STAR experiment launches the QCD Critical Point Search Program at the Relativistic Heavy Ion Collider facility

Bedangadas Mohanty

Physical systems undergo phase transitions when external parameters such as temperature (T) or a chemical potential (μ) are tuned. A phase diagram tells us how matter organizes itself under external conditions at a given degree of freedom. The theory of strong interactions, quantum chromodynamics (QCD), predicts that nuclear matter at high temperature and/or densities makes a transition from a state where quarks and gluons (colour charge carrying basic constituents of matter) are confined in hadrons and chiral symmetry is broken, to a state where they are de-confined and chiral symmetry is restored. QCD has several conserved quantities: the baryon number (B), electric charge (Q) and strangeness (S). Each of these is associated to a chemical potential. As a result, the QCD phase diagram in principle is four-dimensional. It has been observed that μ_Q and μ_S are relatively small compared to μ_B (baryonic chemical potential). T and μ_B are varied in a typical QCD phase diagram as shown in Figure 1 (ref. 1).

Experimentally, the phase diagram can be accessed by colliding heavy ions at varying beam energies. Both T and μ_B vary as the function of beam energy of the collisions[2]. This strategy is followed by several experimental programmes like STAR and PHENIX experiments at the Relativistic Heavy Ion Collider (RHIC) in the Brookhaven National Laboratory (BNL), NA49 and SHINE experiments at the Super Proton Synchrotron (SPS) in the European Organization for Nuclear Research (CERN), CBM experiment at the Facility for Anti-proton and Ion Research (FAIR) in the Gesellschaft für Schwerionenforschung (GSI), and NICA at the Joint Institute for Nuclear Research (Russia) (JINR)[3].

Current understanding

Figure 2 depicts our current (both theory and experiment combined) understanding of the QCD phase diagram[4]. Close to $\mu_B = 0$, according to lattice QCD calculations, a crossover[5] occurs from the hadronic state to one where the relevant degree of freedom is partonic. The critical temperature (T_c) calculated from lattice QCD for such a transition is also shown; the range reflects the uncertainties in the theoretical calculations. Figure 2 also shows the temperatures at various stages of evolution in the heavy-ion collisions as a function of μ_B (or at different centre of mass energies, $\sqrt{s_{NN}}$). The μ_B values shown are estimated at chemical freeze-out (when inelastic collision ceases). The initial temperatures ($T_{initial}$) achieved at top RHIC and SPS energies are obtained from models that explain the direct photon measurements

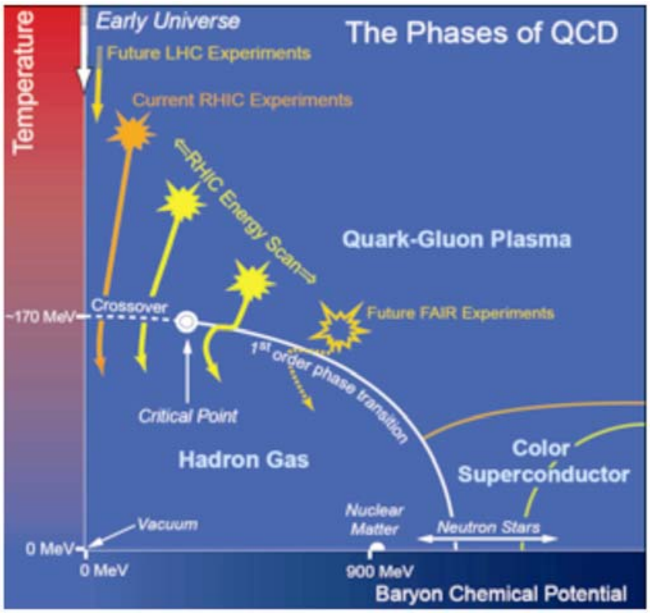

Figure 1. Typical quantum chromodynamics (QCD) phase diagram[1]. At high temperature and density, the phase is governed by quark and gluon degrees of freedom. At low temperature, the phase is governed by hadronic degrees of freedom. At zero baryonic chemical potential and at a temperature of about 170 MeV, transition between above two states is expected to be a crossover. At large baryonic chemical potential, the transition is conjectured to be a first order that ends with a critical point. The region explored by accelerator-based experimental programs at the Relativistic Heavy Ion Collider (RHIC), the Large Hadron Collider (LHC) and in future at the Facility for Anti-proton and Ion Research (FAIR) is shown. The QCD phase transition is the only one occurring in the early universe that has the right energy scale (Λ_{QCD} ~ 200 MeV) to be accessible by the experiments. At very large densities, other interesting phases like the colour superconducting phase start to appear. These regions start resembling matter existing in neutron stars.

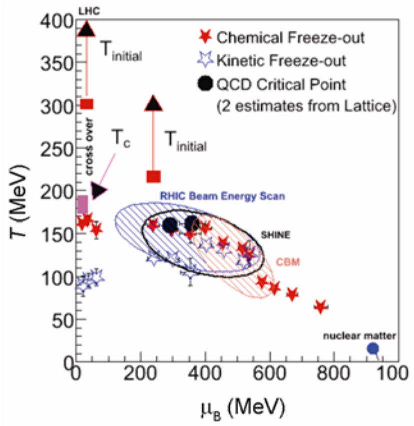

Figure 2. Current understanding of the QCD phase diagram[4]. Open star and solid star represent the chemical and kinetic freeze-out parameters (T, μ_B) in high-energy nuclear collisions respectively. The shaded area shows the regions of phase space covered by various experimental programmes to search for the critical point.

from the PHENIX experiment at RHIC, and the WA98 experiment at SPS. From these models, which assume that thermalization is achieved in the collisions within a timescale of 0.1–1.2 fm/c, the T_{initial} extracted is greater than 300 and 200 MeV at RHIC and SPS respectively. The T_{ch} (chemical freeze-out temperature) and T_{kin} (kinetic freeze-out temperature where elastic collision ceases) values extracted from particle ratios and momentum distributions of various hadrons respectively, from models assuming thermal equilibrium are also shown. It is interesting to observe that T_{ch} and T_{kin} values approach each other in the high-μ_B regime, implying that the chemical freeze-out and kinetic freeze-out take place simultaneously. Most QCD-based model calculations suggest that the phase transition at large μ_B is of first order. Two recent estimates of the QCD critical point in the $T-\mu_B$ plane taking T_c = 176 MeV show that it lies in the μ_B range 250–400 MeV (ref. 7). The shaded bands in Figure 2 indicate the region that will be covered by the various experimental programmes to search for the critical point.

The following are experimentally missing in the phase diagram and are proposed to be addressed by the STAR experiment in this decade at RHIC: (i) Location of the QCD critical point. (ii) Establishing the QCD phase boundary.

Strategy for the search of QCD critical point

The critical point search program requires a careful choice of experimental observables and steps in μ_B for this experimentally driven approach to locate the critical point. A non-monotonic dependence of observables sensitive to critical point on $\sqrt{s_{NN}}$ and an increase of long wavelength or low momentum number fluctuations should become apparent only near the critical point. For example, the rise and then fall of this signal as μ_B increases should allow us to ascertain the (T, μ_B) coordinates of the critical point. The magnitude of these non-monotonic excursions, as well as the probability that they will survive the final state interactions, are difficult to predict. Fortunately for the experiments, there may not be a need for the evolution trajectory of the system to pass precisely through the critical point in the (T, μ_B) plane to observe the signatures, as some hydrodynamic calculations show that the critical point attracts the evolution trajectories[6]. In such a case, if the trajectory misses the critical point by a few tens of MeV along the μ_B axis, the signature will be just as strong as if it were to pass directly through it. Note, however, that this attraction is not generic, and relies on specific features of the equation of state (EOS) near the critical point. Available lattice QCD calculations suggest the μ_B region of influence around critical point would be around 100 MeV (ref. 7).

One key observable

The STAR experiment has recently developed a new observable, based on results at previous energies, which can be used to look for critical point fluctuations at RHIC.

In a thermal system, the correlation length (ξ) diverges at the critical point. ξ is related to various moments of the distribution of conserved quantities such as net-baryons, net-charge and net-strangeness. Finite size and time effects in heavy-ion collisions put constraints on the values of ξ. A theoretical calculation suggests $\xi \approx$ 2–3 fm for heavy-ion collisions at RHIC[8]. It was recently shown by Stephanov[9] that higher moments of distribution of conserved quantities, measuring deviations from a Gaussian, have a sensitivity to critical point fluctuations that is better than that of variance (σ^2), due to a stronger dependence on ξ. As discussed by Stephanov[9], the numerator of the skewness goes as $\xi^{4.5}$ and kurtosis (κ) goes as ξ^7. In addition, crossing of the phase boundary can manifest itself by a change of sign of skewness as a function of energy density[10]. Furthermore, the lattice calculations and QCD-based models have shown that the moments of net-baryon distributions are related to the baryon number susceptibilities. The product $\kappa\sigma^2$, related to the ratio of fourth-order to second-order susceptibilities, shows a large deviation from unity near the critical point. Due to the connection between the ratios of the susceptibilities and the high-order correlation function, one can make a direct comparison between the quantities from experiment and lattice calculations[7]. Experimentally measuring event-by-event net-baryon numbers is difficult. However, the net-proton multiplicity distribution can serve as a reasonable replacement. Theoretical calculations have shown that net-proton fluctuations reflect the singularity of the charge and baryon number susceptibility as expected at the critical point[11].

Figure 3 shows the recent experimental results[12] on the energy dependence of $\kappa\sigma^2$ for net-protons, compared to several model calculations that do not include a critical point. Also shown at the top of Figure 3 are the μ_B values corresponding

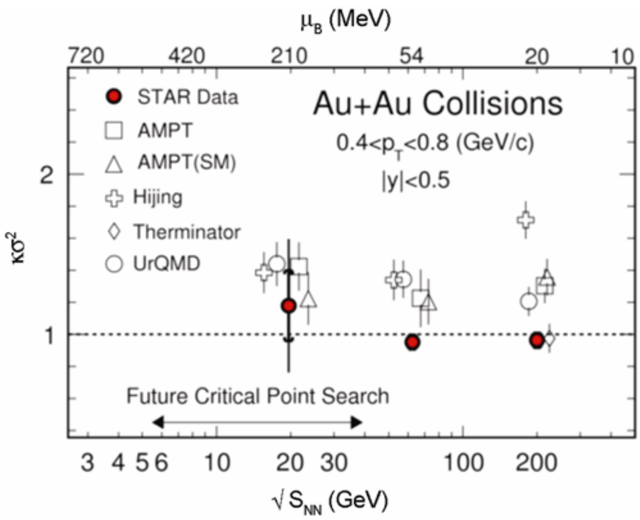

Figure 3. Energy and baryon-chemical potential dependence of $\kappa\sigma^2$ (proportional to ratio of fourth-order baryon number susceptibility to second-order baryon number susceptibility) for net-protons, compared to several model calculations that do not include a critical point. Experimental and model results are shown as filled symbols and open symbols respectively. Figure adapted from Aggarwal *et al.*[12].

Table 1. Collision energy and the corresponding chemical potential μ_B

$\sqrt{s_{NN}}$ (GeV)	5.0	7.7	11.5	18	27	39
μ_B (MeV)	550	410	300	230	151	112

Data from Cleymans *et al.*[13].

to various $\sqrt{s_{NN}}$. Within the experimental statistics and kinematics range, we have not yet observed any nonmonotonic beam energy dependence. The results, $\kappa\sigma^2$, from three collision energies are consistent with unity, which could imply that the system is thermalized with a small value of correlation length. The results from non-critical point models are constant as a function of $\sqrt{s_{NN}}$ and have values between 1 and 2. The result from the thermal model is exactly unity. Within the ambit of the models studied, the observable changes little with a change in non-critical point physics (such as collective expansion and particle production) at the various energies studied. From comparison to models and the lack of non-monotonic dependence of $\kappa\sigma^2$ on $\sqrt{s_{NN}}$ studied, we conclude that there is no indication from our measurements for a critical point. Clearly the data at RHIC during 2010 and 2011 will be crucial to bridge the gap in baryon chemical potential regions to search for the critical point in the QCD phase diagram. Lattice QCD provides predictions for these ratios. Away from the critical point, the fireball is expected to come to thermal equilibrium and the lattice results should agree with observations. Near the critical point the fireball will fall out of equilibrium because of critical slowing down[8], and hence the lattice results would not describe the data. If a non-monotonic behaviour of the $\kappa\sigma^2$ is seen, then it will be clear that the system has passed or is close to the critical point.

Experimental status and plan

The experimental plan is to vary the centre of mass energy ($\sqrt{s_{NN}}$) of heavy-ion collisions to scan the phase plane and, at each energy, search for signatures of the critical point that might survive the evolution of the system. This programme has started and the first phase of the STAR experimental programme[4] at RHIC is expected to be completed in 2010–2011 (Table 1).

The second phase of the BES programme at RHIC will depend on the results from the first phase. Finer steps in the beam energies or μ_B, and focused analysis are envisioned. From the collider side, electron cooling is expected at RHIC in order to increase the luminosity at the low-energy region. We anticipate that the second phase of this programme will be carried out during the period 2014–2015.

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Bedangadas Mohanty is in the Variable Energy Cyclotron Centre, Kolkata 700 064, India.
e-mail: bedanga@rcf.rhic.bnl.gov

United we land: Statistical physics explains decision making in bird flocks

Anjan K. Nandi

Animals moving collectively are a spectacular sight. Flocks of flying birds (Figure 1), schools of fish, herds of quadrupeds – examples of coordinated movement in a group, are abundant in nature. Humans also sometimes display similar kinds of behaviour, like pedestrian motion, vehicular traffic movements, etc. Even at the microscopic level, bacteria are known to exhibit collective motion for their survival under unfavourable conditions. How do they manage to do so? This question has been of great interest to scientists for many years. It appears that all the individuals in a group get the information about what all the others are doing, and act appropriately. But for a very large group, this is not a plausible assumption. Then how do they take such decisions and coordinate themselves in an orderly manner? This phenomenon of creating order, such collective decision-making for example, out of an initial disordered situation comes in the realm of statistical physics. Therefore, it is not surprising that physicists have become interested in this field,