critRHIC: The RHIC Low Energy Program

G S F Stephans
Laboratory for Nuclear Science, Massachusetts Institute of Technology, Cambridge, MA 02139 USA
E-mail: gsfs@mit.edu

Abstract.
Recent experimental and theoretical developments have motivated interest in a more detailed exploration of heavy ion collisions in the range $\sqrt{s_{NN}} = 5–15$ GeV. In contrast to interactions at the full RHIC energy of $\sqrt{s_{NN}} = 200$ GeV, such collisions result in systems characterized by much higher baryon chemical potential, $\mu_B$. Extensions of lattice QCD calculations to non-zero values of $\mu_B$ suggest that a critical point may exist in this region of the QCD phase diagram. Discovery of the critical point or, equivalently, determining the location where the phase transition from partonic to hadronic matter switches from a smooth crossover to 1st order would establish a major landmark in the phase diagram. Initial studies of Pb+Pb collisions in this energy range have revealed several unexpected features in the data. In response to these results, it has been suggested that the existing RHIC accelerator and experiments can be used to further the investigation of this important physics topic. This proceeding briefly summarizes the theoretical and experimental situation with particular emphasis on the conclusions from a RIKEN BNL workshop held in March of 2006.

PACS numbers: 25.75.-q, 25.75.Nq, 24.85.+p

Submitted to: J. Phys. G: Nucl. Part. Phys.

1. Introduction

The primary goal of experimental studies of heavy ion collisions at relativistic energies is the exploration of QCD matter at extremes of high temperature and density, in effect to map out a section of the QCD phase diagram. Recent work at the Relativistic Heavy Ion Collider (RHIC) at Brookhaven National Laboratory (BNL) has explored the high temperature, low baryon density regime [1,2]. The data show evidence for the creation of a novel equilibrated medium whose primary degrees of freedom are partonic. The constituents of this matter interact unexpectedly strongly with each other and it is almost opaque to high energy partons. Work exploring the properties of this new state of matter and the conditions necessary for its creation are ongoing. Simultaneously, recent experimental and theoretical developments have suggested that equally important discoveries are possible at higher baryon chemical potential, $\mu_B$. Specifically, lattice
QCD calculations suggest the presence of a critical point where the phase transition from partonic to hadronic degrees of freedom switches from the smooth crossover believed to exist at RHIC to a 1st order transition. On the experimental side, a variety of data in the range $\sqrt{s_{NN}}=5$–$15$ GeV, primarily unexpectedly non-monotonic behavior of several observables, hint at the presence of some novel processes. These factors led to the suggestion that the RHIC program might be extended to explore this additional region of the QCD phase diagram [3]. A detailed discussion of both the experimental and theoretical issues took place at a RIKEN BNL Research Center Workshop held from March 9–10, 2006 [4]. The workshop program is given in Table 1.

2. Theory of the QCD Critical Point

The possibility of a critical point in the QCD phase diagram is not a recent idea. While not specifically related to the critical point of current interest, early work used the so-called Glasgow method to extend QCD studies to non-zero $\mu_B$ [5]. Other more directly related theoretical work is reviewed in [6]. It was also realized early on that heavy ion collisions could be used to explore this physics [7]. Later, efforts began to extend lattice QCD into the high baryon density region [8], and this remains an area of active interest [9] [10] [11] [12] [13] [14] [15]. The existence of the critical point itself is not generally questioned since the presence of a smooth crossover at $\mu_B \approx 0$ is well established from lattice QCD calculations while there are equally valid, although less rigorous, expectations of a 1st order transition at very high $\mu_b$ and very low temperature [16]. Therefore, efforts are focused on determining the location and characteristics of the critical point. This remains very much a work in progress but values in the vicinity of $\mu_B \approx 450 \pm 250$ MeV appear quite reasonable. This is exactly the range at chemical freezeout extracted from fitting ratios of particles emitted in heavy ion collisions at $\sqrt{s_{NN}}=5$–$15$ GeV [17]. Preliminary indications are that the temperature of the critical point is not too far above those extracted from particle ratio data. Provided that the critical point and its associated 1st order phase transition line are not located at very high $\mu_B$ or at temperatures far above the chemical freezeout point, the systems created in heavy ion collisions should be sensitive to their influence.

3. Existing Data at High $\mu_B$

Another motivation for the interest in exploration of the high $\mu_B$ region of the phase diagram arises from unexpected features in several experimental observables measured by the NA49 experiment at the SPS [18]. Data were taken for Pb+Pb using a fixed target and beam energies of 20, 30, 40, 80, and 158 A·GeV. The results showed significant deviations from monotonicity, especially in the spectral shapes for kaons and the ratios of kaons to pions, which are difficult to reproduce in existing models [19]. A preliminary extraction of event-by-event fluctuations in the $K^+$ over $\pi^+$ ratio showed a significant excess over the expectations from hadronic cascade models [20]. Since these data were...
covered by other talks at this conference, they will not be discussed further.

4. Experimental Signatures of the Phase Structure

At present, there are many suggestions for how to search experimentally for evidence of the critical point and/or the 1st order phase transition. Most of the ideas are more qualitative in nature. Although the manifestations of the phase structure are unambiguous in some models, making quantitative connections to specific observables remains challenging. Not surprisingly, many of the proposals relate to fluctuations and correlations, including particle ratios, multiplicity, baryon number, and transverse momentum\cite{21, 22, 23, 24, 25}. In addition, bulk properties such as directed and elliptic flow, especially comparing pions to protons, are expected to be sensitive to this physics\cite{26, 27}. One aspect of particular interest to the experimental design is that the properties of initial interest are predominantly more global in nature and therefore do not require large event samples. Two aspects of the critical point itself may have significant consequences. First, although signals such as large susceptibilities peak exactly at the point, their values are significantly different from the average over an extended region in both temperature and $\mu_B$\cite{28}. Second, hydrodynamic calculations suggest that the phase space trajectories of evolving hot and dense QCD matter may be attracted to the vicinity of the critical point\cite{29}. If true, this implies that an experimental scan will not need to use very fine steps in $\sqrt{s_{NN}}$ to find evidence of the phase structure.

5. Machine and Detector Capabilities

By far the most important consideration in planning a low energy physics program at RHIC concerns the capability of the Tandem/AGS/RHIC complex to accelerate and collide ions at almost 2 orders of magnitude below the full RHIC design energy. From the start, the accelerator physicists focused their studies on the idea of injecting and colliding at each separate beam energy in RHIC, rather than injecting at a single energy and accelerating as was done for the higher energy running. The Tandem/AGS combination had previously been used to generate Au beams down to 2 A·GeV for the fixed target program so the only questions concerned transferring, circulating, and colliding the ions in RHIC. The very low beam rigidities present complications of magnet and power supply stability at low current and the low velocities result in beam physics issues of emittance and intrabeam scattering.

These potential problems have been evaluated and no clear obstacles to running RHIC in the range $\sqrt{s_{NN}}=5-15$ GeV were found. The emittance of the beam out of the AGS at the lowest energy is large, typically 5–6 $\pi$mm mrad, but this does not exceed the acceptance of the transfer line or the injection system for RHIC. Although some work will likely be needed on improving power supply quality, this is a well understood process. Tests described below indicate that there are no dramatic unexpected magnet problems. One disappointment in the early studies was that injecting Au ions which were not fully
Figure 1. Projections of minimum bias Au+Au event rate as a function of the energy in one beam (i.e. half of $\sqrt{s_{NN}}$). The line at the upper right represents rates already achieved, which scale closely with $\gamma^2$. At lower energies, the rate is expected to drop more quickly. The lines shown represent scaling with $\gamma^3$ and $\gamma^4$.

stripped will not be effective. This was investigated as a way to allow higher magnet currents at the lowest energies but calculations indicate that the RHIC vacuum is not good enough for stable circulating beams with remaining electrons. For fully stripped ions, beam lifetimes are expected to be more than sufficient for a physics program, with the dominant luminosity loss mechanism being the expansion of the bunches due to space charge effects. One challenge which remains to be solved is luminosity monitoring, which is done at higher energies using the Zero Degree Calorimeters. The resolution of the ZDC drops with beam energy and the increasing spread of the neutrons due to Fermi motion causes significant inefficiencies due to the limited aperture of the detector.

The most difficult aspects to evaluate without testing involve intrabeam scattering, bunch stability, beam profile, and other effects which impact the luminosity. The expected range is illustrated in Fig. 1 which shows the minimum bias Au+Au event rate as a function of the energy in an individual beam (i.e. half of $\sqrt{s_{NN}}$). The line starting at the upper right shows rates already achieved in the range from the normal injection energy of 9.8 A-GeV up to full RHIC energy. Recent improvements should allow raising these values by factors of $\sim 2$–5. The observed scaling with $\gamma^2$ is well understood and dominated by emittance and the fixed machine aperture. Below the current injection energy, it is expected that intrabeam scattering and other effects may be more dominant so that the rate will drop more quickly. Two possibilities (scaling with $\gamma^3$ and $\gamma^4$) are shown for illustration. Studies with colliding ion beams will be needed before the achievable rates can be better established.

One distinct advantage of lower energy beams is that the luminosity can be improved much more easily using electron cooling. Prototyping and testing is underway at BNL to develop a cooling system to increase the full energy luminosity for the future
RHIC-II and eRHIC facilities. Cooling of lower energy ion beams is easier technologically and therefore much simpler and less expensive to implement. Potential exists to increase low energy luminosity using cooling in both the AGS and RHIC. It is possible that existing equipment, either from other machines or being built as part of the RHIC-II development project, could provide most of the necessary hardware. Simulations have been performed which show that a fairly small installation could achieve dramatic reductions in the emittance in times of the order of minutes or less.

The overall conclusion of the machine evaluation to date is very encouraging. No major difficulties which would prevent running RHIC in collider mode at significantly lower energies were found. The projected rates are more than sufficient for an initial physics program and several possibilities of future improvements are available.

The RHIC program has been a spectacular success with the detectors producing a wealth of high quality physics results from a plethora of colliding systems. Since the physics observables and analyses of interest for lower energy running are largely those already studied at RHIC, the capability to perform the required measurements is well established. Of particular note is that many of these analyses have also been performed for p+p collisions which have much lower multiplicities. Therefore, even the needed adjustments for lower numbers of particles per event have been extensively investigated. Some adjustments to the normal Au+Au mode of operations, especially in the areas of triggering and centrality selection, must be made, but again the p+p experience will help. This area of the program appears to have almost no uncertainties to address.

One important issue that must be considered is the relative merit of studying the energy range of interest using colliding beams or fixed targets. The latter have a clear advantage in event rate which can in some cases be trivially boosted using multiple or thicker targets. Also, kinematic focusing concentrates a larger fraction of the center of mass frame solid angle into a specific detector area so larger acceptance can be achieved more easily. However, for measurements which do not depend on the highest possible event rate, and in particular when scanning a range of beam energies, the colliding beam arrangement has major advantages. Due to the fixed correspondence between detector geometry and the center of mass frame for the interaction, the acceptance, location, and absolute momentum of tracks at a given rapidity, as well as other aspects of the measurement, are independent of beam energy. This unchanging environment has enormous benefits in reducing systematic errors associated with comparing results across beam energies.

An illustration of another advantage of collider geometry is shown in Fig. 2 where the hit density on the detector is plotted versus $\sqrt{s_{NN}}$. For colliding beams, the hit density rises very slowly while kinematic focusing causes a much steeper dependence for fixed target experiments. This parameter directly relates to the detector occupancy and average track separation which can have a significant impact on the analysis capabilities. In addition, troublesome detector effects such as space charge and electronic baseline shifts, among others, get much worse as hit density increases. As for the effects mentioned above, this weak dependence of the detector environment on beam energy
critRHIC: The RHIC Low Energy Program

6. RHIC Machine Tests

Encouraged by the results of the RIKEN BNL workshop, RHIC management accepted the suggestion to perform preliminary machine studies to explore the machine capabilities for low energy running. In early June, 2006, protons were injected, circulated, and collided at $\sqrt{s}=22$ GeV. The choice of beam was dictated by the primary RHIC objective during this period which was collisions of high luminosity polarized protons. The magnet settings for this test corresponded to those needed for Au+Au at about $\sqrt{s_{NN}}=9$ GeV, or equivalently fixed target running with a beam energy of $\sim 40$ GeV. These values were chosen to be significantly lower than any used previously while sufficiently high for a reasonable chance of success. The results of this test were quite encouraging, with 2–3 hour lifetimes of the beam with collisions. No significant show-stoppers were found. Not surprisingly, some challenges were evident but they are ones the machine physicists know how to approach. In addition, extensive optics measurements were performed which allow development of machine settings for even lower energy. Plans for tests at lower energy using ions rather than protons are ongoing.

7. Related Experimental Programs

Exploring the QCD phase diagram using low energy running at RHIC is part of a broad heavy ion physics program. Higher energy running at RHIC will continue in order to extract detailed information about the novel partonic system formed at low baryon chemical potential [30]. In the future, these studies will be pushed to even higher energy using the LHC under construction at CERN [31]. More directly related experimental efforts using fixed targets are being planned both at the CERN SPS [32] and the future CBM experiment at the FAIR facility [33].

---

Figure 2. A comparison of particle densities at a distance of 1 m from the interaction for fixed target (upper points) and colliding beam (lower points) experiments. The beam energies range from the AGS (triangles) through the SPS (squares) and the lowest RHIC energy to date (circle). substantially reduces the relative systematic errors associated with an energy scan.
8. Conclusions

Recent experimental and theoretical results suggest that major discoveries are possible in the region of high baryon density accessible using heavy ion collisions at $\sqrt{s_{NN}} = 5\text{–}15$ GeV. Evaluations of machine and detector capabilities have shown that colliding beam experiments at RHIC have the potential to make enormous contributions in this area. The details of the proposed program are under active development.

References

[1] All four RHIC experiments summarized their early results in Nucl. Phys. A757; Arsene I et al (BRAHMS Collaboration) 2005 Nucl. Phys. A757 1, Back B B et al (PHOBOS Collaboration) 2005 Nucl. Phys. A757 28, Adams J et al (STAR Collaboration) 2005 Nucl. Phys. A757 102, Adcox K et al (PHENIX Collaboration) 2005 Nucl. Phys. A757 184

[2] BNL 73847-2005 Formal Rep. [http://www.bnl.gov/bnlweb/pubaf/pr/docs/Hunting-the-QGP.pdf]

[3] Stephans G S F 2003 Forward Physics at RHIC Workshop [http://www4.rcf.bnl.gov/~videbaek/fphar/Index.html]; presentations at BNL High Energy and Nuclear Physics Town Meeting and Nuclear Science Advisory Committee Meetings; 2004 Forward Physics Workshop at Kansas State Univ.; Workshop on Exploring the Phase Diagram of Strongly Interacting Matter [http://www.ikp.physik.uni-frankfurt.de/users/mitrov/Workshop/Workshop_StonyBrook.html]; 2005 Poster presentation at Quark Matter 2005 [http://www.rmkikfki.hu/~sikler/qm2005_poster.pdf]

[4] BNL 75692-2006 Formal Report, see also https://www.bnl.gov/riken/QCDRhic/

[5] BarBour I M et al 1997 Phys. Rev. D 56 7063

[6] Stephanov M A 2004 Prog. Theor. Phys. Suppl. 153 139, Stephanov M A 2005 Int. J. Mod. Phys. A20 4387, Stephanov M A 2004 Preprint hep-ph/0402115

[7] Stephanov M, Rajagopal K and Shuryak E 1998 Phys. Rev. Lett. 81 4816, Stephanov M, Rajagopal K and Shuryak E 1999 Phys. Rev. D 60 114028

[8] Fodor Z and Katz S D 2001 Preprint [hep-lat/0106002]

[9] Allton C R, Ejiri S, Hands S J, Kaczmarek O, Karsch F, Laermann E and Schmidt C 2003 Phys. Rev. D 68 014507

[10] Fodor Z and Katz S D 2004 J. High Energy Phys. 04 050

[11] Gavai R V and Gupta S 2005 Phys. Rev. D 71 114014

[12] See the contribution by K. Redlich to these proceedings.

[13] Stephanov MA 2006 Phys. Rev. D 73 094508

[14] Fujii H and Ohtani M 2004 Preprint [hep-ph/0401028]

[15] Philipsen O and de Forcrand P 2004 Preprint [hep-lat/0409034]

[16] Schäfer T 2003 Preprint [hep-ph/0304281]

[17] Cleymans J, Oeschler H, Redlich K and Wheaton S 2005 Preprint [hep-ph/0511094]

[18] See the contribution by M. C. Mitrovski to these proceedings.

[19] See the contribution by L. Sándor to these proceedings.

[20] Roland C 2004 J. Phys. G: Nucl. Part. Phys. 30 S1381

[21] Jeon S and Koch V 2003 Preprint [hep-ph/0304012]

[22] Koch V, Majumder A and Randrup J 2005 Phys. Rev. C 72 064903

[23] Koch V, Majumder A and Randrup J 2005 Phys. Rev. Lett. 95 182301

[24] Gavai R V and Gupta S 2006 Phys. Rev. D 73 014004

[25] Karsch F, Ejiri S and Redlich K 2005 Preprint [hep-ph/0510126]

[26] Stöcker H 2005 Nucl. Phys. A750 121, Stöcker H 2004 Preprint [nucl-th/0406018]

[27] Shuryak E 2005 Preprint [hep-ph/0504048]

[28] Hatta Y and Ikeda T 2003 Phys. Rev. D 67 014028
critRHIC: The RHIC Low Energy Program

[29] Asakawa M and Nonaka C 2005 Phys. Rev. C 71 044904
[30] The ongoing RHIC program is covered in many contributions to these proceedings as well as the recent Quark Matter 2005 conference.
[31] See the contributions by F. Antinori, P. Nevski and G. Veres to these proceedings.
[32] Gażdzicki M 2005 Preprint nucl-ex/0512034
[33] See the contribution by V. Friese to these proceedings.

Table 1. RIKEN BNL Workshop: Can We Discover the QCD Critical Point at RHIC?

| Title of talk                                                                 | Name                        |
|------------------------------------------------------------------------------|-----------------------------|
| Can we discover the QCD critical point at RHIC? Theoretical                   | K. Rajagopal               |
| Lattice results on the QCD critical point                                     | F. Karsch                  |
| QCD critical point and correlations                                         | M. Stephanov               |
| Can we discover the QCD critical point at RHIC? Experimental                 | G. Roland                  |
| Prospects for RHIC low energy operations                                     | T. Satogata                |
| Energy dependence of Pb+Pb collisions at the CERN SPS                        | P. Seyboth                 |
| Four special points of the high-mu RHIC                                      | E. Shuryak                 |
| Soft mode of the QCD critical point                                          | H. Fujii                   |
| Baryon number fluctuation near the critical point                            | Y. Hatta                   |
| Hydrodynamical evolution near the QCD critical point                         | C. Nonaka                  |
| Prospects of a new ion program at the CERN SPS                               | M. Gazdzicki               |
| PHENIX capabilities for the low-energy RHIC run                              | P. Steinberg               |
| Search for the critical point of QCD: STAR capabilities for low $\sqrt{s_{NN}}$ running | T. Nayak                   |
| Low energy operation of RHIC: AGS low energy extraction performance          | N. Tsoupas                 |
| Luminosity monitoring issues for low energy RHIC operations                  | A. Drees                   |
| Electron cooling in RHIC at low energies                                     | A. Fedotov                 |
| Energy dependence of thermal parameters in heavy ion collisions              | K. Redlich                 |
| Observable power laws at the QCD critical point                              | N. Antoniou                |
| The Compressed Baryonic Matter experiment at FAIR                            | P. Senger                  |
| Excitation function; experimental perspective                               | N. Xu                      |
| Experience with CERES                                                        | H. Appelshauser            |
| Critical point at SPS?                                                       | R. Stock                   |
| Lattice calculations at finite baryon potential                              | Z. Fodor                   |
| Fluctuations                                                                | V. Koch                    |
| Strangeness and phase changes in relativistic heavy ion collisions           | J. Rafelski                |
| Can we discover the first-order phase transition at RHIC?                    | J. Randrup                 |
| $v_1$- and $v_2$-flow: Barometry @ HiMu-RHIC - Pinning down the order of the phase transition | H. Stöcker                 |
| Summary/discussion: Prospects for experiments at RHIC                        | H.-G. Ritter T. Roser      |