral symmetry lacking in the conventional formalism. They pioneered a number of calculations, including the CP-violating decays of K meson and simulations including dynamical effects of up and down quarks. QCDSP has advanced the computational field considerably and is heavily utilized at this time. During this period, R&D progress in lattice gauge calculations promises to have a major impact on theory and experiments where hadronic processes are involved.

Work on a 10 teraflop machine commenced in 2002. These activities resulted in the dedication of the QCDOC in May 2005. The QCDOC opens up new horizons in the lattice gauge theory calculations. Capabilities of the QCDOC machines will allow for inclusion of dynamical effects of the strange quarks and for removal of some of the approximations used, and hence much more precise calculations. These calculations will bring with them a much better understanding of structure of the hadrons and the strong force. The QCDOC is already oversubscribed for computing time by theorists, and this situation will remain for the foreseeable future. Collaboration with individuals in Japan on computing is increasing.

Implementing a spin physics program at RHIC was a key motivation for the RIKEN-BNL Collaboration, as expressed in the 1995 MOU. To enable this physics program, Siberian snakes, spin rotators, and polarimeters would need to be added to the RHIC accelerator complex. With the significant participation from RIKEN, these components have been completed. RHIC is now fully instrumented with a polarized H^- source, two sets of Siberian Snakes, spin rotators at PHENIX and STAR, and two types of polarimeters. All of these are needed for a polarized proton collider program to succeed. Also, preserving spin through the AGS is critical to the spin program, so a warm partial snake, constructed by RIKEN, has been in operation for the recent polarized proton runs. A new superconducting partial snake has been added to the AGS and tested, but not yet fully commissioned for operation. The polarimeters have been put into operation. Operations at 100 GeV per beam at $\approx$ 50% polarization has now been achieved.

On the experimental side the PHENIX Muon South Arm was constructed and brought online for the most recent RHIC run. With the successful polarized proton runs in 2004-2005 at RHIC, the successful tests of the cold snake at the AGS, and the acceleration beyond 200 GeV, RHIC is poised to exploit the spin physics program that has been under development since the beginning of the RBRC. A successful and productive physics analysis workshop was held at the Wako campus during this Summer 2005. PHENIX data were transmitted by high speed network to RIKEN and analyzed in the CCJ computing center at RIKEN. Results of these analyses are now becoming available. The 5 year extension will be the period when these preparations give maximum payout from these investments.

The spin inside the proton remains a mystery. The past experiments to probe the proton spin are incomplete. Those experiments using the electron and muons for probes are blind to the gluon. We know that the gluon is a major player inside the proton, but only RHIC has the capability to observe directly the gluonic effects in the spin of the proton. Polarized protons scattering off polarized protons can shed data on the mystery of the proton's spin. The planned runs at 100 GeV on 100 GeV (later 250 on 250 GeV), will be used for direct γ, π°, and jet signatures of the gluonic component of the proton's spin. W boson production will be studied to determine the anti-quark contribution to the spin. The RBRC has high expectations for exciting results in spin physics in the next 5 years. Brookhaven National Laboratory has been organizing its leadership to exploit fully the potential of RHIC.

RHIC's current run plan for spin physics assumes 10 weeks per year through 2012. In 2007-2009, running will be at 200 GeV center-of-mass energy (100 GeV protons colliding on 100 GeV protons). Starting in the latter half of

2009, the energy will be raised to 500 GeV center-of-mass energy. Test runs (engineering runs) have already demonstrated polarization around 30% and energy > 200 Gev for a single beam. More engineering runs are needed to commission the full capability of RHIC, but 500 GeV at 70% polarization seems to be well within reach.

The dramatic results from RHIC's heavy ion collisions are now evolving and maturing. Clear evidence now exists for a new state of matter in these collisions. The upcoming runs of RHIC with heavy ions will put this unique capability to full use. The RBRC is poised to play a major role in this new physics direction, through its close collaboration between heavy ion theorists and heavy ion experimenters.

The future expectations for an exciting physics program are described in the following sections.

II. The Program Elements for the Period of the Requested Extension

(i) The Spin Program - Understanding the Proton

All protons carry an angular momentum of 1/2 unit of spin. This feature, long known from the early days of atomic physics, is used in many applications, most notably in the medical technique of magnetic resonance imaging (MRI).

The spin of the proton remains a mystery to the particle physicist. The underlying nature of the proton is, in principal, well understood in the language of the strong force - Quantum Chromodynamics (QCD). The theory contains the quarks and gluons that are the building blocks. However applying these elements to a calculation of the structure is difficult. The multi-body calculations are still largely beyond our capabilities, and the details of the proton remain somewhat of a mystery.

The history of surprises in these matters is a character of the field. One outstanding puzzle is the makeup of the proton (and neutron) spin. Experiments using electrons and muons to probe the proton spin have been done, but these probes do not see the gluon (which has no electric charge). To everyone's surprise, the quarks were found to contribute only $\sim$ 20% of the proton spin. This was far below expectations.

The role RHIC spin physics can play is the direct measurement of the gluons contribution to the spin. Gluons, excited by collisions of high energy protons, radiate π°s and γs. By reversing the spin directions and observing the changes in the amounts of π°s and γs, the amount of polarized gluons in the protons can be determined. The extraction of the gluonic contribution relies somewhat on the QCD understanding and on the removal of interfering background processes. Experimenters are faced with the tasks of making these corrections accurately and correctly. They rely on help from the theoretical physicists and help from experts for the apparatus to do this.

The RBRC is properly staffed with experts in both the experimental techniques and the theoretical techniques to achieve these goals. The PHENIX detector has been designed to exploit the spin physics program and has the strengths to measure the π°s and direct γs. These measurements are a major part of the program during the planned extension period. The early part of the 5-year period will be RHIC running at 200 GeV center-of-mass energy. The latter part of this period will be at a higher energy of 500 GeV, where the signals from the gluons are expected to be cleaner.

At the 500 GeV energy, production of the weak charged bosons, $W^\pm$, becomes possible. The charged bosons can be used to probe the quark component of the proton. By detecting the sign of the W boson, specific types of quark and anti-quarks can be separated. Measurement using the Ws give a detailed understanding of the proton spin at the quark-anti-quark level.

With these measurements, the full picture of the proton spin will be complete and the story can hopefully be concluded.

(ii) Theory - Understanding Nuclear Matter

Theoretical studies at RBRC focus on the physics of strong interactions and Quantum Chromodynamics (QCD). They provide support to the RHIC heavy ion program and the spin physics program. RBRC researchers benefit at Brookhaven National Laboratory from an ideal environment, which favors close collaborations between theorists and experimentalists. The theory activity is strengthened by the presence of the Nuclear Theory Group, the Particle Theory Group and the newly formed Lattice Gauge Theory Group. The level of exchanges and interactions between these groups and RBRC physicists is quite remarkable.

The fundamental questions addressed by RBRC theorists concern the state of matter at high temperature and density, the form of hadron wave-functions at high energy, and the spin content of the proton.

RBRC physicists have played a major role in the exploration of the phase diagram of dense and hot matter, and will likely continue to do so. At small temperature, but large density, phenomena related to color superconductivity lead to a rich structure that RBRC theorists contributed to identify. Detailed information on the phase diagram can be obtained from lattice calculations. RBRC physicists are in a unique position to make decisive progress in this area (this is discussed in another section of this report).

A lot of theoretical activity has been devoted in the recent years to the study of the asymptotic form of the wave-functions of hadrons, or nuclei, at high energy. Because the gluon distribution rises rapidly as the collision energy increases, the density of gluons in the wave-functions increases, and becomes eventually large enough for non linear QCD effects to play a dominant role. RBRC theorists, together with their colleagues of the Nuclear Theory group, have been at the forefront of the research in this domain: on the formal side, by deriving the equations that describe the non linear evolution of gluon distribution functions; on the phenomenological side, by developing models which incorporate, in the nuclear wave functions, components with high gluon density. Such models can account successfully for some of the RHIC data.

The study of spin reveals important aspects of the structure of the proton that one should, in principle, be able to understand in terms of the first principles of QCD. The fact that quarks appear to carry only a small fraction of the total spin of the proton has prompted experimentalists to measure the contribution of the gluons. Perturbative QCD calculations need to be done to a high precision in order to properly analyze these experiments. RBRC theorists have established themselves as leaders in this domain, and are developing the necessary tools to successfully complete such analysis.

Aside from studying the fundamental questions mentioned above, RBRC theorists are engaged in a variety of works related more directly to the phenomenology of heavy ion reactions. The diversity of these activities reflects that of the field and its complexity. It is, to a large extent, driven by the flux of new and beautiful data coming from RHIC. RBRC researchers contribute in a major way to the interpretation of these data, by developing models. A significant part of their effort aims at incorporating in those models as much as they can of the information acquired in the fundamental studies discussed above.

(iii) Computing on the Lattice - Tools for calculating hadronic structure and the strong force

The QCDOC machines are now running well, and effort to exploit its capability will occupy the RBRC lattice theorists over much of the requested extension period.

A major effort will be pushing the domain-wall simulations fully including the dynamical effects of all three light quarks (up, down, and strange). This is a natural extension of work pioneered on QCDSP which included only up and down quark. Precise results with small systematic errors are expected for a large variety of physical quantities, either confirming QCD at a very precise level or providing novel understanding and predictions on the structure of hadrons and the strong interactions. They include the light hadron spectrum and decay constants, quark masses, structure functions of nucleon, properties of hadrons containing heavy quarks (charm and bottom), and the K meson amplitudes relevant for understanding of CP violation within the Standard Model. This will be carried out in collaboration with the BNL theorists, the group at Columbia and the UKQCD Collaboration in the United Kingdom who also runs an independent QCDOC at Edinburgh. Preliminary calculations on a $16^3 \times 32 \times 8$ lattice have been completed, and production calculations on a $24^3 \times 64 \times 12$ lattice for three values of light quark masses are underway.

Calculating the properties of quark gluon plasma is another major goal posed for QCDOC. BNL has a serious commitment in this goal, and the newly formed group of F. Karsch in nuclear theory will play an important role in a collaboration with RBRC and the Columbia group in this effort. The phase diagram in the temperature-density plane, the critical temperature separating the hadron phase and the quark gluon plasma phase, equation of state, and the spectral functions of hadrons are some of the most interesting quantities characterizing the plasma. Calculations are already underway using the improved staggered fermion formalism, and results for several lattice spacings to be obtained over the next several years should advance this field considerably.

(iv) Heavy Ions - Probing a New State of Matter

The recent experiments at RHIC have shown that in these collisions a new state of matter called the Quark Gluon Plasma (QGP) is produced. Perhaps even more exciting is the fact that these measurements pose a number of mysteries, a situation which is often a harbinger of a significant advance in physics. Very briefly we list some of the most striking of these below. However, in a deep sense the underlying question (mystery?) is how this system can at least approximately thermalize in the very short time ($\leq 10^{-23}$ sec), which the evidence indicates that it does. This may be related to yet another class of systems, appropriate in the very earliest phase of the collision called the Color Glass Condensate.

(i) The high transverse momentum particles, which are produced by early scattering of the colliding partons (quarks and gluons) are strongly suppressed in central collisions. This was predicted and is one of the important indicators that the scattered partons are traveling through a new, and more energy dense medium. However, the theory predicts that at sufficiently large transverse momentum the suppression should stop. This is definitely not observed. Rather the suppression appears to continue up to the highest transverse momentum studied! Why does this happen? What does this say about the dense medium produced in the collision? What does this say about the theory of the interaction?

(ii) The theory of the suppression also predicts that when the scattered parton is a charm quark or a beauty quark, the suppression should be much less. The evidence from the so called nonphotonic electrons, which should be largely from charm quarks, shows the same suppression, also out to the highest transverse momenta.

(iii) The data on the angular distribution of particles from non central collisions shows extraordinary agreement with a hydrodynamical model which uses ideal hydrodynamics. The viscosity of this "liquid" seems to be very small. This too is surprising. Before these results many theorists expected the QGP to behave like an almost free gas of quarks and gluons. Such a system would not have such a low viscosity.

(iv) The behaviour of the angular distribution of particles from non central collisions is summarized by a parameter, called v_2. At transverse momenta below about 1.5 GeV/c the v_2 parameter agrees well with the hydro theory. In this range of transverse momenta the different particles behave in the manner predicted by the hydro theory, which envisions all particles flowing in the nearly ideal liquid. But at higher transverse momenta the different particles behave in what appears to be a chaotic fashion.

However, if one plots instead of the particle v_2, the quark v_2, that is if one plots the particle v_2 divided by the number of valence quarks in the particle, versus the transverse momentum also divided by the number of valence quarks in the particle, one finds that all the data coalesce into a universal curve. This is as if the production of particles occurs through simple quark coalescence. This interesting phenomenon is a clue to the process of hadronization and clearly needs further experimental and theoretical study.

The RBRC extension focusses on instrumentation and analysis which directly bear on these and similar key questions. For example, the vertex detector will be crucial in definitively determining the suppression of the charm and beauty jets; the study of direct photons will help elucidate the nature of the QGP, to list just two examples. The theoretical studies of the RBRC Fellows are also very important in gaining an understanding of the fascinating physics of this new state of hadronic matter. The interplay of theory and experiment has been and will continue to be a crucial factor in advancing the physics.

(v) R&D - Preparing for a Bright Future

Elements of the Extension Request are devoted to planning for the future. Although these R&D efforts are a relatively small part of the work planned, for the RBRC, planning for future directions is an imperative, and work on potential ideas must be done to guide the planning process.

The RBRC proposes to carry on R&D activities in the following areas:

(i) eRHIC

This idea is to augment the spin physics program ($\vec{p}$ on $\vec{p}$) with a polarized 10 GeV electron ring which would enable $\vec{e}$ on $\vec{p}$. The physics measurement that could result would probe the soft ("low x") regime of the gluon spin component of the proton. The electron ring would also be useful in collisions with ions, e on Au, for example, where unique measurements of the nuclear structure could result.

(ii) Advanced computing hardware

The RBRC would continue the collaborative effort with Columbia University, BNL, and Edinburgh to develop more advanced computers, and to modify the software as needed. The computer envisioned ("QCDAP") would increase the lattice QCD computational speeds by factors up to 100.

(iii) PHENIX Detector Elements

Development of components for PHENIX would bring improved capabilities to the program. The RBRC envisions a Muon Trigger Upgrade, a Vertex Detector addition, a Nose Cone Calorimeter addition, and a hadron-blind detector. These elements are desired to exploit the 500 GeV running expected in the near future. The Muon Trigger Upgrade is needed for the W boson program (for quark-anti-quark separation), while the Vertex Detector and the Nose Cone Calorimeter improve the overall detector efficiency for γs and jets, improving the detector for the gluon studies and heavy ion studies. The vertex detector is crucial for event by event identification of charm (via displaced vertex observation) in the collisions.

III. Comments and Recommendations

Overall, the presentations by the RBRC leadership show a vigorous and coherent theoretical and experimental program based on the RHIC capabilities for heavy ion and polarized proton collisions. The planning for exploiting fully the now-existing hardware and for upgrading the PHENIX detector capabilities are well advanced. These activities will take proton spin physics and heavy ion physics into new and unexplored territory.

Below in this section we mention some of the specific issues discussed in our review, and give a summary recommendation.

(i) The reported experimental results and expectations convinced the Committee that the experimental group would clarify the contribution of gluon spin polarization, no matter whether the answer was positive, small, or negative. The Committee agreed that the direct photon experiment should have high priority due to the importance of these results.

(ii) Theoretical activity on the lattice-gauge program is very impressive. The Committee wishes to express appreciation for this accomplishment, particularly to the Columbia group for their strong contributions. In order to enhance the active role of RBRC in this work, the RBRC might consider providing a position in which a senior scientist could oversee the RBRC and the Japanese contributions.

(iii) The Committee appreciates that Brookhaven is making a dedicated effort to meet its RHIC commitments. Thomas Roser heads the Accelerator Department, and has the responsibility for the operations of RHIC. He is an exceptionally talented expert in the field of accelerators in general, and high energy polarized protons in particular. He is the inventor of the so-called "partial Siberian Snake" spin manipulators that were built by the RIKEN/BNL Collaboration and are now installed in the AGS. He also contributed much to applying the idea of the helical snake to the actual accelerators. In particular, helical snakes are now successfully installed in RHIC. Thomas Roser is recognized internationally for his expertise. The IEEE Nuclear Physics and Plasma Society awarded Thomas Roser the 2005 Particle Accelerator Science and Technology Award for his successful acceleration of polarized protons to high energy. In addition to his accelerator responsibilities in RHIC, he is Chairperson for the International Spin Physics Symposium Advisory Committee. (The next symposium, SPIN2006, will be held in Kyoto in the Fall of 2006.)

Sam Aronson, until recent times the Spokesperson for PHENIX, has been assigned to the position of BNL's Associate Director of the High Energy & Nuclear Physics Division. The importance of the spin physics program at RHIC and the role that PHENIX will play in that program has been recognized by BNL through the placement of these very talented individuals in the key positions.

We encourage the accelerator group to continue making every effort toward obtaining higher luminosity and higher polarization in order to achieve the scientific goals desired.

(iv) The RBRC program could benefit by a larger commitment experimentally in the area of heavy ion physics. The present level of activity is headed by Y. Akiba (RIKEN) who is deputy Spokesperson for PHENIX. Since Akiba assumed this role, the RBRC has started expanding its involvement in heavy ion physics.

(v) The following three experimental aims were listed in the RBRC Proposal for a 5 Year Extension; 1) precision improvements of the gluon polarization with direct gamma measurements; 2) measurements of anti-quark polarization with W-boson detection; and 3) investigation of the role of angular momentum (or transversity). All three are very important and justify the 5 year extension. The direct gamma measurement is indispensable to the effort to complete the first stage of the RHIC-spin program. The R & D and experimental efforts for the W-boson detection (the beam energy upgrade to 500GeV and the PHENIX detector upgrade) are challenging but definitely will open new possibilities not only in the RHIC-spin but also the RHIC-heavy-ion programs.

The angular momentum (or transversity) on the proton spin has become a major issue recently. The RHIC-spin data on $A_{LL}(\pi^\circ)$ and the COMPASS(CERN) data have indicated that the gluon polarization may not be as large as expected for the interpretation of the missing part of proton spin. Feasibilities of the items 1) and 2) were well presented to convince the Committee both from scientific and technical point of view. In comparison with those, the presentation on item 3) was premature, possibly because the importance was recognized very recently. Intensive efforts in both theoretical and experimental investigations are required to design the experimental plan.

The Committee discussed whether further study of the contribution of orbital angular momentum to the proton spin can be considered a good reason to extend the program. Experimental techniques to permit studying the orbital motion are now under development. The committee noted that RHIC will provide unique opportunities to study gluon contribution on the orbital angular momentum effect inaccessible to DIS experiments. RHIC *may* become the best laboratory for answering these issues. Since the subject is fairly new and under current development, the Committee feels that the importance of this experimental issue (item 3) can't be clearly established yet, but the subject should be watched closely.

(vi) There is no commitment to the eRHIC concept yet. The R&D activities should be kept to a relative modest level until the possibility of this facility can better be understood. This facility would require a new detector concept, asymmetric in design, to accommodate the asymmetric event topologies expected. The RHIC interaction regions would not have to be modified, however. Construction could not begin before 2010 in the most optimistic schedule.

(vii) The Committee wishes to take special note of the success of the University Fellows Program. Theory Fellow graduates have been quite successful in obtaining academic positions. Most of these are at the tenured level. On the experimental side, promotion to tenure for two of the recent graduates is anticipated. This program is expanding, with discussions underway between RBRC and several prospective universities.

(viii) We have mentioned the importance of the RIKEN contributions at several times above, but the Committee wishes to take special note here that the cooperation of RIKEN with RBRC and BNL has been very helpful in achieving the success of this program.

Having expressed these comments and observations, the Committee finds the overall RBRC program to be healthy, vigorous, and well organized for a productive scientific future.

Recommendation:

The Committee recommends a 5 year extension of the collaborative agreement between RIKEN and Brookhaven National Laboratory to allow for the full utilization of RHIC for spin physics, heavy ion physics, and lattice gauge computation.

Appendices:

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November 22, 2005

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Dear Dr. Kaya,

I am pleased to enclose with this short letter the Report from the RIKEN-BNL-Research-Center Scientific Review Committee (SRC) on the request for a 5-year extension of the RIKEN-BNL Memorandum of Understanding. The SRC held its review at Brookhaven National Laboratory on October 10-12, 2005. The Report covers briefly the background of the RBRC and the past science accomplishments and the future science to be studied during a 5 year period. The section on Comments and Recommendations comes at the end of the Report and covers some items that came up during the deliberations on the third day and through email exchanges in the following days.

The Committee endorses a 5 year extension of the MOU. I repeat here the final recommendation in the Report:

> "The Committee recommends a 5 year extension of the collaborative agreement between RIKEN and Brookhaven National Laboratory to allow for the full utilization of RHIC for spin physics, heavy ion physics, and lattice gauge computation."

On behalf of the full Committee, I would like to express our appreciation for your hospitality during the Review. I would also like to take special note and to express our appreciation for the wise advice provided by Professors Nakai and Ukawa, who were invited to serve on the SRC this year because of the importance of this Review. Their input and perspective on the RIKEN-Brookhaven Collaboration from the Japanese side was especially helpful to the rest of the SRC members.

With our best wishes for the RBRC,

Sincerely yours,

Charles Y. Prescott
Chair, RBRC Scientific Review Committee

RBRC Scientific Review Committee Membership 2005

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