Review of Results from the NA49 Collaboration

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Abstract. New results of the NA49 collaboration on strange particle production are presented. Rapidity and transverse mass spectra as well as total multiplicities are discussed. The study of their evolution from AGS over SPS to the highest RHIC energy reveals a couple of interesting features. These include a sudden change in the energy dependence of the $m_t$-spectra and of the yields of strange hadrons around 30 $A$GeV. Both are found to be difficult to be reproduced in a hadronic scenario, but might be an indication for a phase transition to a quark gluon plasma.

1. Introduction

In the recent years the NA49 experiment has collected data on Pb+Pb collisions at beam energies between 20 to 158 $A$GeV with the objective to cover the critical region of energy densities where the expected phase transition to a deconfined phase might occur in the early stage of the reactions. In this contribution the energy dependence of $m_t$- and rapidity-distributions, as well as the production rates of strange particles are reviewed. NA49 is a fixed target experiment at the CERN SPS and consists of a large acceptance magnetic spectrometer equipped with four TPCs as tracking devices and a forward calorimeter for centrality selection. Details on the experimental setup can be found in [1].

2. Rapidity spectra

The large acceptance of the NA49 spectrometer allows to measure particle spectra over a wide range of the longitudinal phase space. Fig. 1 shows a compilation of the rapidity distributions of $\pi^-$, $K^+$, $K^-$, $\phi$, $\Lambda$, and $\Lambda$. The shapes of these distributions are generally well described by a Gaussian. Only the $\Lambda$-distributions exhibit a strong variation of the shape. While at 30 $A$GeV they are still Gaussian-shaped, a clear plateau develops with increasing beam energy.

An increase of the RMS-widths of the rapidity spectra, calculated from the fits shown in Fig. 1 with beam energy can be observed which for the pions exhibits to a good approximation a linear dependence on the beam rapidity in the center-of-mass system $y_{beam}$ over the whole energy range covered by the AGS and SPS (see Fig. 2). Between 20 $A$GeV and 158 $A$GeV this is also true for the other particle types having
Figure 1. The rapidity spectra of hadrons produced in central Pb+Pb collisions (7% at 20-80 AGeV, 5% (π⁻, K⁺, K⁻) and 10% (φ, Λ, Λ) at 158 AGeV). The closed symbols indicate measured points, open points are reflected with respect to mid-rapidity. The solid lines represent fits with a single Gaussian or the sum of two Gaussians.

Figure 2. The RMS values of the rapidity distributions of π⁺, K⁺, φ, and Λ in central Pb+Pb (Au+Au) collisions as a function of y_{beam}. AGS data are taken from [2, 3]. The solid line is a linear fit to the pion data. The dashed lines have the same slope, but shifted to match the other particle species.
a Gaussian-like distribution, with a clear hierarchy in the widths: $\sigma(\pi^{-}) > \sigma(K^{+}) > \sigma(K^{-}) \approx \sigma(\phi) > \sigma(\Lambda)$. However, this seems to break down at lower energies, where the widths of the kaons apparently approach the ones of the pions.

![Figure 3](image.png)

Figure 3. The RMS-widths of the rapidity distribution as a function of the particle mass for central Pb+Pb collisions at different beam energies. Open symbols indicate negatively charged particles. The line has always the same slope and are plotted to guide the eye.

The dependence of the RMS-widths on the particle mass at SPS energies is shown in Fig. 3. An approximately linear mass dependence is observed, which appears to have the same slope for all SPS-energies. This mass dependence can be interpreted as a result of the thermal spectrum of hadrons superimposed on the longitudinal collective expansion.

3. Transverse mass spectra

The increase with energy of the inverse slope parameter $T$ of the kaon $m_t$-spectra, as derived from an exponential fit, exhibits a sharp change to a plateau around 30 AGeV [4]. Since the kaon $m_t$-spectra – in contrast to the ones of the lighter pions or the heavier protons – have to a good approximation an exponential shape, the inverse slope parameter provides in this case a good characterization of the spectra. For other particle species, however, the local slope of the spectra depends on $m_t$. Instead, the first moment of the $m_t$-spectra can be used to study their energy dependence. The dependence of $\langle m_t \rangle - m_0$ on the center of mass energy $\sqrt{s_{NN}}$ is summarized in Fig. 4. The change of the energy dependence around around a beam energy of 20 – 30 AGeV is clearly visible for pions and kaons. While $\langle m_t \rangle - m_0$ rises steeply in the AGS energy range, the rise is much weaker from the low SPS energies on. To a lesser extend this change is also seen for protons.
4. Particle yields

By integrating a measured rapidity distribution, as shown in Fig. 1, the total multiplicity of a given particle type can be determined. In Fig. 5 the energy dependence of the total multiplicities for a variety of strange hadrons, normalized to the total pion yield, is summarized and compared to model predictions. A detailed discussion can be found in [10]. Generally, it can be stated that string hadronic models UrQMD and HSD [11, 12] do not provide a good description of the data points. Especially the Ξ and Ω production is substantially underestimated and the maximum in the K⁻/π⁻ ratio is not reproduced. The statistical hadron gas models [13, 14], on the other hand, provide a better overall description of the measurements. However, the introduction of an energy dependent strangeness under-saturation factor γₜ is needed [14], in order to capture the structures in the energy dependence of most particle species (K⁺, K⁻, φ, Ξ).

From the measured total yields of the strange particles the energy dependence of the number of produced strange quarks and anti-quarks is constructed (see left panel of Fig. 6). The strange quark carriers which are taken into account are K⁻, K⁰, Λ (including Σ⁰), Ξ⁰, Ω⁻, and Σ±. For the strange anti-quark these are K⁺, K⁰, Λ (including Σ⁰), Ξ⁰, Ω⁺, and Σ±. The s- and ¯s-yields derived from the NA49 measurements agree at all energies, illustrating the consistency of the analysis. A departure from the energy dependence of strangeness production as observed at lower energies (indicated by the straight line) is observed around 30 AGeV. If divided by the total number of pions a clear maximum of the relative strangeness production at the same energy can be seen (right panel of Fig. 6). While the statistical hadron gas model with full strangeness

‡ The K⁰ contribution is calculated using isospin symmetry (∥K⁺∥ ≈ ⟨K⁰⟩, ⟨K⁻⟩ ≈ ⟨K⁰⟩). If no measurement is available, the values for the Ξ and Ω yields were taken from statistical model fits [14]. The Σ± contribution is estimated based on the empirical factor (∥Σ±∥ + ⟨Λ⟩)/⟨Λ⟩ = 1.6 [15]. Note that the strange quarks from the φ and η are not included.
equilibration [16] matches the data below this maximum quite well, it over-predicts the measurements at higher energies.

5. Conclusions

The results of the NA49 energy scan program have revealed a variety of interesting features. Among these are a clear change in the energy dependence of the $m_t$-spectra and a maximum in the strangeness to pion ratio around 30 AGeV. Both are difficult to explain in a hadronic scenario, but can be understood as a reflection of a phase transition [17, 18]. One of the most remarkable features of the phase diagram, shown in Fig. 7, is the fact that the line of the first order phase transition ends in a second order critical point $E$ (for a review of the current theoretical situation see [19]). Its position is subject to large theoretical uncertainties, but recent lattice calculations [20, 21] with physical quark masses indicate that it might be around $\mu_B = 360$ MeV. If this estimate...
Figure 6. Left: The total number of strange quarks and anti-quarks as carried by kaons and hyperons versus the collision energy for central Pb+Pb (Au+Au) reactions. The line represents a linear fit to the low energy data. Right: The ratio of the number of strange quarks and anti-quarks to the pion yield as a function of $\sqrt{s_{NN}}$. The solid line represents the prediction of the statistical hadron gas model with full equilibration of strangeness [14].

Figure 7. The phase diagram of strongly interacting matter. The curved lines represent the phase boundary between a hadron gas and a quark gluon plasma as expected from lattice calculations. The critical point $E$ is the endpoint of the first order transition line (thin line on the right side of $E$) [19]. On the left side of $E$ a smooth cross over is expected. The points are the chemical freeze-out points as derived from a fit with a statistical hadron gas model [14]. The open symbols schematically indicate possible initial parameters of the reaction systems, which then might evolve along paths as depicted by the vertical lines.

holds, it might be possible to access the critical endpoint with heavy ion reactions at
SPS energies. Since the above described results on the energy dependence of hadronic observables might indicate that the phase transition is already reached at beam energies of 30 AGeV, where the chemical freeze-out happens at \( \mu_B > 360 \) MeV. This would imply that at this energy the first order transition line is crossed (see vertical lines in Fig. 7), while at the top SPS energy the evolution passes through the rapid crossover region. Therefore, a careful scan of this region of beam energy, accompanied by an additional variation of the system size, might allow to experimentally identify the position of the endpoint. An indication for the endpoint would possibly be a strong increase of fluctuations in e.g. transverse momentum, particle ratios or multiplicities. So far, only limited attempts of systematically studying these effects in the interesting energy range have been made. Significant non-statistical fluctuations of the kaon to pion ratio at low SPS energies are reported in [22]. Also, large multiplicity and \( p_t \) fluctuations in collisions of small systems at 158 AGeVhave been observed [4]. However, these effects are still far from having a clear connection to the critical point. Future measurements that would scan the interesting energy range and the system size more closely, might have a chance of seeing stronger evidence for its existence.

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Notes
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