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Prospects for an energy scan program at RHIC

Hans Georg Ritter*
LBNL
E-mail: HGRitter@lbl.gov

Plans are developed at RHIC to perform an energy scan down to very low energies, corresponding to the fixed target equivalent of the top AGS energy. The physics motivation is the search for the QCD critical point. Both, the STAR and the PHENIX experiments, are very well suited for such a program. The physics motivation, the experimental opportunities, the accelerator implementation, and the relationship to other programs, in particular the planned CBM experiment at FAIR/GSI, are discussed.

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1. Introduction

Experiments at RHIC have shown the existence of matter that is quite opaque to strongly interacting probes and whose constituents appear to be partons rather than hadrons [1 – 4]. The ongoing program of nuclear collisions at RHIC and the future heavy-ion program at LHC are devoted to determining the properties of the matter produced in high energy nuclear collisions. In heavy-ion collisions at RHIC energies and above, the area of high temperature and low net baryon density of the QCD phase diagram is populated. Our present understanding is that the partonic state is reached through a rapid cross-over from the regime where hadronic degrees of freedom are prevalent.

Stephanov, Rajagopal, and Shuryak predicted the existence of a QCD critical point at finite baryon density [5]. This finding was later confirmed by lattice QCD calculations [6 – 8]. Thus our present understanding of the QCD phase diagram is that at high baryon density a first order phase transition line separates the partonic regime from the hadronic one. This line terminates in a critical point. Beyond this point in the area of low net baryon density and high temperatures we encounter a cross-over.

Finding and identifying the QCD critical point is of fundamental interest. Experimentally the critical point might be reached by varying the center of mass collision energy within an appropriate range. Several experimental initiatives have embarced on this journey. This paper describes the prospect for a low energy scan at RHIC using the existing detectors.

2. Motivation for a Physics Program

Figure 1 shows a sketch of the phase diagram of nuclear matter where the temperature is shown as a function of net baryon density. The area of deconfined quarks and gluons can be reached with heavy-ion collisions in two different ways, indicated here by two different trajectories. At relatively low energies (FAIR SIS 300) the region of deconfinement is reached through a first order phase transition, whereas the corresponding trajectory at high energies (RHIC, LHC) would enter the quark-gluon plasma beyond the critical point that terminates the first order phase separation line. By varying the energy, e.g. going down from RHIC energies, one can expect two transitions, one where near the critical point the cross-over becomes a first order phase transition and one where the energy becomes too low to reach the deconfinement region. Each of the transitions is expected to leave experimentally detectable fingerprints.

Of particular interest of course is the quest to localize the critical point. Reaching the critical point in general requires an experimentally extremely carefully controlled environment, a condition that is not given in heavy-ion collisions, where the beam energy is the main control parameter. There are, however, indications from theory that some properties of the critical point may make direct identification possible. The susceptibilities are largest at the critical point, and the values are expected to be large over an extended area of temperature and baryon density [9, 8]. Hydrodynamical calculations also indicate that the critical point might attract the phase space trajectories [10]. In the absence of a clear experimental signature for a critical end point its existence probably could be inferred from the observation of a transition from a cross-over to a second order phase transition.

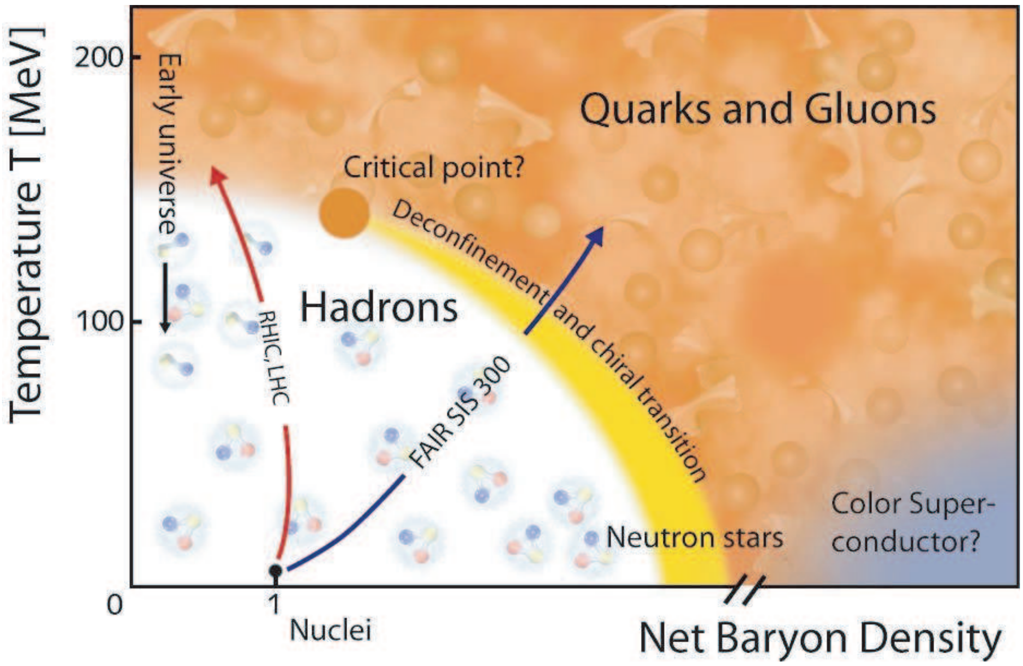

Figure 1: Phase diagram of nuclear matter. Plotted is the temperature as a function of net baryon density.

The observables proposed for the low energy scan at this early point are rather general in nature and need to be developed in the near future. On general grounds fluctuations [11 – 13] are expected to be large, especially in the vicinity of the critical point. Flow observables and in particular elliptic flow are expected to indicate a phase transition [14]. The program will concentrate on testing the possibility that the signatures for partonic collectivity observed at RHIC [1] will disappear once the collision energy is too low for a phase transition to occur.

There are experimental indications that the lower end of the CERN energy scan is a natural place where to start the search for the critical point. NA49 has measured a narrow enhancement (the "horn") of the kaon to pion ratio in this energy range [15]. Later NA49 also showed that the fluctuations of the ratio are large in the area of the "horn" [16].

3. Accelerator and experiment considerations

At RHIC the injection energy into the rings is 9.8 GeV/u. As the energy is increased, the attainable luminosity increases as γ^2. Figure 2 shows the expected rate in the zero-degree calorimeter as a function of beam energy. γ^2 scaling is indicated by the top curve. Machine physicists expect γ^2 scaling to be too optimistic if the machine operates in a mode where the beams are injected below the present injection energy, as is anticipated for the planned low energy runs. It is believed that a more realistic assumption would be scaling with γ^3 (middle curve) and that γ^4 scaling (lower curve) would be a lower limit [17]. From this graph we can conclude that we might expect interaction rates of the order of 1 per second for a run with $\sqrt{s} = 5GeV/u$. Initial tests have shown that those expected rates might be realistic and no show stoppers have been identified.

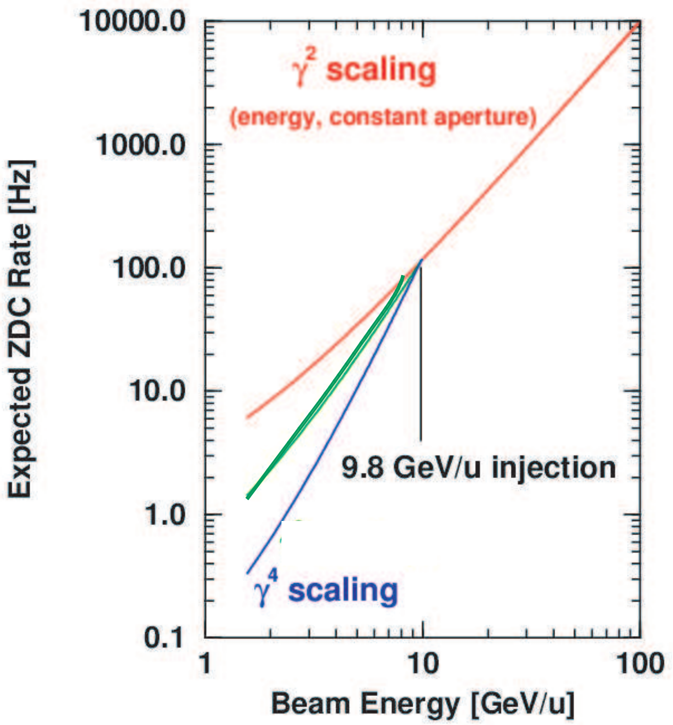

Figure 2: The expected trigger rate as a function of beam energy for different assumptions about scaling with γ below the normal injection point.

Machine studies also have indicated that the rates shown in Figure 2 could be improved by orders of magnitude with a relatively modest investment. By installing electron cooling in the RHIC ring, rates are expected to increase by a factor of 100, and cooling in the AGS could increase rates by another order of magnitude. It should be noted that the electron cooling needed for the low energy run is very different from the electron cooling discussed for the RHICII project (at very high energies) and much less challenging.

Performing a search for the critical point at RHIC experimentally has many advantages over a comparable program at a fixed target facility, like the SPS. The main advantage is that when performing a measurement at mid-rapidity, the detector acceptance remains constant for all collision energies [18]. Also, at mid-rapidity the particle density increases much slower compared to fixed target operation. In addition, at RHIC there are two calibrated experiments with excellent coverage and very good particle identification capabilities.

RHIC currently plans to have a short run at one energy in 2007. Depending on the outcome a longer run could be planned for 2009 or 2010. It is planned to do the scan of energies at the energies that correspond to the fixed target beam energies run at CERN. The correspondence between the fixed target energies at CERN and the beam energies at RHIC [19] are shown in the table below.

Both experiments, STAR [20] and PHENIX [21] are performing feasibility studies and are developing an attractive physics program.

$\sqrt{s}$	Fixed Target	Collider
4.86	11.6	2.43
6.27	20	3.13
7.62	30	3.81
8.77	40	4.38
12.3	80	6.15
17.3	158	8.65

4. Relationship to CBM at FAIR

The search for the critical point is part of the overall heavy-ion physics program. At the CERN SPS NA49 is proposing a moderate detector upgrade [22]. One of the main goals is to confirm the "horn" in the kaon to pion ratio measured by NA49 [15] and to mesure fluctuations with much better statistical significance [16].

If we assume that the planned programs to search for the critical point will answer the basic question of the existence of a critical point, such information will help to focus the physics program of the planned CBM experiment [23] at the FAIR facility. In this case CBM could concentrate on the measurement of D-meson and dileton production in the area of the critical point and thus perform a detailed study of the onset of deconfinement and chiral symmetry restoration.

5. Summary

Preparations at RHIC have started for a focused program to search for the QCD critical point by performing a low energy scan. The RHIC experiments are developing a compelling physics program that will be on its way a few years from now.

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