Studies on the QCD Phase Diagram at SPS and FAIR

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Abstract. A review of results of the energy scan program at the CERN-SPS by the NA49 experiment is given. Presented are observables related to the search for a critical point in the QCD phase diagram and for the onset of deconfinement. Furthermore, the ongoing experimental program of NA61 at the CERN-SPS and the plans of the CBM experiment at FAIR are discussed.

1. The QCD Phase Diagram
The search for the onset of deconfinement and for a potential critical point in the QCD phase diagram is one of the main subjects of heavy ion physics today. Figure 1 summarizes in a schematic way the features of the QCD phase diagram. While there is a general consensus that the deconfinement phase transition is of the type of a cross over for $\mu_B = 0$ [1], little is known for the case $\mu_B > 0$. Several calculations predict that the cross over line will turn into a first order phase transition [2, 3, 4, 5], thus giving rise to the presence of a critical point in the QCD phase diagram, while other lattice QCD investigations result in a cross over for all $\mu_B$ [6]. Besides these theoretical considerations there are several experimental programs that try to address this point as well. In order to make progress on this issue, one needs to answer basically three questions:

- Is it possible to locate the onset of deconfinement in the $T-\mu_B$ plane experimentally?
- Can the data provide any evidence for a first order phase transition at higher $\mu_B$?
- Are there observables that would allow to uniquely identify a potential critical point?

By varying the center-of-mass energies $\sqrt{s_{NN}}$ of the heavy-ion reactions, experiments can scan large regions of the phase diagram. Depending on $\sqrt{s_{NN}}$ the chemical freeze-out happens at different positions along the freeze-out curve and therefore the trajectories of the reaction systems in the $T-\mu_B$ plane have to cross different areas of the phase diagram (as schematically indicated by the arrows in Fig. 1) and might even hit the critical area. In addition, the system size could provide a second control parameter for a systematic scan of the QCD phase diagram. In the following we review the most important experimental facts obtained by the energy scan program of the NA49 experiment at the CERN-SPS and discuss the programs of NA61 at the CERN-SPS and CBM at FAIR.
Figure 1. The QCD phase diagram. The arrows roughly indicate the different regions that can be explored by the current and future experimental programs.

2. Result from the SPS Program

In order to locate the onset of deconfinement one needs observables that are sensitive to the change of the number of degrees of freedom that is characterizing the transition from a Hadron Gas (HG) to a Quark-Gluon Plasma (QGP). Promising candidates are e.g. different flow observables. In [7] it has also been argued that the energy dependence of particle yields should reflect a phase transition as well. Indeed, a sharp maximum in the energy dependence of the $K^+/\pi^+$ ratio has been found [8], which is not described by any transport model and also not present in p+p data, but might be a signature for a first order phase transition [7].

The evolution of radial flow is to some extent visible the $\sqrt{s_{NN}}$ dependence of the mean transverse mass $\langle m_t \rangle - m_0$, as shown in Fig. 2 for three different particle species. While $\langle m_t \rangle - m_0$ exhibits a steep increase at lower energies, the rise is only very moderate for $\sqrt{s_{NN}} > 7 - 8$ GeV. This sudden change in the energy dependence might be indicative for a change of the equation-of-state [9], even though a further interpretation will require also a more thorough analysis with hydrodynamical models.

When the system trajectories in the $T$-$\mu_B$ plane get close to the critical point critical opalescence should set in, i.e. correlation lengths and susceptibilities will diverge. However, since heavy-ion reactions are naturally limited in their system size, correlations lengths $\xi$ can never exceed the size of the reaction system. Therefore, the critical behavior will be somewhat washed out in comparison to a infinite size system. Nevertheless, the critical behavior might manifest itself in enhanced fluctuations of observable quantities. These could include fluctuations of multiplicity, average $p_t$, or particle ratios. Of particular interest are fluctuations of conserved quantities, such as strangeness $S$, baryon number $B$, and charge $Q$ [11]. A sensitivity to higher orders of $\xi$ can be achieved by measuring higher moments of the related distributions.

Figure 3 shows the energy dependence of multiplicity fluctuations, as measured by the NA49 collaboration. The fluctuations are quantified by the scaled variance $\omega = \text{Var}(n)/\langle n \rangle$, where $n$ is the event-by-event multiplicity. While for all charged particles taken together $\omega$ is close to unity, it is slightly below one if negatively and positively charged particles are analyzed.
Figure 2. Energy dependence of the mean transverse mass \( \langle m_t \rangle - m_0 \) measured at midrapidity in central Pb+Pb and Au+Au collisions for \( \pi^\pm \) (left), \( K^\pm \) (middle), and p (p) [8]. Positively (negatively) charged hadrons are indicated by the solid (open) symbols.

separately, i.e. the distributions are a bit narrower than the corresponding Poissonian in these cases. However, in none of the studied charge combinations a significant energy dependence has so far been observed. Also shown in Fig. 3 are theoretical expectations for \( \omega \) which result from the combination of several assumptions [12]: the position of the critical point in terms of \( T \) and \( \mu_B \) is taken from a lattice QCD calculation [2], the magnitude of the fluctuations at the critical point is based on [14, 15], assuming two different correlation lengths \( \xi = 3 \text{ fm} \) (solid line) and \( \xi = 6 \text{ fm} \) (dashed line), while the widths of the enhancement around the critical point has been chosen according to [4] as \( \sigma(\mu_B) \approx 30 \text{ MeV} \). Both predictions are at variance with the data, so that up to now there is no evidence for a critical point in fluctuation measurements.

3. The Program of NA61 and CBM

The experimental setup of NA49 was inherited by the NA61 collaboration. After an upgrade of the apparatus (faster readout, addition of a Participant Spectator Detector (PSD)) this collaboration has started to extend the original NA49 program by a two-dimensional, i.e. system size and beam energy, scan. In order to produce beams of light ions the primary Pb ions from the SPS are send onto an internal C-target and the requested nucleus type is selected with high purity from the produced secondary ions by a beam spectrometer. After just finishing the measurement of p+p (six energies), p+C and Be+Be (three energies), the collaboration plans to continue with larger systems (Ar+Ca and Xe+La). First results from the p+p and p+C runs are already published [16, 17].

The study of the QCD phase diagram is also the main pillar of the physics program of the Compressed Baryonic Matter (CBM) experiment at FAIR (Facility for Antiproton and Ion Research). It will be a fixed target experiment at the SIS-100/300 accelerator, covering a beam energy range of 10–45 A GeV, and is currently being designed to cope with highest beam luminosities (up to \( 10^9 \) ions/s). Apart from the study of all soft hadronic observables, it will therefore also allow to systematically measure various rare probes (e.g. J/\( \psi \), open charm, multi-strange baryons, di-leptons, photons). In a startup phase (\( E_{\text{beam}} < 10 \text{ A GeV} \) at the SIS-100) it is planned to move the HADES spectrometer into the CBM cave and to combine it with a first version of the CBM setup. First data taking is planned for 2019. The physics program of CBM is presented in detail in the CBM physics book [18].
Figure 3. Energy dependence of multiplicity fluctuations, given by the scaled variance $\omega$, for the 1% most central Pb+Pb collisions in the forward rapidity region $(1.1 < y_\pi < y_{beam})$ as measured by the NA49 experiment [10, 12]. The different beam energies are represented by the corresponding $\mu_B$ values, determined by a statistical model fit [13]. The lines correspond to predictions for for critical point (see text).

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