ENERGY DEPENDENCE OF PARTICLE PRODUCTION IN 
NUCLEUS-NUCLEUS COLLISIONS AT THE CERN SPS

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1 Introduction

From lattice QCD calculations, it is expected that hadronic matter undergoes a phase transition to a deconfined state, the so-called Quark Gluon Plasma (QGP), at an energy density of approximately 1 GeV fm$^{-3}$ or a temperature of 170 MeV.\textsuperscript{1} The NA49 experiment is studying central lead-lead collisions at different energies to search for signs of this transition. One of the signals which is examined in this programme is the energy dependence of strange particle production. New preliminary results on kaon and pion production in central Pb+Pb collisions at 30 $A$ GeV beam energy are presented. These results are compared to the published NA49 data at 40, 80 and 158 $A$ GeV and to results from other experiments at lower and higher energies. The data are then compared to expectations from models with and without a phase transition to the QGP.

2 Experiment and results

The NA49 detector\textsuperscript{3} consists of four large Time Projection Chambers (TPCs) which provide charged particle tracking and particle identification through a measurement of the ionisation energy loss $dE/dx$. Two of the TPCs are operated inside a magnetic field. In addition, there are two Time-of-Flight (TOF) detectors, which improve the particle identification capabilities at mid-rapidity.

In Fig. 1 we present, for the four available beam energies, the transverse mass ($m_T = \sqrt{m^2 + p_T^2}$) spectra of charged kaons at mid-rapidity, as obtained from an analysis using the combined TOF and $dE/dx$ information for particle identification.

The lines indicate fits of an exponential distribution $dN/(m_Tdydm_T) \propto \exp(-m_T/T)$. The energy dependence of the inverse slope parameter $T$ of the $K^+$ spectra is shown in Fig. 2. It can be seen that this parameter strongly increases at AGS energies and then stays constant in the SPS energy range from 30 to 158 $A$ GeV.

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There is some indication of a further increase towards RHIC energies. The same behaviour is found for the inverse slopes of the $K^-$ spectra (not shown). 4 In a hydrodynamic picture of the collision, the increasing slope parameter is due to an increase of the initial pressure with collision energy. The observed energy dependence is qualitatively in agreement with a softening of the equation of state due to a phase transition. 4, 5

The rapidity spectra of $\pi^-$, $K^+$ and $K^-$ at 30 AGeV are shown in Fig. 3. The kaon yields were determined using the combined TOF-$dE/dx$ information at mid-rapidity (squares) and $dE/dx$ information only at forward rapidities (circles). Due to their low momenta, it is not possible to identify pions by $dE/dx$. The pion yields were therefore determined from the spectra of negative hadrons, subtracting contributions from $K^-$ and feeddown from weak decays. The rapidity spectra were fitted with a double Gaussian (full line) to determine the total yields.

3 Energy dependence of total yields

The energy dependence of the kaon to pion ratios are shown in Fig. 4 where it can be seen that $K^-/\pi^-$ increases monotonically with $\sqrt{s}$, while $K^+/\pi^+$ shows a relatively sharp maximum at 30 AGeV and is constant at the higher SPS energies (80 and 158 AGeV) up to RHIC energies. For comparison, the $K^+/\pi^+$ ratio in proton-proton collisions is also shown. This ratio is lower in proton-proton collisions than in nucleus-nucleus collisions at all energies. This is true even at low
energies, where certainly no QGP formation is expected. There is no indication of a maximum in $K^+/\pi^+$ at 30 $A$GeV in proton-proton collisions, contrary to nucleus-nucleus collisions.

The measured kaon to pion ratios are compared to different model expectations as indicated by the lines in Fig. 4. Two of these models, RQMD (full line) and UrQMD (dashed line) are event generators based on string excitation and decay. Secondary collisions between produced particles are also taken into account. The relatively large difference between the expectations of RQMD and UrQMD indicates that there is a considerable uncertainty in such models.

The dash-dotted line in Fig. 4 is the expectation from the Hadron Gas Model. In this model, the $K/\pi$ ratios are determined by only two thermodynamical parameters: the temperature $T$ and the baryon-chemical potential $\mu_B$. The energy dependence is provided by a smooth parameterisation of the energy dependence of $T$ and $\mu_B$, based on measurements at AGS and the highest SPS energy.

A common feature of all three models is a smooth evolution of $K/\pi$ with energy. Only in the Hadron Gas Model a maximum in the $K^+/\pi^+$ ratio is expected at low SPS energies. This maximum, however, is much less pronounced than observed in the data.

In Figs. 5 and 6 the experimental data are compared to the Statistical Model of the Early Stage (SMES) in which it is assumed that a phase transition to the QGP occurs.

In Fig. 5 the number of produced pions $\langle \pi \rangle = 1.5(\langle \pi^- \rangle + \langle \pi^+ \rangle)$ per wounded nucleon is shown as a function of collision energy, characterised by $F \equiv (\sqrt{s} - 2m_N)^{3/4}/\sqrt{s}^{1/4}$, where $m_N$ is the nucleon mass. Within the SMES, the pion multiplicity per wounded nucleon is proportional to the initial entropy per wounded nucleon, which, in turn, is proportional to $F$. The change of slope of the energy dependence of the $\langle \pi \rangle/N_W$ ratio in nucleus-nucleus collisions (inset of Fig. 5) would then indicate an increase of the initial number of degrees of freedom in the collision.

In Fig. 6 the energy dependence of the total strangeness to pion ratio $E_s = (\langle \Lambda \rangle + 2(\langle K^+ \rangle + \langle K^- \rangle))/\langle \pi \rangle$ is compared to the expected ratio in the SMES. The lambda yields were estimated as $\langle \Lambda \rangle = (\langle K^+ \rangle - \langle K^- \rangle)/0.8$ since no published data are available. Within the SMES, the sharp peak in the strangeness to entropy (or pion) ratio is due to the phase transition which is assumed to set in at a temperature of $T = 200$ MeV (or $F \approx 2.2$ GeV$^{1/2}$). The strangeness to entropy ratio in the pure QGP phase, above $F \approx 2.7$ GeV$^{1/2}$, is a parameter-free prediction because it is determined by the ratio of the number of strange degrees of freedom to the total number of degrees of freedom.

To summarise, we observe that the kaon slope parameters in nucleus-nucleus collisions show an overall increase with collision energy, but are energy-independent at the SPS. Furthermore,
the $K^+/\pi^+$ ratio shows a pronounced maximum at about 30 AGeV which seems to be specific to nucleus-nucleus collisions. Qualitatively, these observations can be understood by assuming that a phase transition occurs between the highest AGS energy and 30 AGeV (SMES model), while, at present, they cannot be accommodated in hadronic descriptions of the collision such as RQMD, UrQMD and the Hadron Gas Model.

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