We argue that the main features of baryon and anti-baryon enhancement observed by the WA97 collaboration can be described using canonical formulation of strangeness conservation. Within this formulation strangeness enhancement could be larger at lower collision energies.

1 Introduction

Ultrarelativistic heavy ion collisions provide a unique opportunity to study the properties of highly excited hadronic matter under extreme conditions of high density and temperature. From the analysis of rapidity distribution of protons and of their transverse energy measured in 158 A GeV/c Pb+Pb collisions an estimate of the initial condition leads to energy density of $2-3$ GeV/fm$^3$ and a baryon density of the order of 0.7/fm$^3$. Lattice QCD at vanishing baryon density suggest that the phase transition from confined to the quark-gluon plasma (QGP) phase appears at the temperature $T_c = 173 \pm 8$ MeV which corresponds to the critical energy density $\epsilon_c \sim 0.6 \pm 0.3$ GeV/fm$^3$. One could thus conclude that the required initial conditions for quark deconfinement are already reached in heavy ion collisions at SPS energy. It will be discussed to what extend the composition of the final-state hadrons, in particular their strangeness content can be considered as a probe of quark deconfinement in the initial state.

2 Strangeness in quark-gluon plasma

It was argued that enhanced production of strange particles could be a signal of QGP formation in heavy ion collisions. In the QGP the production and equilibration of strangeness is very efficient due to the a large gluon density and a low energy threshold for dominant QCD processes of $s\bar{s}$ production. In the hadronic system the higher threshold for strangeness production was...
expected to make the strangeness yield considerably smaller and the equilibration time much longer. (Recently, it was argued\textsuperscript{11} and shown in terms of a microscopic transport approach\textsuperscript{9} that multi-mesonic reactions could, however, accelerate the equilibration time of antibaryons in high density hadronic medium.)

From these strangeness QGP characteristics one expects: a global strangeness enhancement measured by the total number of produced $< s \bar{s} >$ quarks per participant $A_{part}$ or per produced light quarks $< u \bar{u} + d \bar{d} >$ which should increase from pp, pA to AA collisions and enhancement of multistrange (anti-)baryons in central AA collisions, with respect to proton induced reactions.

Large strangeness content of the QGP plasma should be reflected in a very specific hierarchy of multistrange baryon enhancement: $E_{\Lambda} < E_{\Sigma} < E_{\Xi}$. This hierarchy is observed by the WA97 and NA57 collaboration\textsuperscript{23} which measure the yield per participant in Pb+Pb relative to p+Pb and p+Be collisions. Indeed the enhancement pattern of the (anti)hyperon yields is seen to increase with strangeness content of the particle and there is a saturation of this enhancement for $A_{part} > 100$. Recent results of the NA57 collaboration are showing in addition an abrupt change of anti-cascade enhancement for lower centrality. Similar behavior was previously seen on the $K^+$ yield measured by the NA52 experiment in Pb-Pb collisions\textsuperscript{24}. These results are very interesting as they might be interpreted as an indication of the onset of new dynamics. However, a more detailed experimental study and theoretical understanding are still required here. It is, e.g, not clear what is the origin of different centrality dependence of $\Xi$ and $\bar{\Xi}$ as well as inconsistencies between the NA52 and the WA97 data.

A number of different mechanisms\textsuperscript{14,15,11,12,13} was considered to describe the magnitude of the enhancement and centrality dependence of (multi)strange baryons measured by the WA97. Microscopic transport models make it clear that the WA97 data can not be explained by pure final state hadronic interactions. Only the combination of the formers with an additional pre-hadronic mechanisms like baryon junction processes, color ropes or color flux tubes overlap can partly explain the enhancement pattern and the magnitude for the most central collisions. However, the detailed centrality dependence is still not well reproduced within the microscopic models. An alternative description of multistrange particle production was formulated in terms of macroscopic thermal models with\textsuperscript{29,22} and without\textsuperscript{23} chemical equilibrium. In equilibrium the parameters are temperature $T$, baryon and strangeness chemical potentials. In non-equilibrium one also uses two other parameters $\gamma_u$ for $u$ and $d$ quarks and $\gamma_s$ for $s$ quark. These parameters measure deviations from full equilibrium. The fits of reference\textsuperscript{22} with more parameters are more precise, but fail to reproduce the $\Omega$ and $\bar{\Omega}$ yields. Besides, the hadronization temperature is found lower ($T_f \sim 145$ MeV) than the one found in equilibrium ($T_f \sim 170$ MeV). This led to the development of sudden hadronization model with super-cooling\textsuperscript{24}.

However the equilibrium thermal model\textsuperscript{29,22} describes all existing WA97 and NA49 data. The model was formulated in the grand canonical (GC) ensemble with a partition function which contains the contributions of most hadrons and resonances and preserves the baryon number, strangeness and charge conservation. The particle ratios depends only on two parameters; temperature $T$ and baryon chemical potential $\mu_B$. With $T_f \sim 170$ MeV, corresponding to the energy density $\epsilon_f \sim 0.6$GeV/fm$^3$, and with the baryon chemical potential $\mu_B \sim 270$MeV, corresponding to baryon density of $0.16$GeV/fm$^3$, the statistical model reproduces the experimental data. Furthermore this model is also consistent\textsuperscript{22,23,24} with the recent data of the STAR collaboration in Au+Au collisions at RHIC\textsuperscript{25}. The main difference with SPS, as expected because of higher collision energy with less stopping, is a smaller value ($\mu_B \sim 50$ MeV) of baryon chemical potential. The freezeout temperatures in central A+A collisions at the SPS and RHIC coincide within errors\textsuperscript{25} with the critical temperature from lattice QCD. This could indicate that all particles are originating from deconfined medium and that the chemical composition of the system is

\textsuperscript{a} At RHIC a precise determination of $T_f$ is not yet possible as fits with $160 < T_f < 200$ give similar value of $\chi^2$. Data like, e.g, $\Omega/\pi$ or $\Xi/\pi$ ratios are necessary to a better determination of $T_f$.\textsuperscript{22}
established during hadronization.

Figure 1: Particle multiplicities per participant normalized to its value in p+A system as a function of $A_{\text{part}}$ calculated in statistical model in (C) ensemble.

Figure 2: $K^+ / \pi^+$ ratio at midrapidity in A+A relative to p+p collisions. For the compilation of data see refs. [33,34].

3 Canonical description of strangeness enhancement

The enhancement of strange(anti)-baryons reported by the WA97 and its variation with centrality may be explained in canonical formulation of statistical thermal model. What the WA97 measures is the ratio of strange (anti-)baryon yields in the large Pb-Pb system and in the small p-Be or p-Pb system. For small systems with rare production of strange particles strangeness conservation must be implemented locally on an event-by-event basis, i.e, canonical (C) ensemble for strangeness conservation must be used. The (C) ensemble is relevant in the statistical description of particle production in low energy heavy ion, or high energy hadron-hadron or $e^+e^-$ reactions as well as in peripheral heavy ion collisions at SPS. The exact conservation of quantum numbers, that is the canonical approach, is known to severely reduce the phase-space available for particle productions.

Fig.1 shows the multiplicity per participant of $\Omega$, $\Xi$, and $\Lambda$ relative to its value in a small system with only two participants. One sees that the statistical model in (C) ensemble reproduce the basic features of WA97 data: the enhancement pattern and enhancement saturation for large $A_{\text{part}}$ indicating here that (GC) limit is reached. The quantitative comparison of the model with experimental data requires an additional assumption on the variation of $\mu_B$ with centrality to account for larger value of $\bar{B}/B$ ratios in p+A than in Pb+Pb collisions. However, an abrupt change of enhancement seen in the NA57 data for $\Xi$ is very unlikely to be reproduced in terms of this approach.

One of the consequences of the model is that the enhancement pattern seen in Fig. 1 should not be only a feature of the SPS data. In terms of statistical model strangeness enhancement and enhancement pattern should be also present in heavy ion collisions at lower energies and should be even more pronounced. This is in contrast e.g. to UrQMD predictions which are showing increasing enhancement with beam energy. In Fig.2 we show a compilation of the data on $K^+ / \pi^+$ ratio in A+A relative to p+p collisions. This double ratio could be referred to as a strangeness enhancement factor. The enhancement is indeed seen to be larger at the smaller beam energy and is smoothly decreasing towards higher energy. If strangeness enhancement is indeed of thermal origin then similar behavior is also expected for multistrange baryons. This could put in question the observed strangeness enhancement from p+p to A+A as an appropriate characteristics to signal deconfinement. To possibly observe QGP from the
strangeness composition of the fireball one should rather search for non-monotonic behavior of strange particle species versus centrality or collision energy.

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