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Evidence for the Onset of Deconfinement and Search for the Critical Point of QCD at the CERN SPS

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Abstract. Results of the NA49 experiment from an energy scan at the CERN SPS provided evidence for the onset of deconfinement. Theoretical considerations predict a critical point of strongly interacting matter accessible in the SPS energy range. A search in central Pb+Pb collisions has not found indications so far. A systematic continuation of the search will be performed by the successor experiment NA61/SHINE at the SPS.

Keywords: deconfinement, quark-gluon-plasma, critical point
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1. Introduction

Relativistic heavy-ion collisions have been widely used to study the properties of matter at extreme temperatures and densities. The study of nucleus–nucleus collisions at the CERN SPS offered for the first time the possibility of reaching energy densities in excess of ≈ 1 GeV/fm^3 during the early stage of the reaction. Under these conditions QCD predicts a phase transition between hadron gas and a state of quasifree quarks and gluons, the quark gluon plasma (QGP). Although predicted signatures of the QGP, e.g. strangeness enhancement, charmonia suppression and dilepton enhancement were observed in Pb+Pb collisions at the top SPS energy [1] their specificity has come under renewed scrutiny and motivated measurements of the energy dependence of various hadron production properties. These showed anomalies at low SPS energies which indicate that indeed the onset of deconfinement appears to occur around 30*A* GeV beam energy [2]. Final results from these studies will be reviewed. Moreover, QCD suggests that the first order phase transition boundary between QGP and hadrons at high baryon density ends in a critical point (see Fig. 1 (left)) and then turns into a rapid crossover at low baryon density [3]. In the vicinity of the critical point large fluctuations are expected [4]. This paper reports the status of the search for such fluctuations in central Pb+Pb collisions at the SPS. The successor experiment NA61/SHINE [5] will continue the search for evidence of this important prediction of QCD.

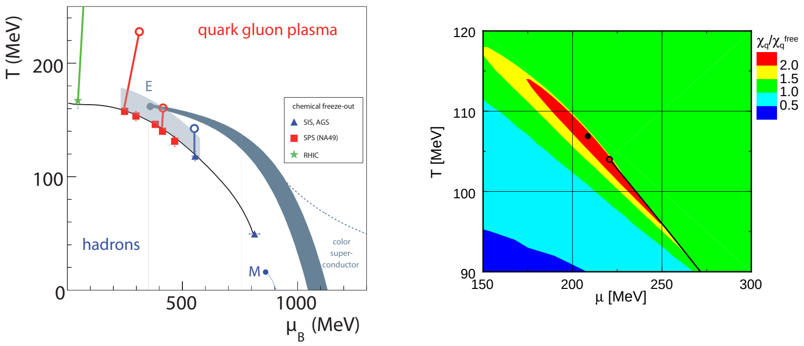

Fig. 1. Left: Phase diagram of strongly interacting matter with locations of freeze-out of the hadron composition at RHIC (star), SPS (squares), AGS and SIS (triangles). The shaded band indicates the first order phase boundary and E its critical endpoint as estimated by lattice QCD [3]. Right: Increase of the quark susceptibility in the vicinity of the critical point from effective QCD theory [7].

The NA49 detector is a large acceptance spectrometer [6] employing a system of time projection chambers (TPCs) for efficient tracking in the forward hemisphere of the reactions, precise momentum reconstruction and particle identification using the energy loss dE/dx in the TPC gas. Two time of flight (TOF) walls of 800 scintillator tiles each augment particle identification mainly near midrapidity. A forward calorimeter (VCAL) measures the energy of projectile spectator nucleons to determine the collision centrality. Results will be presented from an analysis of central Pb+Pb collisions which were recorded for SPS beam energies of 20A, 30A, 40A, 80A, and 158A GeV ($\sqrt{s_{NN}}$ = 6.3, 7.6, 8.7, 12.3 and 17.3 GeV).

2. Onset of deconfinement

The large acceptance of the NA49 detector, its particle identification capability and the forward-backward symmetry of Pb+Pb reactions allow the determination of total yields of numerous particle species. The statistical hadron gas model provides a good fit to these yields with 3 parameters, namely a temperature T, a baryochemical potential μ_B and a strangeness saturation parameter γ_s [8]. The resulting freeze-out points are plotted in the phase diagram of hadronic matter in Fig. 1 (left) and are seen to approach the estimated phase boundary and its critical end point [3]. In order to find out whether the early stage fireball actually reached hadron deconfinement the energy dependence of hadron production properties was studied in more detail. Rapid changes were found in central Pb+Pb collisions at the low

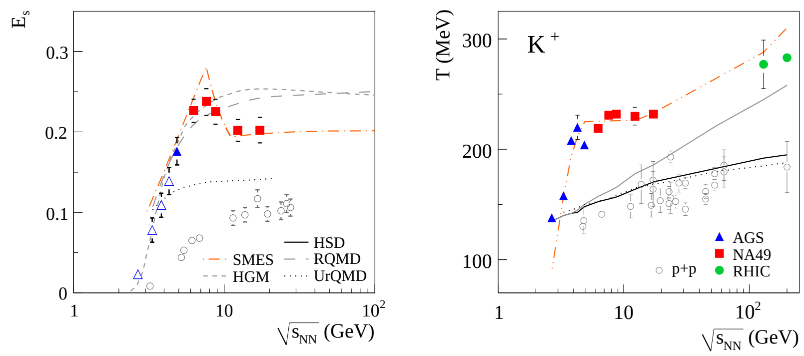

Fig. 2. Left: Ratio $E_S = (\langle K \rangle + \langle \Lambda \rangle)/\langle \pi \rangle$ of total number of strangeness carriers to pions versus collision energy. Right: Inverse slope parameter T of the invariant transverse mass distribution of K^+ mesons versus collison energy. Square symbols show NA49 results and are compared to measurements at lower and higher energies. Open circles show measurements in p+p reactions. The curves show various model predictions (see text).

end of the SPS energy range [9]. The increase of the pion yield per participating nucleon clearly steepens in the SPS energy region. In a statistical model scenario this can be interpreted as an increase of the effective degrees of freedom [10] by a factor ≈ 3 [9], consistent with the activation of quark-gluon degrees of freedom. The energy dependence of the production ratio of the total number of s and $\bar{s}$ quarks (as deduced from strange particle yields) to pions is plotted in Fig. 2 (left). It exhibits a sharp peak at low SPS energy with a fall-off to a lower plateau value consistent with the expectation for a deconfined phase (dash-dotted curve [10]). The described features are neither seen in p+p collisions (open dots) nor in purely hadronic model calculations using microscopic transport models (UrQMD [11] and HSD [12]) or the statistical hadron gas model (HGM [13]).

A phase transition is expected to also manifest itself in the momentum distributions and correlations of produced particles. A plot of the inverse slope parameter T of the invariant transverse mass distribution of K^+ mesons at midrapidity is shown in Fig. 2 (right). One observes a steep rise at low energies (due to increasing radial flow in the fireball) turning into a plateau at SPS energies which is not found in p+p reactions. This feature, also found for pions, protons and antiprotons [9], cannot be described by available hadronic models and suggests the onset of the phase transition with hadronisation through an intermediate mixed phase. A microscopic model incorporating a first order transition [14] can in fact reproduce the measurements (dash dotted curve). The softness of the equation of state near the onset of deconfinement is also seen in the sound velocity c_s (see Fig. 3 (left)) which has been derived from the pion rapidity distributions using the Landau hydrodynamical

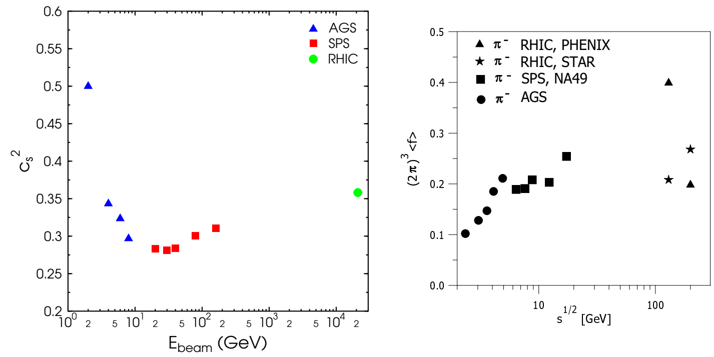

Fig. 3. Left: Sound velocity c_s in the fireball as determined from the width of the pion rapidity distribution using the Landau hydrodynamic model [15] versus energy. Right: Pion phase space density as determined from transverse mass spectra and fireball size derived from Bose-Einstein correlations [16]. Square symbols show NA49 results and are compared to measurements at lower and higher energies.

model [15]. Finally, a step in the energy dependence of the pion phase space density (see Fig. 3 (right)), as deduced from the pion transverse mass spectra and the fireball volume estimated from Bose-Einstein correlations [16], may also be related to the onset of deconfinement.

On the other hand, it was conjectured that a first order phase transition might results in a long lifetime of the fireball. This was predicted to show up in an increase of the ratio R_{out}/R_{side} in Bose-Einstein correlation measurements and a narrowing of the balance function. Neither of these effects was observed [19, 20]. Moreover, charge fluctuations should be smaller in a deconfined phase due to the smaller charges of quarks. Such a reduction was not seen experimentally (see Fig. 4 (left) [21]; apparently the hadronisation process erases this signature.

The discussed energy dependence of hadron production properties showed anomalies at low SPS energies [9] which indicate that deconfinement is reached in the early stage of the produced fireball for beam energies above about 30A GeV. Thus the evolution path of the fireball could pass close enough to the critical point such that its effect may show up as a maximum in fluctuations [4], in particular of particle multiplicity or transverse momenta. The results of the NA49 study of multiplicity [17] and transverse momentum fluctuations [18] are plotted in Fig. 5 and compared to expectations [4, 7] for the QCD critical point assuming the location estimated in [3]. Note that its effect is reduced both by the finite lifetime and size of the fireball (correlation length ξ between 3 and 6 fermi) as well as by the limited acceptance of NA49. Unfortunately, no indication of a peak is observed in the data.

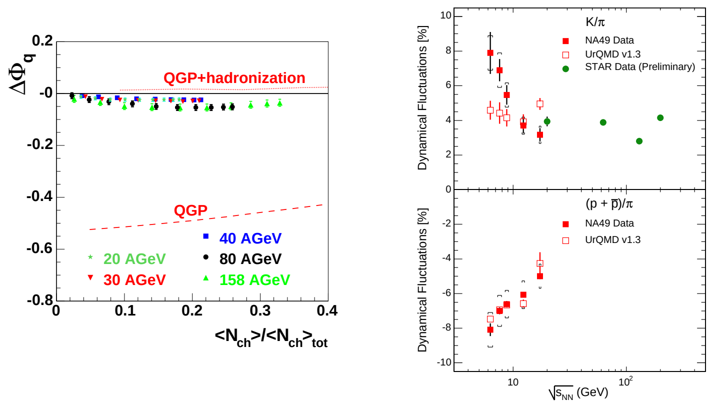

Fig. 4. Left: Electric charge fluctuations at SPS energies as function of the fraction of accepted particles (rapidity window). The plotted measure $\Delta\Phi_q$ is corrected for global charge conservation. Right: Non-statistical event-to-event fluctuations of the K/π and $(p+\bar{p})/\pi$ ratios versus energy. NA49 data are shown as solid squares, predictions of the UrQMD model by open squares and results from RHIC by dots.

3. Search for the critical point in fluctuations in NA49

Particle ratio fluctuations might also be affected by the critical point. Figure 4 (right) shows the non-statistical event-to-event fluctuations of the K/π and $(p+\bar{p})/\pi$ ratios versus energy [22]. The rise of the K/π fluctuations towards lower SPS energies is probably due to the onset of deconfinement [23] whereas the negative values for $(p+\bar{p})/\pi$ can be understood as an effect of nucleon resonance production.

4. Continuation of the search for the critical point in NA61

The indication that the fireball matter reaches deconfinement at the early stage of central Pb+Pb collisions at low SPS energies and theoretical estimates that place the critical point of QCD within reach at the SPS strongly motivate a systematic and more sensitive continuation of the NA49 studies. Figure 6 summarises the data sets taken in NA49 (left) and shows the explored region in T, μ_B of the phase diagram (right, square symbols). Experiment NA61/SHINE [5] will further explore the phase diagram by using lighter nuclei (see dots in Fig. 6 right), attempting to move the freeze-out point of the produced matter closer to the critical point. The planned data sets are shown in Fig. 7 (left). If the critical point is located in the theoretically estimated region and the expected fluctuations are not too much depressed by the finite size and lifetime of the fireball, a hill in fluctuations should

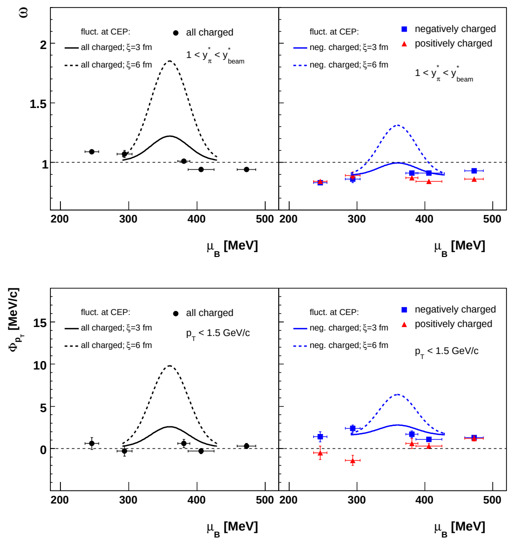

Fig. 5. Left: Dependence of the scaled variance ω of the multiplicity distribution on the baryochemical potential μ_B for center-of-mass pion rapidities $y_\pi > 1$. Right: Transverse momentum fluctuation measure Φ_{p_T} versus μ_B for $1.1 < y_\pi < 2.6$. Curves show expectations for the estimated critical point at $T \approx 160$ MeV and $\mu_B \approx 360$ MeV [3] and correlation lengths ξ of 6 (dashed) and 3 (solid) fermi. The values of μ_B were taken from statistical hadron gas model fits to particle yields [8] at each collision energy.

be observed in this scan as schematically drawn in Fig. 7 (right). In addition, the data of NA61/SHINE will allow a precision study of the location and the properties of the onset of deconfinement.

The NA61/SHINE experiment reuses most of the NA49 detector (magnets, TPCs, TOF walls) and features important upgrades. The DAQ system and the TPC readout after the front-end cards have been replaced to obtain a factor 10 increase of the data taking rate. A new forward calorimeter is under construction which will provide single spectator nucleon energy resolution. It will tightly constrain projectile spectator number fluctuations and thus improve the sensitivity of fluctuation studies. While primary light ion beams from the SPS would be preferable, conversion of the H2 beamline to a fragment separator is under study in order to be able to run in parallel with the LHC Pb program. Begin of the NA61/SHINE ion program is anticipated for 2011.

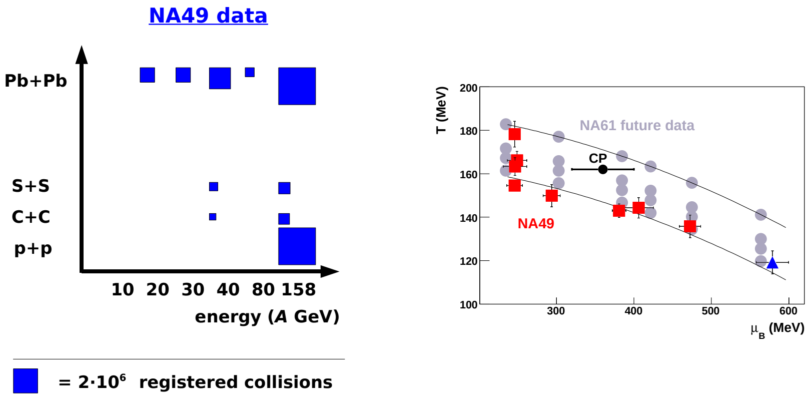

Fig. 6. Left: Data sets collected by NA49. Right: Patch of the T, μ_B phase diagram of matter. The squares show the freeze-out points of the hadron composition obtained from NA49 measurements. The dots represent the estimated freeze-out points for the future NA61/SHINE experiment. CP denotes the estimated position of the QCD critical point [3].

5. Conclusion

Measurements of NA49 at the CERN SPS indicate that deconfinement starts to occur at the early stage of central Pb+Pb collisions for beam energies above about 30A GeV. The freeze-out of the produced fireball happens close to the estimated position of the critical point in the phase diagram of hadron matter. However, no signals for fluctuations associated with the existence of the critical point have been found. The search for the critical point will continue at the SPS with experiment NA61/SHINE using lighter nuclei in order to possibly move the freeze-out point of the fireball closer to the critical point. Furthermore, the STAR experiment will search in Au+Au collisions with a low energy scan at RHIC with better acceptance and sensitivity. These complementary programs are expected to start in 2010/2011. Finally, there are also low-energy experiments planned at NICA in DUBNA and CBM at GSI which will join the search in later years.

Acknowledgments

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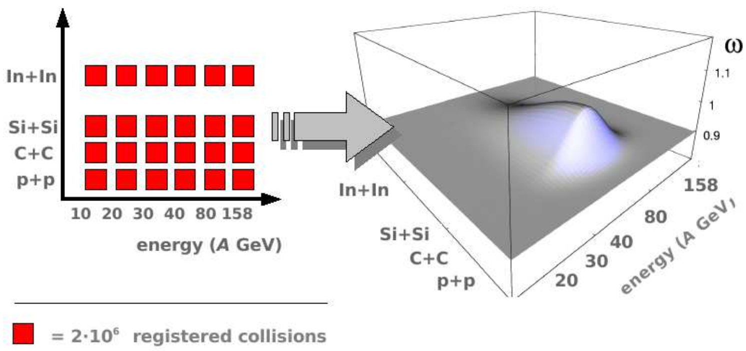

Fig. 7. Left: Data sets planned for NA61/SHINE. Right: Expected hill of fluctuations from effects of the critical point of QCD.

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