Indications of the onset of deconfinement at low SPS energies

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Abstract.
We present evidence for an onset of deconfinement at low SPS energies obtained by the NA49 experiment in central Pb+Pb collisions in an energy scan from 20 to 158 AGeV. As indicators for such an onset, the independence of mean $m_t$ on beam energy, a sharp peak in the strangeness-to-pion ratio and dynamical fluctuations in the event-by-event $K/\pi$ ratio are discussed.

1. Introduction
According to lattice QCD calculations, hadronic matter undergoes a transition to a deconfined phase once a critical energy density is surpassed [1]. High-energy collisions of heavy ions provide a tool to study the properties of strongly interacting matter under extreme conditions and, in particular, the phase transition and the deconfined phase. The NA49 collaboration has investigated central Pb+Pb collisions at beam energies between 20 and 158 AGeV ($\sqrt{s_{NN}} = 6.3 - 17.3$ GeV) in a search for signals of the onset of deconfinement.

The production of strange particles is one of the observables proposed as a signal of a deconfined state [2]. Therefore, one of the prime interests of NA49 is to measure spectra and yields of a multitude of strange particle species. In addition, event-by-event fluctuations possibly connected to a critical point in the phase diagram of strongly interacting matter have recently attracted attention. In the following, we present results on these observables obtained in the context of the NA49 energy scan programme, which indicate that indeed the transition from confined to deconfined matter occurs at low SPS energies.

NA49 [3] is a fixed target experiment operating at the CERN-SPS. Its basic components are four large-volume TPCs for the detection of the major part of the charged particles produced in the collisions. The large rapidity coverage allows the determination of rapidity-integrated yields. Particle identification is provided by the energy loss measurement in the TPCs. The PID capabilities are augmented by TOF detectors covering kaons at mid-rapidity.

For the study of the energy dependence of the relevant observables, the NA49 results are compared to data obtained at AGS and RHIC. A compilation of references to these data can be found in [4].

2. Transverse dynamics
The transverse-mass spectra of the particle species measured by NA49 at mid-rapidity for the beam energies 20 and 30 AGeV ($\sqrt{s_{NN}} = 6.3$ and 7.6 GeV) are shown in figure 1. The full lines
Figure 1. Transverse-mass spectra at midrapidity for various particle species in central Pb+Pb collisions at (left) 30 AGeV and (right) 20 AGeV beam energy. The full lines show the result of a simultaneous blast-wave fit [5] to the spectra. The pions were excluded from the fit.

Figure 2. (Left) Transverse-mass spectra of K$^+$ in central Pb+Pb collisions at five different beam energies. The full lines show exponential fits to the spectra. (Right) Inverse slope parameter of K$^+$ in central Pb+Pb (Au+Au) as function of CM energy. The open points show results from pp collisions.

show the result of a simultaneous blast-wave fit with constant velocity [5] to the spectra. Due to the influence of feeddown to the their yield, pions were excluded from the fit. Although such a parametrisation provides only an approximate description of the hydrodynamical behaviour, the good overall agreement indicates a common kinetic freeze-out behaviour of the measured particles. This also holds for the higher SPS energies (40, 80 and 158 AGeV, not shown).

While generally, the transverse spectra are curved in logarithmic representation due to the effect of transverse flow, the kaons turn out to be almost perfectly exponential as demonstrated in figure 2 (left). Surprisingly, the kaon inverse slopes are nearly the same for all SPS energies
measured by NA49. The excitation function shown in figure 2 (right) exhibits a steep rise at AGS energies, followed by a plateau st SPS energies and a further rise toward RHIC. Since the apparent temperature is caused by the "true" temperature and the transverse flow, this behaviour indicates a soft region in the equation of state which can be attributed to the mixed phase of a first-order phase transition [6, 7].

For other particles than kaons, the inverse slope parameter is less meaningful due to the deviation of the transverse-mass spectra from pure exponential. We thus calculated the mean \( m_t \) instead. Its energy dependence is presented in figure 3 for pions, kaons and protons. In all cases, the plateau-like structure is again observed, strengthening the conclusion of non-continuous behaviour of both temperature and transverse flow.

3. Strangeness-to-pion ratio

The broad rapidity coverage of the NA49 detector gives access to integrated particle yields. Figure 4 shows the energy dependence of the yields of the main strangeness carriers \( K^+ \), \( K^- \) and \( \Lambda \), normalised to the total pion yield. While \( K^+ \) and \( \Lambda \) exhibit a sharp maximum around 30 AGeV beam energy, the relative \( K^- \) yield evolves rather smoothly from AGS over SPS to RHIC energies. The full lines in figure 4 show the predictions of the hadron gas model (HGM), which smoothly parametrises the dependence of temperature and baryochemical potential on collision energy [8]. The comparison with the data shows that kaons are well described up to 30 AGeV but overestimated at higher SPS energies. In particular, the sharp peak in the \( K^+/\pi^- \) ratio cannot be accounted for by a smooth evolution of the system parameters as assumed by the model. For the \( \Lambda \) excitation function, the data at lower energies are less conclusive. While the overall description by the HGM is good, it predicts a maximum in the \( \Lambda/\pi^- \) ratio at top AGS energy, whereas NA49 observes a peak at 30 AGeV just as for the \( K^+ \).

Further information about the appropriateness of a purely hadronic description will arise from the measurement of the rare strange particles \( \Xi \) and \( \Omega \). At present, NA49 data are only available at 40 and 158 AGeV for these particles. Since the HGM predicts the maximum of the \( \Xi/\pi^- \) ratio to be above 40 AGeV beam energy, the \( \Xi \) measurement at lower energies could have discriminative power. Results of NA49 on \( \Xi \) production at low SPS energies are expected soon.

The measurement of the bulk strangeness carriers \( K \) and \( \Lambda \) allows the study of the total strangeness-to-pion ratio as a function of CM energy. Figure 5 presents the excitation function of the variable \( E_S = (\Lambda + 2(K^+ + K^-))/\pi \), compared to the prediction of the statistical model of the early stage [9], which assumes a phase transition from hadronic matter to the quark-gluon
plasma to take place at 30 AGeV beam energy. The good agreement between model and data provides strong evidence for such a scenario.

4. Event-by-event fluctuations
Lattice QCD predicts a critical endpoint in the phase diagram of strongly interacting matter, separating a region of first-order phase transition at high baryochemical potential from a smooth crossover at higher collision energies [1]. If the system passes near this critical point, large fluctuations are expected. NA49 has studied the eventwise kaon to pion ratio at five different beam energies. Figure 6 shows the results of this study compared to the fluctuations obtained with the hadronic transport model UrQMD [10]. The dynamical fluctuations, calculated as the quadratic difference of the widths of the same-event and mixed-event $K/\pi$ distributions, show a rise towards lower CM energies, which is not reproduced by UrQMD. In contrast, for the negative fluctuations seen in the proton-to-pion ratio, probably reflecting correlations due to resonance decays, perfect agreement between data and model is observed. A quantitative interpretation of the dynamical fluctuations in the $K/\pi$ ratio is, however, still lacking.
Figure 6. Dynamical event-by-event fluctuations of (left) the kaon-to-pion ratio and (right) the proton-to-pion ratio in central Pb+Pb collisions as functions of the CM energy. The NA49 data points correspond to 20, 30, 40, 80 and 158 AGeV, respectively.

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