Strangeness in Quark Matter 2003

Strangeness from $20\,A\mathrm{GeV}$ to $158\,A\mathrm{GeV}$

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Abstract. New results from the energy scan programme of NA49, in particular kaon production at 30 *A*GeV and ϕ production at 40 and 80 *A*GeV are presented. The K^+/π^+ ratio shows a pronounced maximum at 30 *A*GeV; the kaon slope parameters are constant at SPS energies. Both findings support the scenario of a phase transition at about 30 *A*GeV beam energy. The ϕ/π ratio increases smoothly with beam energy, showing an energy dependence similar to K^-/π^-. The measured particle yields can be reproduced by a hadron gas model, with chemical freeze-out parameters on a smooth curve in the $T-\mu_B$ plane. The transverse spectra can be understood as resulting from a rapidly expanding, locally equilibrated source. No evidence for an earlier kinetic decoupling of heavy hyperons is found.

1. Introduction

Strange particle production provides an important tool to understand the reaction dynamics of relativistic heavy-ion collisions. The measured yields at top SPS energy can be interpreted as the result of the decay of a coherent prehadronic state, filling the available hadronic phase space. Several indications suggest that this state is indeed a deconfined phase of matter [1]. In order to search for onset phenomena signalling a phase transition at lower collision energies, the NA49 collaboration proposed an energy scan programme for central Pb+Pb collisions, spanning the beam energies between top AGS (11.7 *A*GeV) and top SPS (158 *A*GeV). This programme was completed in 2002 with data taking at 20 and 30 *A*GeV. In this contribution, we will focus on preliminary results on kaons at 30 *A*GeV and ϕ mesons at 40 and 80 *A*GeV. NA49 results on the energy dependence of Λ production were shown recently [2]; preliminary data of Ξ and Ω were presented in this conference [3, 4].

Table 1. Data sets taken in the NA49 energy scan programme. For the analysis at 158 *A*GeV, the 5 % most central events were selected offline.

E_{beam} [AGeV]	$\sqrt{s}$ [AGeV]	y_{cm}	Centrality	Event Statistics	Run period
158	17.3	2.91	10 %	800 k	1996
158	17.3	2.91	20 %	3,000 k	2000
80	12.3	2.57	7 %	300 k	2000
40	8.8	2.22	7 %	700 k	1999
30	7.6	2.08	7 %	400 k	2002
20	6.4	1.88	7 %	300 k	2002

2. Experiment and data sets

The NA49 detector [5], operating in fixed-target mode at the CERN-SPS, consists mainly of four large tracking chambers backed up with TOF scintillator walls. Momentum determination is provided by tracking in the field of two superconducting magnets; the collision centrality is determined from the measurement of the energy deposited in a zero-degree calorimeter. Particle identification is achieved by the measurements of the specific energy loss dE/dx (resolution $\approx 4\,\%$) in the TPCs and the time-of-flight (resolution $\approx 60\,\mathrm{ps}$) with the scintillator walls. The magnetic field was scaled proportional to the beam energy to achieve similar geometrical acceptances. Table 1 summarises the data sets taken within the energy scan programme. The data at 20 *A*GeV are not yet analysed.

3. Kaon and pion production

In addition to the published results for 40, 80 and 158 *A*GeV [6], we have recently analysed kaon and pion production at 30 *A*GeV. Depending on their momentum, charged kaons were identified by TOF, combined TOF and dE/dx or dE/dx alone, as figure 1 illustrates. GEANT calculations were used to correct the raw yields for geometrical acceptance, in-flight decay and the efficiency of the time-of-flight system. The losses due to track reconstruction inefficiencies were studied by embedding simulated tracks into real raw data events and reconstructing them with the standard software. π^- yields were obtained from the distributions of all negatively charged hadrons by subtraction of the contributions from K^-, $\bar{p}$, e^- and secondary hadrons from weak decays and interactions in the detector. The π^+ were not measured directly but calculated from the π^- yield assuming that the π^+/π^- ratio, which was measured in regions where both TOF and dE/dx information were available, is constant over phase space. Details of the kaon and pion analyses are given in [6].

The newly obtained midrapidity m_t spectra of K^+ and K^- at 30 *A*GeV, measured in the TOF system, are compared in figure 2 to those at higher beam energies. At all

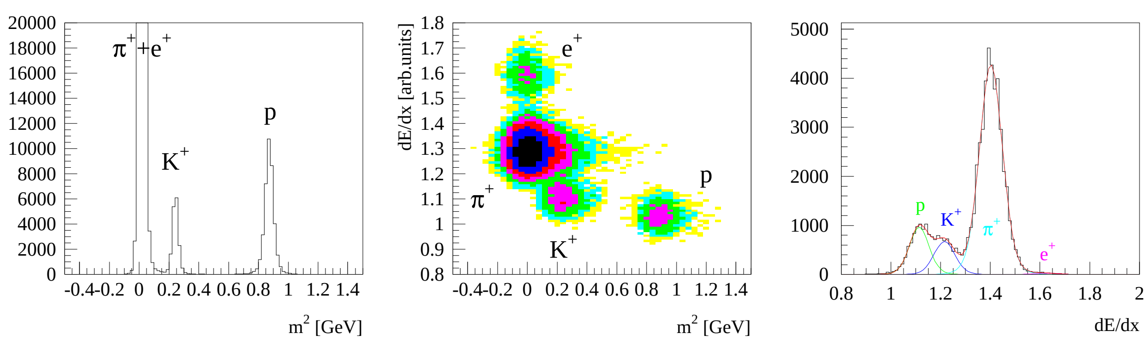

Figure 1. Examples for kaon identification in NA49 at 40 *A*GeV. Left: TOF ($p = 2\,\mathrm{GeV}$); centre: TOF+dE/dx ($p = 6\,\mathrm{GeV}$); right: dE/dx ($p = 15\,\mathrm{GeV}$).

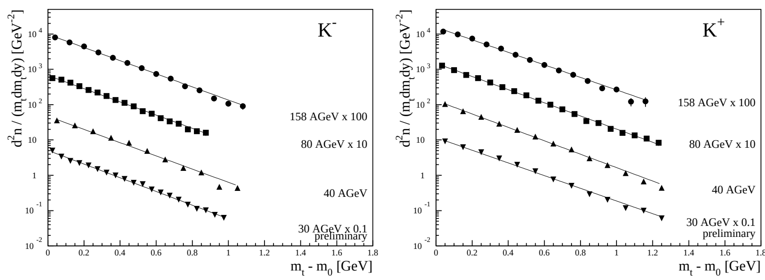

Figure 2. Transverse spectra at midrapidity for K^- and K^+, measured in the time-of-flight system. The spectra for the different beam energies are scaled for better visibility.

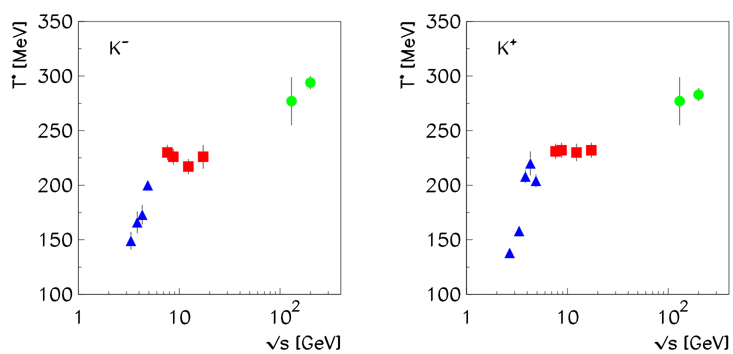

Figure 3. Slope parameters for K^+ and K^- as measured by NA49, compared to measurements at AGS and RHIC (for references see [6]), as functions of collision energy.

energies, the spectra exhibit an exponential shape to very good accuracy. Moreover, a thermal fit of the form $\frac{\mathrm{d}N}{m_t \mathrm{d}m_t \mathrm{d}y} \propto \mathrm{e}^{-m_t/T}$ yields almost identical slope parameters for all beam energies as demonstrated in figure 3. The excitation function of T shows a steep rise for AGS energies, stays constant over the complete SPS energy range and rises again towards the values measured at RHIC. This surprising result points towards a softening of the equation of state at SPS energies as discussed in [7].

Extrapolating the measured yields to full p_t by the exponential fit function, we obtained the midrapidity yield ratios as plotted in figure 4. The K^+/π^+ ratio at 30 AGeV confirms the previously observed trend of a decrease in this ratio with beam energy at SPS [6]. The K^-/π^- ratio seems to also show a small irregularity at 30 AGeV. In contrast, no anomalous behaviour is seen in the K^-/K^+ ratio.

The rapidity spectra of charged kaons and π^- as measured by NA49 are shown in figure 5. They were parametrised by the sum of two Gaussians displaced symmetrically with respect to midrapidity as indicated by the full lines. We observe an increase of the width of the rapidity distributions with beam energy for all three particle types.

Total yields were obtained by integrating the fits to the measured rapidity

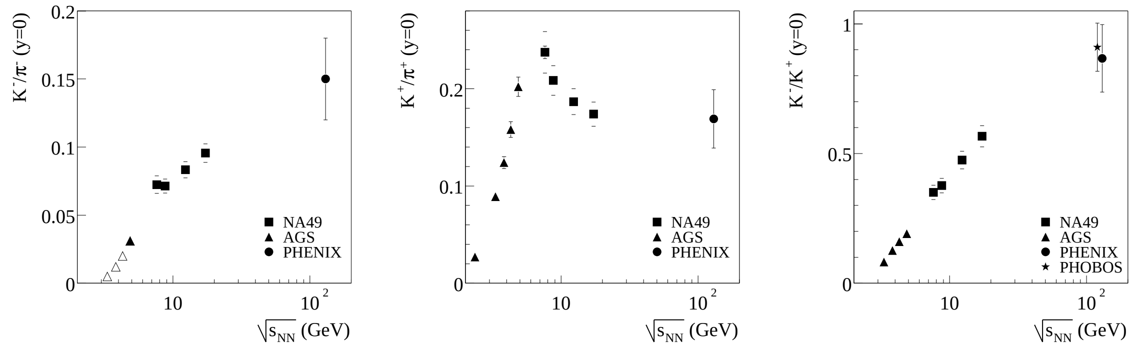

Figure 4. Midrapidity yield ratios as functions of collision energy. References for the measurements at AGS and RHIC can be found in [6].

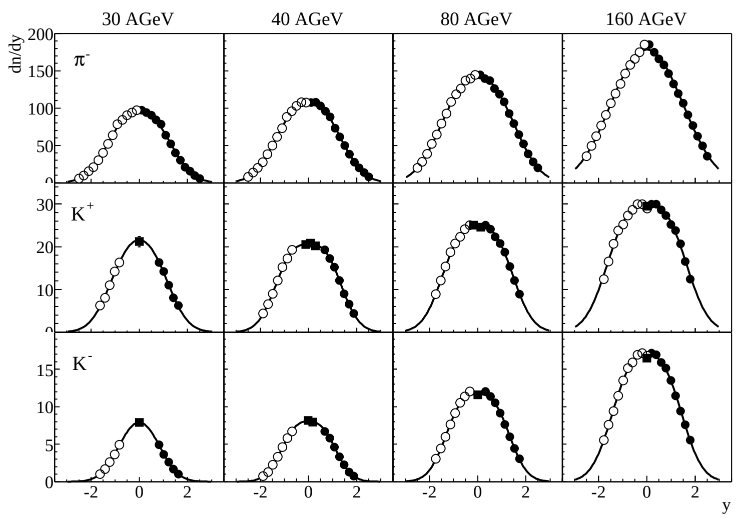

Figure 5. Rapidity distributions of π^-, K^+ and K^- for four different beam energies. Filled symbols are measured, open ones are reflected at midrapidity. Squares denote the TOF measurements, circles the dE/dx results.

distributions. Comparing figure 6 to figure 4, it can be seen that the energy dependencies of the K/π ratios in full phase space are similar to those at midrapidity. A sharp maximum is observed at 30 AGeV in K^+/π^+, which is not reproduced by either the extended hadron gas model [8] or transport codes [9, 10]. It should be noted that this behaviour is not seen in p+p collisions. On the other hand, a spiky feature in the excitation function of the total strangeness to pion ratio E_S was predicted by the Statistical Model of The Early Stage [11], assuming a phase transition from confined matter to a Quark-Gluon-Plasma at low SPS energies. As figure 6 demonstrates, the preliminary data at 30 AGeV together with the measurements at higher SPS energies are in good agreement with the predictions of this model. Note that the error bars for the NA49 results are dominated by systematic uncertainties which are to a large extent common for all measured beam energies.

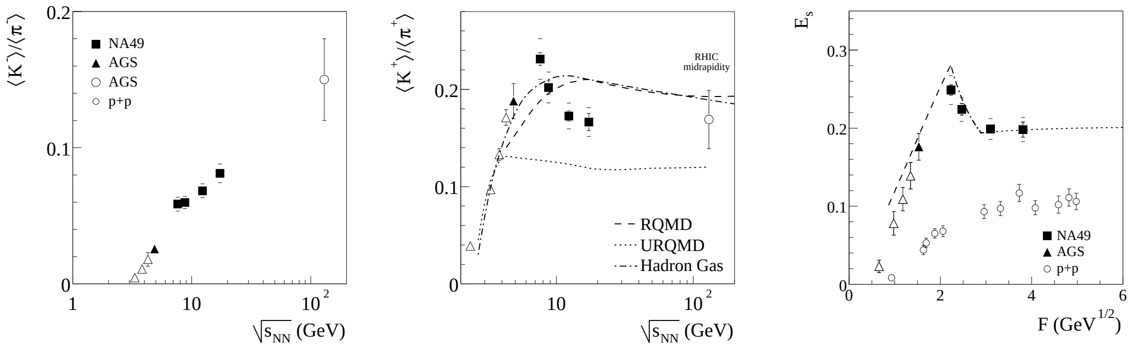

Figure 6. K/π ratios in full phase space as functions of collision energy. Left: K^-/π^-; centre: K^+/π^+, compared to the predictions of RQMD [9], UrQMD [10] and the extended hadron gas model [8]; right: Strangeness-to-pion ratio $E_S = \frac{\langle\Lambda\rangle + \langle K + \bar{K}\rangle}{\langle\pi\rangle}$, compared to the prediction of the SMES [11]. References for data not measured by NA49 can be found in [6].

4. ϕ meson production

In the context of strange particle production, the ϕ meson is of particular interest. Its overall strangeness neutrality makes it insensitive to the strange chemical potential in hadro-statistical models. On the other hand, consisting of a strange and an anti-strange quark it should be more sensitive than kaons to strangeness enhancement if the number of available strange quarks is determined in a prehadronic stage of the collision. Previously, an enhancement in ϕ production per pion at top SPS energy of about a factor of 3, comparing central Pb+Pb to p+p collisions at the same beam energy, has been reported [12]. We have now extended the analysis to central Pb+Pb at 80 AGeV and 40 AGeV.

In NA49, the ϕ meson is measured by its decay into charged kaons. Details of the analysis method can be found in [12]. Figure 7 shows the invariant-mass signals at the two energies in the forward rapidity hemisphere. The depletion on the left side of the

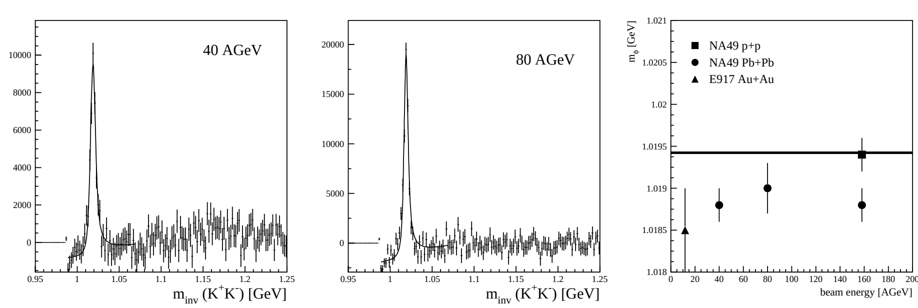

Figure 7. Invariant K^+K^- mass in the forward hemisphere for 40 AGeV (left) and 80 AGeV (centre). The full lines represent fits of a relativistic Breit-Wigner distribution on top of a linear background in the vicinity of the signal. Right: ϕ mass as a function of beam energy. The full line represents the literature value [13].

signal can be shown to stem from the final state strong interaction of K^+ and K^-. The widths of the ϕ peaks are consistent with the free-particle width [13] folded with the experimental resolution of about 1 MeV. For the peak positions, we find at all three energies analysed so far a slight (≈ 0.5 MeV) deviation from the literature value [13], as depicted in the right panel of figure 7. A similar deviation has been observed at the AGS [14], albeit with a larger error. In contrast, our analysis of p+p collisions at 158 *A*GeV [12] gives exactly the book value. It is still under investigation whether this shift is an experimental effect, possibly linked to the distortion in the background-subtracted invariant-mass spectra.

The transverse spectra of the ϕ can be seen in figure 8. Again, they are reasonably well described by exponential distributions, but in contrast to kaons, the slope parameter increases with beam energy (right panel of figure 8). It should be noted, however, that NA50 reports a different T at 158 *A*GeV [15].

Figure 9 shows the measured rapidity distributions of the ϕ meson at 40 and 80 *A*GeV in comparison to the published spectrum at top SPS energy. In all cases, a Gaussian distribution gives a good description of the data, with a width increasing with beam energy. This trend is in line with observations for pion and kaon production.

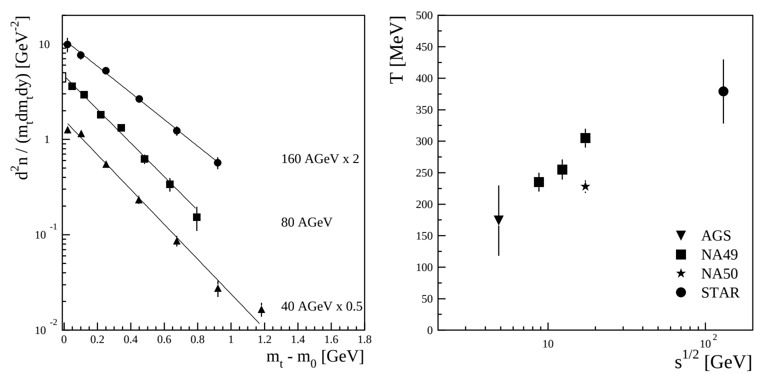

Figure 8. Left: m_t spectra of the ϕ meson. The spectra at different beam energies are scaled for better visibility. Right: ϕ slope parameter as a function of collision energy. Data not measured by NA49 are taken from [14][15][16].

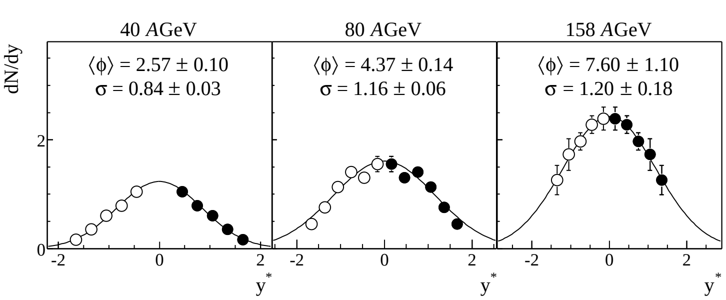

Figure 9. ϕ rapidity distributions. Solid symbols are measured data, open symbols are reflected at midrapidity. The full lines represent Gaussian fits. Left: 40 *A*GeV; centre: 80 *A*GeV; right: 158 *A*GeV.

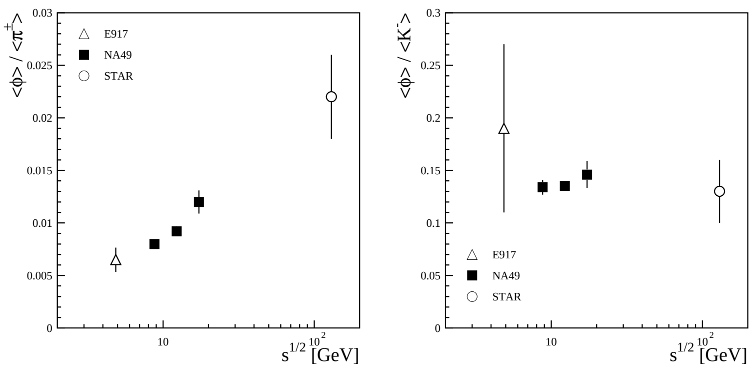

Figure 10. The ratios of $\phi/\pi^{\pm}$ (left) and ϕ/K^{-} (right) as functions of collision energy. For the data not measured by NA49, see [14][16][6] and references therein.

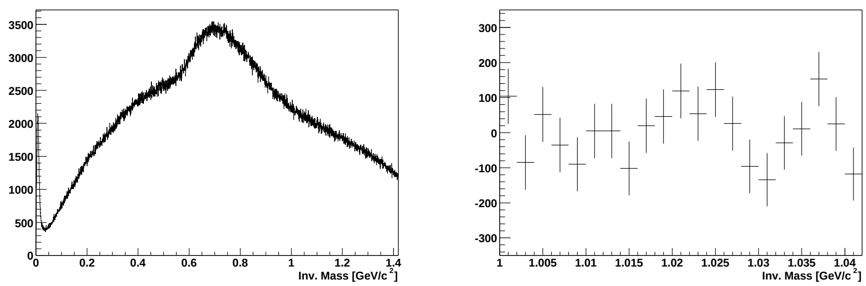

Figure 11. Left: $e^{+}e^{-}$ invariant-mass spectrum; right: invariant-mass spectrum after background subtraction in the ϕ mass region.

Summing the measured bins and extrapolating to full phase space using the Gaussian fit, we obtained the total ϕ yield, which is shown in figure 10 normalised to the average of the π^{+} and π^{-} yields and to the K^{-} yield. We observe a monotonic increase in ϕ/π from AGS via SPS to RHIC energies, quite similar to the excitation function of K^{-}/π^{-}. This similarity can be straightforwardly seen in the ϕ/K^{-} ratio, which is, within errors, independent of $\sqrt{s}$.

In the light of the discrepancies between the ϕ measurements in the $K^{+}K^{-}$ and $\mu^{+}\mu^{-}$ channels [12, 15], both in slope parameter and total yield, NA49 has undertaken an effort to reconstruct the ϕ signal in the $e^{+}e^{-}$ decay channel, which should be similar to the decay into $\mu^{+}\mu^{-}$. For this analysis, the high-statistics data set at 158 *A*GeV has been used. As figure 11 demonstrates, we do not observe a signal in this channel. Using the expected invariant-mass resolution obtained from a detailed detector simulation, we estimate the upper limit resulting from this analysis to be $\langle\phi\rangle <\approx 40$, with currently large systematic errors. Most probably, this measurement will unfortunately have no discriminating power to clear up the reported experimental differences.

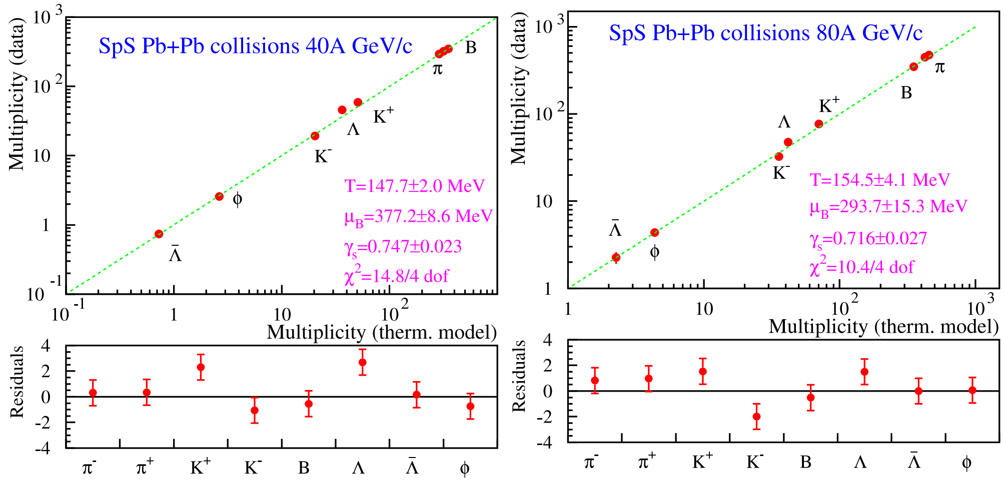

Figure 12. Comparison of the thermal model fit [17, 18] with measured particle yields at 40 *A*GeV (left) and 80 *A*GeV (right).

5. Chemical and kinetic freeze-out

With a still growing wealth of data on strange particle production, the question arises whether these data give rise to a consistent picture of the reaction dynamics in heavy-ion collisions. Particle yields provide information about the chemical freeze-out stage of the collision, while the transverse spectra give insight into the kinetic freeze-out, i. e. the stage when elastic interactions cease.

It has been shown before that the measured particle yields or yield ratios resulting from Pb+Pb collisions at top SPS energies can be reproduced by statistical models based on a grand canonical ensemble with hadronic degrees of freedom. We thus employ a representative of this kind of models [17] to fit the NA49 data measured so far at 40, 80 and 158 *A*GeV. Note that the model used employs a strangeness suppression factor γ_s, which accounts for an incomplete saturation of strangeness with respect

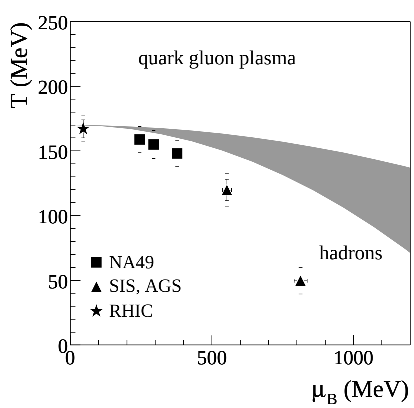

Figure 13. Chemical freeze-out points in the $T - \mu_B$ plane from the hadron gas model fits [18, 19]. The shaded region represents the phase boundary given in [20].

to a fully equilibrated hadron gas. This additional parameter enables the model to reproduce the yields also at the lower beam energies with reasonable accuracy as figure 12 demonstrates. The fit parameters, namely the temperature T, the baryochemical potential μ_B and γ_s reflect the conditions at chemical freeze-out. Figure 13 shows the results in the T-μ_B plane together with results obtained for SIS, AGS and RHIC energies. It appears that chemical freeze-out occurs on a smooth curve in this plane which has been interpreted as being determined by a constant energy per particle [19]. Moreover, at SPS the freeze-out curve approaches the expected phase boundary between hadronic matter and the Quark-Gluon-Plasma as calculated with lattice QCD [20].

Figure 14 depicts a compilation of hadron transverse mass spectra, measured by NA49 at 40 *A*GeV and 158 *A*GeV. The lines represent a radial-flow fit [21], assuming a constant transverse expansion velocity and common kinetic freeze-out for all particle types. Pions have been excluded from the fit because of the significant contribution of resonance decays to their low-p_t yields. Obviously, the model can well describe all data at both energies, which is also true for 80 *A*GeV. The values of the fit parameters, temperature T and expansion velocity β_T, are similar for all three energies. Although the model used may employ oversimplified assumptions, it shows that the available data can be understood in the framework of a locally equilibrated, rapidly expanding fireball. We observe no deviations of the heavy hyperons (Ξ, Ω) from this picture, which would signal an earlier freeze-out for these particles.

6. Summary

We have presented new experimental results obtained within the energy scan programme of NA49, in particular kaon production at 30 *A*GeV and ϕ production at 40 *A*GeV and 80 *A*GeV. The excitation function of the K^+/π^+ ratio shows a sharp maximum around 30 *A*GeV, which has been predicted by the Statistical Model of the Early Stage, thus supporting the scenario of a phase transition at low SPS energies. The observation that

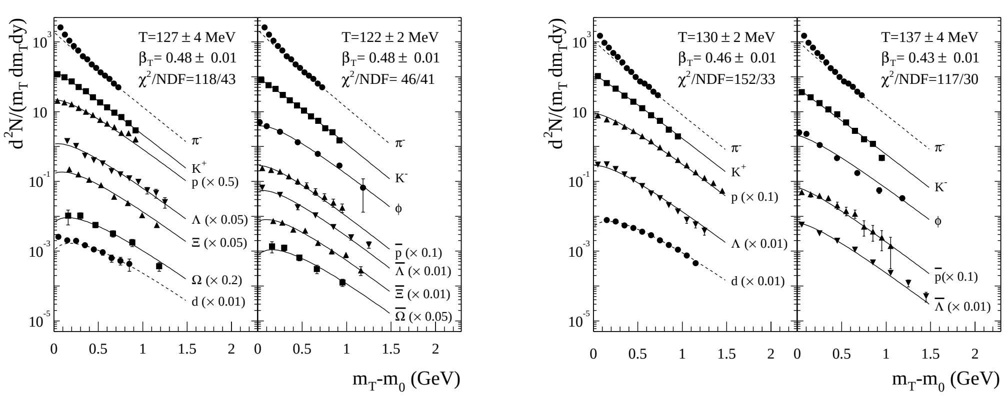

Figure 14. Blast wave fits [21] to the transverse spectra measured by NA49. Pions and deuterons were excluded from the fits. Left: 158 *A*GeV; right: 40 *A*GeV.

the kaon slope parameters do not depend on beam energy in the SPS regime supplies further evidence for this picture. The slope of the ϕ meson, in contrast, rises with beam energy. The ϕ/K^- ratio is found to be independent of collision energy; the ϕ/π ratio thus increases smoothly from AGS via SPS to RHIC. The measured particle yields can be well reproduced by a hadron gas model employing a strangeness undersaturation factor γ_S. Chemical freeze-out seems to occur on a smooth curve in the $T - \mu_B$ plane, close to the expected phase boundary to the QGP. The transverse spectra can be interpreted at the three energies analysed so far by a rapidly expanding thermal source, showing no evidence of an earlier decoupling of the heavy hyperons.

Acknowledgments

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