Report of the RBRC Scientific Review Committee
to the President of RIKEN

Brookhaven National Laboratory
November 17-18, 2008

I. Introduction

The last time the RBRC Scientific Review Committee met was November 5-6, 2007. This report discusses not only important developments over the past year and the immediate future plans of the RBRC, but also assesses the overall achievements and impact of the RBRC from its beginnings, and prospects for the future.

The Scientific Review Committee consists of four members from past reviews, plus two new members. The continuing members are Professors Wit Busza (Chair), Akira Masaike, Alfred Mueller and Akira Ukawa. The two new members are Professors Miklos Gyulassy and Richard Milner. The committee membership is listed in an appendix to this report, with members' addresses and affiliations.

At the opening of the meeting, at an executive session, the committee was pleased to hear the opening remarks given by Dr. Yasushige Yano, Director of the RIKEN Nishina Center for Accelerator-Based Science, who traveled to BNL specifically for the purpose of attending this Review.

Dr. Yano presented to the committee the organization of the RIKEN Nishina Center, the RIKEN Advisory Panels, and the role this review and report play in the flow of decisions at RIKEN. Important dates were highlighted for the Committee. He specifically mentioned the date of January 15-17, 2009 when the RIKEN Nishina Center Advisory Council will prepare recommendations of future programs (including RBRC) to forward to the RIKEN Advisory Council at the April 22-25, 2009 meeting. The Chairman of the RBRC Scientific Review Committee is expected to attend the January meeting to present a summary of their report. Dr. Yano emphasized that the current committee's report will constitute an important step in the decision on the future program of RBRC, and that the report should address the following questions posed by the President to the advisory council of each center:

1) Are there achievements with major scientific significance or achievements with significant social impacts?
    -Are there achievements that will be notable in the history of science?
2) How does the Center compare with similar research institutions abroad? Make recommendations for possible improvements based on this investigation.
    -Where does RIKEN rank in the worldwide research community?
3) Evaluate the Center's collaborations within RIKEN and with outside institutions, and evaluate the center's effort to promote international collaboration.
    -Are the center's collaborations resulting in better research achievements and more contributions to society?

In view of Dr. Yano's request, the committee decided to concentrate during this year's review not only on recent activities and achievements, but also on the "big picture" – on how successful RBRC has been over the years since it was founded, what scientific impact it has had, what has been its contribution to the education of young scientists and future leaders in the field as well as to international collaboration. Most important what are its future prospects?

In the report we start with a discussion of the current program and achievements of the recent past and plans for the future. Our assessment of the "big picture" is given at the end in lieu of a conclusion.

II. Overview of current program and plans

Dr. Nick Samios, the RBRC Director, presented an overview of progress since the November 2007 RBRC Review, on future plans, and on management issues.

He emphasized that the main physics interests of RBRC is the understanding of the spin structure of the proton, studying QCD matter at ultrahigh energy densities and Lattice QCD Calculations.

Related to the spin of the proton, he was particularly proud of the role RBRC physicists played in the Global Analysis of proton structure function data and in the measurements with spin polarized protons which indicate that the Gluon Contribution to the spin of the proton is small, consistent with zero.

Related to the high energy density matter studies he was particularly proud of the important contributions of RBRC theorists to the development of the Color Glass Condensate, Glasma and strongly interacting Quark Gluon Plasma (sQGP) concepts, and experimentalists for their sQGP studies with high P_t, J/ψ, heavy quark, and low P_t photon probes. Discussing lattice QCD calculations he pointed out the impressive quantity, breadth, and variety of results obtained with QCDOC. Dr. Samios also pointed out the important contribution of RBRC staff to the RHIC luminosity upgrade work, eRHIC capability studies and the development of the QCDX (300 Tflop) facility, and gave us an overview of recent RHIC performance and plans for the future. In the most recent run in d+Au, ten times the previous run luminosity was achieved, and in p+p, three times the previous p+p luminosity. Overall accelerator developments point to very promising future runs.

There have been suggestions based on theoretical considerations, lattice QCD calculations, and previous data obtained at CERN, that there is a Critical Point in the QCD phase diagram at lower energies. To clarify the situation a low energy ($\sqrt{s}$ = 9.2GeV) Au+Au trial at RHIC was performed, it was very successful in showing that a detailed search for the Critical Point at RHIC will be possible in the near future.

Tests of running RHIC with polarized protons at $\sqrt{s}$ = 500GeV, so important for antiquark distribution studies, were also successfully carried out, and ≈ 50% polarization in one ring was achieved.

It was clear from Dr. Samios' presentation that RHIC has a well thought out plan of runs through at least 2015.

Between 2009 and 2015 there are plans for 2 spin polarized (longitudinally and transversely) p+p runs at 200GeV, 3 spin polarized p+p runs at 500GeV, 3 Au+Au runs at 200GeV, a U+U run at 200GeV, and 2 low energy scans with heavy ions. During these runs, various detectors will be newly installed and commissioned, and the new ion source EBIS (which allows acceleration of uranium nuclei) commissioned. Polarization and luminosity upgrades will be completed, testing of transverse stochastic cooling and coherent electron cooling begun.

By 2015 very significant quantities of data with polarized p+p at 200GeV and 500 GeV, heavy ions at 200GeV and heavy ions at low energies will be collected and studied, giving crucial information on the spin structure of the proton and on heavy flavors, gamma-jet, and quarkonium production, as well as on multi-particle correlations in heavy ion collisions. Furthermore it will elucidate the question whether there is evidence in low energy collision data of a Critical Point in the QCD phase diagram.

At the end of his presentation, Dr. Samios discussed changes in the management of RBRC and the role RBRC plays in the career development of scientists and scientific leadership. He pointed out that Dr. H. En'yo remains the Associate Director of RBRC with Dr. Y. Akiba the Experimental Group Leader, with Dr. A. Deshpande his deputy.

Dr. Samios proudly showed the successes of RBRC in placing its young scientists in tenure and tenure-track academic positions. The quality of the upcoming scientists in RBRC has been high in the past and remains excellent today. RBRC continues to provide a first class career path for these young scientists.

He emphasized that RBRC scientists continue to be invited to give many talks at prestigious conferences and that in the last 12 months alone RBRC organized 5 high visibility workshops on spin physics and heavy ion collisions.

Dr. Samios concluded with a look to the future of RHIC/RBRC, full of excitements and opportunities. The 200GeV polarized p+p program will be completed and the 500GeV program begun. The role in the proton of the quark and gluon spin and orbital angular momentum will be clarified. In high energy Dense Matter studies more insight will be forthcoming from studies of the ridge, heavy flavors and direct photons, and we will have a better understanding of the sQGP, color glass condensate and Critical Point.
On the lattice computation front, a 300 Teraflop computer may be available. It will give us much information on the high temperature QCD phase transition, equation of state and the CKM matrix.

Furthermore, accelerator upgrades, stochastic cooling and coherent electron cooling will have led to a phased approach to the construction of an electron capability of the RHIC complex. This will allow for collisions of polarized electrons on polarized protons, as well as electrons on heavy ions in a truly unique situation.

III. Scientific Progress

A. Experimental Program

The experimental program of RBRC is to study QCD at the scientific frontiers using the unique capabilities of RHIC: to understand the spin structure of the proton and to explore matter at high temperature and density. We know that the quarks contribute about 25% to the spin ½ of the proton. What is the contribution of the gluons? What is the role of the quark sea? A hot, dense matter has been produced at RHIC with intriguing properties. Is this a plasma or is it a liquid? Can it be described by QCD or hydrodynamics? RBRC is playing a leading role in the quest at RHIC to provide answers to these fundamental questions, questions that are currently of great interest in the nuclear and particle communities.

The RBRC Experimental Group is addressing these questions through participation in the PHENIX Experimental Program.

Dr. Yasuyuki Akiba, in his overview talk in which he discussed recent progress, emphasized the important contributions of RBRC and RIKEN physicists to the operation of RHIC as a polarized pp collider and to the PHENIX research program. He pointed out that Y. Akiba and M.G. Perdekamp are two of the three spokespersons of PHENIX, and A. Deshpande was the PHENIX Run Coordinator during the last major pp run. Also that the RBRC Experimental Group is one of the two (with LBNL) leading institutions of the spin part of the PHENIX experiment.

Since the last review in spin physics at RHIC/PHENIX the RIKEN/RBRC group has focused on the double helicity asymmetry (A_{LL}) of π° production from runs 5 and 6, to obtain a better constraint on ΔG, the contribution to the proton spin from gluon polarization. With the new data, reduction of statistical errors eliminated many theoretical models and amazingly the value of gluon polarization is confirmed to be consistent with zero, too small to be a major carrier of the proton spin.

Other analyses include A_{LL} of the eta mesons, charged pions, direct photons, and electrons from heavy quark decays, as well as the single spin asymmetry at large x and studies of the spin dependence of quark fragmentation functions at the Belle experiment at KEK.

RBRC continues to be very active in the two polarimeters, which are vital components in the RHIC spin program.

In the heavy ion physics program at RHIC/PHENIX, the RIKEN/RBRC group has taken a leading role in the study of the production of particles at high P_t, J/ψ and heavy quark production and in studies of direct low P_t photons. These are some of the most important measurements aimed at elucidating the nature of the (s)QGP.

In order to explore the full physics opportunities at RHIC, The RBRC continues to be deeply involved in the PHENIX detector upgrades, in particular the muon trigger upgrade for W measurements and the Silicon Vertex Tracker Upgrade needed for the heavy quark studies.

We note that the contributions of the RBRC Experimental Group to the PHENIX experiment remains strong. Under the stewardship of Group Leader Y. Akiba, Deputy Group Leader A. Deshpande and RBRC Associate Director H. En'yo, the group is active and playing important roles in the RHIC/PHENIX scientific program. RIKEN/RBRC personnel have important roles in positions in the PHENIX collaboration. They are well represented at the Deputy Spokesperson level (2/3), on the Executive Council (4/14) and in the operations, upgrades, and analysis activities of PHENIX. They are playing a leading role in driving the publication of scientific papers from PHENIX, e.g. they have led the preparation of 27 of the 74 papers published by PHENIX since 2001.

The committee heard many detailed presentations related to this experimental program. They are summarized in the three following sections.

Heavy Ion Physics

Dr. Y. Akiba provided an overview of the activities of the RBRC Experimental Group in heavy ion physics. The recent focus has been on studies of the (s) QGP using penetrating probes. These include study of high p_T pion suppression, J/ψ suppression, and low p_T excess above scaled p-p expectations in direct photon detection. The direct photon excess is in qualitative agreement with the expectations from hydrodynamical models.

Dr. K. Okada made a detailed presentation on the direct photon measurements at PHENIX. Dr. Okada showed that the suppression of high pT hadrons, known as a jet quenching effect, is not occurring in the direct photon production. This is a great finding to support that the jet quenching is due to the creation of QGP. More definitive measurements of the double longitudinal asymmetry A_{LL} will be available in coming years with improved luminosities.

Dr. S. Bathe described his work on hard scattering physics in PHENIX with a possible future extension to work at LHC using the ATLAS detector. He described the effort under his leadership to calibrate the electromagnetic calorimeter towers in PHENIX. This involves six people and is expected to be completed soon. He again presented the R_{AA} vs. p_T plot first shown by Dr. Okada and speculated that if the direct photon data decrease at high p_T is true, then the LHC will have nothing to measure. He then described a program of jet measurements at the LHC using the ATLAS detector.

PHENIX Upgrades

The RBRC group is playing a leading role in the PHENIX upgrades.

Dr. I. Nakagawa presented an overview of the planned PHENIX measurements of the parity violating asymmetry in W production. This will provide a clean flavor separation of the quark polarizations. An upgrade of the muon trigger system in PHENIX is required. Additional trigger electronics for the cathode chamber readout and resistive plate chambers will be used to improve the triggering efficiency of the muon arms. These are being constructed by a collaboration of 12 institutions. The front end electronics for the muon trigger is being constructed by a collaboration of KEK, Kyoto University, RIKEN institute, and Rikkyo University in Japan and Seoul National University in South Korea. The upgrade projects are on schedule to take advantage of the expected increase in RHIC luminosity.

Dr. A. Taketani presented an overview of the PHENIX vertex tracker upgrade and discussed in detail the pixel detector. The vertex tracker is demanded by the need to separate the bottom and charm quark events in high luminosity heavy ion collisions and polarized proton collision. 50 μm displaced vertex resolution in a high luminosity environment is required. The ALICE readout chip is being used. Test beam performance has been encouraging. The pixel ladder design has been finalized for production.

Dr. M. Togawa discussed the strip detector and software development associated with the PHENIX vertex tracker upgrade. The world's first 2-dimensional readout from 1 side has been developed. Tests with a β-source and 120 GeV proton beam at Fermilab have been successful. Final preparations for mass production are underway and should enable installation in 2010. A full Monte Carlo simulation code has been developed and is being used in analysis preparation.

Spin physics

Dr. A. Deshpande provided a comprehensive overview of RBRC's activities in using the polarized beams at RHIC to study the spin structure of the proton using the PHENIX detector. In the years 2002 to 2006, the polarized beam capability at RHIC was developed in a truly impressive fashion. At 200 GeV center of mass energy, proton beams with 60% polarization were used to acquire 46 $pb^{-1}$of data in 2006. Precision polarimeters have been developed and systematic uncertainties are under control at the required level. Measurement of the double longitudinal polarization asymmetry (A_{LL})in the inclusive neutral pion production channel, eliminates the possibility that the gluons can be highly polarized along the proton's spin. Significantly more integrated luminosity data taking will be of great importance to constrain the gluon contribution more definitively.

Dr. K. Boyle described in detail the determination of ΔG by measuring the double helicity asymmetry (A_{LL}) in neutral pion production. The cross section measurement indicates that next-to-leading-order QCD is applicable at 200 GeV center of mass energy in neutral pion production. Global fits to data including PHENIX A_{LL} data yield $\Delta G \sim 0.2 \pm 0.2$.

Dr. D. Kawall described the PHENIX measurement of A_{LL} in charged hadron production at root s = 62.4 GeV. PHENIX recorded 50 nb^{-1} of data in longitudinally polarized pp collisions in 2006. A_{LL} was again consistent with zero and inconsistent with expectations based on gluons highly polarized along the proton spin direction.

Dr. R. Seidl described the measurement of fragmentation functions at Belle. The fragmentation functions which enter in the measurement of quark and gluon hard scattering processes can also be accessed in e+e- annihilation processes. The data clearly indicate that the Collins fragmentation function is large. Detailed studies are continuing. This is a fine example of the RBRC group taking advantage of data from another experiment to extract information essential to the science at RHIC.

Dr. Y. Goto described consideration of future Drell-Yan measurements with polarized proton beams. One motivation is that the sign of the Sivers fragmentation function in deep inelastic scattering is expected to be opposite to that in the Drell-Yan process. Both a collider experiment at center of mass energy 500 GeV and a fixed target experiment at center of mass energy 22 GeV were described. The internal target experiment would require dedicated operation of RHIC. These measurements would require integrated luminosities of more than 1,000 pb^{-1}.

Dr. Y. Watanabe described the analysis of RHIC data at the RIKEN CCJ. This is the principal remote site for computing associated with PHENIX data reconstruction. For example, all the proton-proton data was reconstructed at CCJ. It is also a regional Asia computing center. Since 2000, 18 official projects and 75 research plans have been completed for RBRC. A data transfer rate between BNL and RIKEN of over 5 TB/day has been sustained. The present CPU supports 12 Tflops. There are 20 TBytes of disk storage and 4 PBytes of tape storage. The data volume now is almost 1.5 PByte. By August 2009, all these capabilities will be significantly upgraded.

B. The theoretical program

The committee heard a presentation from Larry McLerran summarizing theory activities at RBRC, and we also had presentations from all current members of the RBRC University Fellows Program and from the current RBRC postdocs whose activities are described in more detail later. Fellows and postdocs are working on a wide variety of problems focused on QCD theory and on the phenomenology of heavy ion and hadronic physics. RBRC theorists interact and collaborate well with not only BNL theorists but also broadly in the US and Japan through their part time work at multiple associated universities and other national laboratories. Larry McLerran has been very successful locally in advising and mentoring the young postdocs as they make the transition from being students to becoming researchers and leaders in the field.

Brookhaven has become the world's leading center for hadronic theory and QCD, and this is in no small part due to the presence of RBRC theory at Brookhaven. It has especially become the leading center for training young theorists and, through the RBRC University Fellows Program, mentoring and nurturing the best of these up to the time that they receive tenure. We are quite impressed with the quality of both the theorists who have gone through the Fellows Program and also those that have been awarded faculty positions in Japan. There is no comparable program in theoretical physics that we are aware off which has trained so many young theorists of such high quality.

Individual theorists' presentations:
Feng Yuan presented a calculation of the angular dependence of mu-pair production in hadronic collisions when double initial state interactions are taken into account. The main result is that at small transverse momentum of the mu-pair a strong violation of the Lam-Tung relation is found. This is the first time a violation of the Lam-Tung relation has been found in a precise calculation. This is one of a number of quite interesting calculations that he has done on spin dependence in a variety of processes in high-energy collisions.

Cecilia Lunardini gave a presentation of a number of problems on which she has been working in neutrino astrophysics. She has been involved in collaborations determining the neutrino flux coming from supernova explosions as well as possible contributions coming from "failed explosions" which lead to collapses forming black holes. She is also looking for geochemical signatures of supernova explosions coming from prehistoric times.

Cyrille Marquet reviewed recent work he has been doing on medium induced energy loss of jets produced in a quark gluon plasma. He compared the picture in weak coupling QCD with that of a strong coupling supersymmetric Yang-Mills theory. He noted that the parametric forms for energy loss are the same in the weak coupling and strong coupling theories with the essential difference given in the value of the saturation momentum that one uses for the energy loss calculation and in the fact that the saturation momentum has a stronger medium length dependence in the strong coupling theory.

Anna Stasto presented recent work, done in collaboration with L. Motyka, on constructing an improved dipole wave function for high energy scattering. The idea is to impose exact kinematic constraints on the splitting which occurs in dipole evolution when one looks at small-x wave functions. They have determined a modified splitting kernel which gives an effective energy dependent cutoff on large dipole sizes and suppresses diffusion in impact parameter space. It appears that imposing exact kinematics includes much of the large next to leading order corrections done in standard small-x evolution.

Kirill Tuchin discussed work he is doing on incoherent and coherent diffractive gluon production in high-energy proton nucleus collisions. Coherent diffraction has a very strong energy dependence while incoherent production has a much weaker energy dependence. Coherent diffraction could be a sensitive way to look for saturation effects at small x, but it is important to, experimentally, distinguish coherent from incoherent diffraction.

Toru Kojo summarized work he has been doing on studying exotic components of meson wave functions, for example the four quark component of the sigma meson. A useful classification of exotic components is provided by determining the dependence of a component on the number of colors in the theory. In the case of the sigma meson the dominant large number of colors correction is given by four quark components which lower the sigma meson by 200 to 300 MeV.

Adam Lichtl presented a new direction of the RBRC theory suggesting a novel beam cooling for application to a muon collider. The scheme involves creating dispersion via a periodic lattice of alternating solenoids with tilts and offsets as pioneered at FNAL. The optimization of parameters of these systems are being studied with beam tracking codes and the work is coordinated with effort of the BNL accelerator design division.

Rainer Fries presented results of RHIC phenomenology studies aimed to identify promising diagnostic probes of the strongly coupled Quark Gluon Plasma at RHIC. Jet fragment into protons versus mesons was suggested to be sensitive to jet mean free path and other rare probes such as heavy quark jet quenching and negative elliptic flow of photons and strange fragments were predicted.

Denes Molnar presented new results based on the second order Israel-Stewart dissipative hydrodynamic equations in comparison to parton transport models on the problem of high transverse momentum elliptic asymmetry. These studies pave the way to use the data to infer a bound on the viscosity to entropy ratio of a strongly coupled quark gluon plasma. Calculations including bulk viscosity effects are underway.

Derek Teany also discussed the progress made during the last year on comparing hydrodynamics simulations with RHIC data on collective flow observables. He also described recent work on deriving the drag and diffusion coefficients of the quark gluon plasma using gravity dual AdS/CFT correspondence. The hope is that this correspondence can provide analytic insight into strongly coupled dynamical phenomena inaccessible via lattice QCD methods.

Yoshimasa Hidaka discussed the qualitatively different dynamics expected in partially deconfined plasmas with temperatures not far from the nominal cross over temperature Tc=196 MeV predicted by lattice QCD work of the RBRC/Columbia/BNL groups. A proposal was made that surprising smallness of the viscosity in the partial deconfined plasma to the fully deconfined plasma is proportional to the square of the Polyakov loop that vanishes rapidly as T decreases through Tc. The model however fails to predict the expected increase of viscosity to entropy ration in the confined phase.

Adrian Dumitru presented predictions of the momentum space asymmetry dependence of the gluon self energy in the Hard Thermal Loop approximation. The effective heavy quark potential and free energy were computed up to second order in the asymmetry parameter, which is proportional to the viscosity to entropy ratio. Plans for computing wavefunctions of quarkonia in anisotropic plasmas were presented.

C. Lattice QCD computing

Progress in lattice QCD computing at RBRC during 2007-2008 was reported in two parts. On the first day of the review, the RBRC postdocs and fellows presented the individual contributions in the Theory Presentations, while on the second day two overview talks encompassing the activities of the RBRC-Columbia-Brookhaven Collaboration as a whole were provided by Robert Mawhinney and Norman Christ. The finite temperature QCD studies carried out jointly with Karsch's group at BNL was briefly reported by Peter Petreczky in his representation as a fellow. Norman Christ also gave an update of the next machine project, which has been named QCDCQ (QCD with Chiral Quarks).

Lattice QCD computing at RBRC has two focuses, domain wall QCD which mainly explores hadron physics and implications to the Standard Model at zero temperature, and p4-staggered QCD which studies high temperature and density behavior of QGP.

In domain wall QCD, the Collaboration has been pushing forward simulations treating all three light quarks (up, down, strange) dynamically ("2+1 flavor simulations"). By the time of last year's Review, the first set of calculations at a lattice spacing of 1/a=1.73GeV on a 24^3x48x12 lattice were well underway. Since then, this set of calculations has been completed, and a second set of calculations at a smaller lattice spacing of 1/a=2.4GeV on a 32^3x64x16 lattice has been pursued. The purpose is to check the stability of results against decrease of the lattice spacing (continuum limit). The pion mass reached 300MeV in these calculations compared to the physical value of 140MeV. The principal results summarized by Robert Mawhinney are: (i) determination of quark masses and pseudoscaler decay constants for up-down and strange quark sector at 1/a=1.73GeV, (ii) determination of B_K, which is one of the crucial parameters for understanding the CP violation in the Standard Model, also at 1/a=1.73GeV, (iii) the finding in the course of (i) and (ii) that SU(3) chiral perturbation theory fails for the strange quark, whereas SU(2) chiral perturbation theory shows reasonable convergence in the up-down quark sector for the pion mass lighter than about 400MeV. The point (iii), albeit theoretical, has an important implication that the evaluation of the CP violation parameter ε'/ε in the K meson system cannot rely on SU(3) chiral perturbation theory, as has been practiced in many lattice calculations in the past; the $K \rightarrow \pi\pi$ decay has to be computed directly.

Study of finite-temperature QCD has been pursued by using the p4 staggered formalism for quarks, which is computationally less intensive than the domain wall formalism. This year's progress presented by Peter Petreczky are: (i) 2+1 calculation of the equation of state and other physical quantities for the temporal lattice size N_t=8, extending the calculations in the previous years for N_t=4, and 6 to examine the stability for smaller lattice spacings, which show that the difference from N_t=6 are small, (ii) calculation of fluctuation of conserved quantities such as charge, strangeness and baryon number as a possible probe of the critical point, (iii) study of screening masses which determines the correlation properties of QGP in the spatial directions.

Individual lattice physicists' presentations:
Masatoshi Hamada discussed how one can extract quark and gluon propagators at finite temperatures from lattice simulations. Using pure gluon background and Wilson-type quark action in the quenched approximation, he explored the behavior of quark propagator in the confined and deconfined phases.

Shigemi Ohta reported a series of calculations exploring the nucleon structure using 2+1 flavor domain wall QCD. The nucleon matrix element g_A/g_V, which was reported last year, has since been completed. It turned out that this quantity suffers from serious finite size effects on an L=2.6fm box employed in the calculation. An interesting finding is that all available data including the domain wall data follows an empirical scaling curve in terms of $m_\pi L$. New results on the moments of structure functions were presented.

Taku Izubuchi, who recently left Kanazawa University in Japan to take up a tenure-track position at BNL, reported a study of the η' meson in domain wall QCD. Using 2-flavor configurations and applying Z_2 random noise to calculate the disconnected part of the propagator, he obtained results for the η' meson mass in a rough agreement with experiment.

Yasumichi Aoki presented an improved method for determining renormalization constants non-perturbatively. He showed that working at a non-exceptional momentum for the operator to be renormalized leads to reduced contaminations from non-perturbative effects such as the pion pole. It was found that this method also leads to smaller truncation errors when matched on to continuum perturbation theory. The total systematic error in the renormalization factors are reduced to a few % level compared to the 10% level typical with the conventional determinations. With this method, systematic errors in the next round of determinations of quark masses and other physical observables are expected to be drastically reduced.

Thomas Blum discussed the motivations and possibilities of a simulation incorporating dynamical effects of photons. The main motivation comes from the recent discussions of the chiral magnetic effect, but other issues such as electromagnetic hadron mass splittings and light-by-light scattering contribution in g—2 are also relevant. He proposed a revision of the 2+1 flavor code into a 1+1+1 (Q=+2/3, -1/3, -1/3) code using the Columbia Physics System of code and libraries.

Tomomi Ishikawa discussed calculation of B meson matrix elements using a static approximation to b quark in domain wall QCD. He calculated the matching factor of O(a) improved heavy-light axial current perturbatively to one-loop order. Applying the results to B meson system, he obtained the decay constant, B parameters, and other quantities, which are important for CP violation in the B meson system.

Assessment of progress:
The Review Committee has learned that Lattice QCD computing has progressed well and at a steady pace at RBRC. Overall, the nature of the progress this year is more a consolidation of results which were already taking shape at the last year's review, compared to an explosive development in the years 2005-2007 which was brought about by the commissioning of QCDOC in 2005. Impressive results are accumulating both in terms of thrustful calculations such as that of B_K with domain wall QCD and the breadth and variety of quantities examined. The former is the best calculation so far of this phenomenologically important quantity, while the latter ranges from nucleon matrix elements to heavy quark properties, and finite-temperature observables for QGP studies.

The review Committee therefore considers that the lattice QCD computing activity has been making significant progress in great strides, fulfilling the aim set out at the beginning of the present MOU.

Experimental research in heavy ion collisions has been making an equally rapid progress, however, so that continued efforts are needed in lattice QCD computing to produce phenomenologically relevant quantities in a timely fashion. This applies perhaps more to finite-temperature/density calculations where the RHIC experiments are moving ahead from the finding of an almost perfect fluid behavior to the next stage of exploration including the identification of the possible critical point in the phase diagram. While this is not an issue specific to RBRC, lattice QCD has not produced quantities such as the transport coefficients in the presence of dynamical quarks which are basic to understand the fluid mechanics of QGP.

Near future of computing:
QCDOC, while exemplary efficient for lattice QCD computing, has been in operation already for three years. Last year, Norman Christ described a next machine project. This year, he presented the status of the joint Columbia-Edinburgh-IBM project to develop the next-generation system for QCD. The machine, now named QCDCQ (QCD with Chiral Quarks), aims to achieve 300 Tflops sustained and is to be completed in the summer of 2010. Two machines are planned, one in United Kingdom and the other in USA.

Lattice QCD computing at RBRC has reached the stage where domain wall QCD simulations on a 3fm box with a pion of mass 300MeV are possible. While this round of simulations have brought much progress, the pion mass is still heavy compared to the physical value of 140MeV. The necessity of an extrapolation from 300MeV to 140MeV to get the physical prediction is still a source of uncertainty and error. The trend has already started with computationally easier Wilson-type quark actions to reach the physical point and carry out simulations there. Domain wall QCD simulations have to follow this trend to maintain the advantage of chiral symmetry, and QCDCQ is meant to respond to this need.

The world of high performance computing is rapidly moving into the petaflops era. There are already two machines exceeding 1Pflops of peek speed in USA, and it is generally expected that 10 Pflops will be surpassed in a few years' time. The Review Committee considers that the development of QCDCQ is an important direction for RBRC to follow in order to keep its competitive edge in lattice QCD computing worldwide.

IV. Career Development

The RBRC continues to attract an excellent community of scientists. Success in its scientific program depends on attracting the finest young talent available and providing for them access to the scientific tools and academic environment where they can pursue their ideas. The RBRC staff has been successful through its close attention to the career development and career opportunities of its young scientists.

The overall staff level of RBRC has grown from about 20 in 2001 to 39 today.

Since the last RBRC Scientific Review in November 2007, three university fellows have been promoted to tenured positions, two have received appointments at universities as RBRC University Fellows, and one graduate of the RBRC program has been promoted to tenure track positions. Within the RBRC, there are two new fellows and two new postdocs. This record of successful academic appointments is an excellent testimonial to the strength of the program as viewed by a broad set of universities and institutions. RBRC fellows have a very fine reputation as evidenced by the number of awards they receive. Since 2007 Derek Teaney received a Sloan Foundation Fellowship, Cyrille Marquet a Marie Curie International Outgoing Fellowship and Raines Fries a IVPAP Young Scientist Prize in Nuclear Physics.

The RBRC regularly sponsors workshops, covering topics closely related to the RHIC physics. These workshops not only further the scientific research, but also provide the venues for exchanges of ideas and opportunities for reporting progress from the young scientists. The table below lists the recent workshops:

Workshop Title	Date	Conveners
Hydrodynamics in Heavy Ion Collisions and QCD Equation of State	April 21-22, 2008	Karsh, Kharzeev, Molnar, Petreczky and Teaney
Understanding QGP Through Spectral Functions and Euclidean Correlations	April 23-25, 2008	Mocsy and Petreczky
PKU-RBRC Workshop on Transverse Spin Physics	June 30 – July 4, 2008	Avakarian, Bunce, and Yuan
PHENIX Spinfest School 2008 at BNL	August 4-8, 2008	Aidala, Goto and Okada
The Ridge	September 2008	Longuare and McLerran

The RBRC has been exceptionally successful at promoting its young scientists into academic positions widely distributed in the US, Japan and other countries. This remains a major strength of the RBRC program.

V. Value, Impact and Opportunities of RBRC

As requested by Dr. Yasushige Yano in his opening remarks to the RBRC Scientific Review Committee, in this concluding discussion we do not limit ourselves to a review of the performance of the RBRC since the last review in November 2007, but give our overall assessment of how important and successful RBRC has been until now and to what extent the opportunities are there for the RBRC to continue fulfilling its mission. We attempt to answer the questions posed by the President to the Advisory Council of each center and stated in the introduction to this report.

To start with the bottom line, it is our overall assessment that the physics issues addressed by the RBRC are among the most important in particle and nuclear physics, that the results obtained to date are highly significant and of long term value, that the contribution of the RBRC scientists to the collaborative efforts have exceeded their relative numbers and that RBRC has in a very significant and positive manner fostered international collaboration and the development of young leaders in the field. Furthermore, there is good reason to believe that prospects are there for the RBRC to continue being a highly successful scientific enterprise with potential for major scientific discoveries.

A major strength of the RBRC research program is its focus on one broad topic, QCD. Its experimental program and theory program including the lattice computation program all are aimed at understanding the structure and properties of QCD matter.

We have a good understanding of the fundamental interactions of QCD and of the building blocks of QCD, the quarks and gluons. The difficulty is the solution of the QCD equations and understanding to what kinds of QCD matter these equations lead. The RBRC experimental program tackles this question with two programs, the proton spin program and the heavy ion program. The former studies the structure of protons, in particular how the various quarks and gluons inside the proton give rise to its one-half spin. It is a study of QCD at low temperature and density. The latter studies the properties of the hot excited high energy density state created in the collision of ultra relativistic heavy ion collisions. The aim is to study the phase diagram of QCD, i.e. see if and what new forms of hot QCD matter exists and what are its properties. The theory program focuses on laying the framework for the understanding of the experimental results and on solving the QCD equations on the lattice.

All this research clearly addresses very fundamental questions that are of great interest to both the nuclear and particle physics communities and have the potential for major scientific discoveries.

Since its inception in 1997, RBRC has been a major participant in the important scientific achievements at RHIC, in spin physics, in relativistic heavy ion physics and in large scale computing. Furthermore it has been instrumental in the training of a new generation of extremely talented physicists and fostering strong international collaboration between physicists in the US and Japan.

RBRC activities within the Spin Collaboration at BNL have been extremely positive. This is true of the numerous hardware components built and installed in the RHIC/AGS accelerator complex for the spin program, of the contributions to the PHENIX detector, and of the role played in the data collection and analysis of the results. Results to date have already ruled out several conjectures as to the gluon spin contribution to the spin of the proton, and more important, have demonstrated the potential at RHIC to finally unravel the mysteries of the origin of the spin of the nucleon.

The physics from the heavy ion program at RHIC has also been extremely exciting, and RBRC scientists have participated in, and often led, many of the analyses of data obtained with the PHENIX detector (as evidence of the important role that RBRC plays in PHENIX is the fact that currently 2 of the 3 spokesperson of PHENIX are from RBRC). A new state of matter has been discovered which is extremely strongly interacting and which appears to have unusually low viscosity. These phenomena are both new and somewhat unexpected, and are not fully understood. As such they have opened a whole new area of investigation, both on the theoretical and experimental fronts. Needless to say RBRC scientists are exploiting this opportunity and are in an excellent position to further exploit this opportunity over the coming years.

In computing, RBRC in collaboration with physicists from Columbia University and the UKQCD Collaboration, developed and explored the domain wall formalism of lattice QCD. This has brought major achievements both in terms of science and computer technologies. Because this formalism preserves chiral symmetry, many physically important quantities have become calculable. The most prominent result so far is the K meson B parameter B_K which is crucial for understanding the CP violation within the Standard Model. The computer power required to carry out these massive calculations were provided by QCDSP and QCDOC developed at Columbia University. In addition to bringing out major progress in lattice QCD, the energy-efficient massively parallel paradigm embodied in this series of computers have had a profound impact on high performance computing and computational sciences at large. This can be clearly seen in the success of IBM's BlueGene series of computers, which grew out of QCDOC.

It has to be said that the RBRC, in mode of operation, is quite unique. It is a relatively small research institute in a major laboratory setting. Its contribution to the overall research output is disproportionate to its size. For example, PHENIX, a collaboration of some 500 scientists last year published 13 papers. Of these, in 4, RBRC with 17 scientists played the leadership role. This example in itself illustrates how cost effective has been the RBRC effort.

The computing group at RBRC has had a very successful collaboration outside RIKEN, i.e., with the Theory Department of BNL, Columbia University, the UKQCD Collaboration in the United Kingdom, in particular Edinburgh University and Southampton University, and also with Bielefeld University in Germany. The research activity has been strengthened through the collaborations as it enhanced both computing resources and researchers focusing on the common target of domain wall QCD and staggered finite-temperature QCD. It is undoubtedly one of the leading collaborations in lattice QCD computing worldwide.

RBRC is a powerful example of the important benefits of international collaboration. It has enhanced the scientific output of RHIC and produced new knowledge for mankind, in the process training a cohort of excellent physicists and fostering a new generation of young leaders in the field of QCD worldwide. The RBRC record here is truly impressive when compared against comparable programs at other laboratories. It is widely admired as a model in international scientific collaboration. RBRC brings great credit to Japan for originating and generously supporting this important international enterprise.

Looking to the future, in a sense, today RBRC at RHIC is in a similar situation it was at inception, with one big difference. As before, in the next decade, there are major scientific opportunities at RHIC for RBRC. With increased collision luminosity, uranium beams and low energy scan capabilities plus the upgraded PHENIX, hot dense matter at RHIC energies will be studied in a comprehensive and precise way. The goal will be to reach a deeper understanding. This will require careful attention to systematic uncertainties, an emphasis on measurement of rare processes and close collaboration with theorists and lattice QCD computing. The RHIC-spin program will focus on achieving by about 2015 the most definitive determination of the gluon contribution to the proton's spin and measurement of the sea quark polarizations using W production.

In the longer term, the focus of RHIC will be on realizing eRHIC. This will be a powerful, unique tool of the study of QCD. Its capabilities will dramatically extend the limits of existing machines to probe the spin structure of the nucleon and the role of partons in nuclei.

As in 1997 RIKEN and Japan can get from RBRC a deep involvement in a world class physics facility for a rather modest cost. The one difference is that now the Japanese experimenters are in such high positions in the PHENIX collaboration and their contributions so significant that it is clear that the involvement is deep and beneficial to both sides. In the future there is the opportunity for RIKEN, again for a modest cost, to be involved in the development of an electron-ion facility, a facility which would become the world's leading hadronic physics facility.

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