Towards strangeness saturation in central heavy-ion collisions at high energies

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Analyses of the centrality binned identified hadron multiplicities at SPS (\( \sqrt{s} = 17 \) AGeV) and RHIC (\( \sqrt{s} = 130 \) AGeV) within the statistical-thermal model point to strangeness saturation with increasing centrality and energy.

1. Introduction

It is now well established that particle abundances can be described by statistical-thermal models. In such a way, a large number of observables can be reproduced with a small number of parameters, namely the temperature, baryo-chemical potential and a factor measuring the degree of strangeness saturation. Here we focus on the centrality dependence of the hadron multiplicities and adjust the thermal parameters so as to reproduce the experimental data.

The recent study in [1] (cf. table III therein) impressively demonstrated that, with increasing system size at SPS energies, the strangeness saturation increases. In [2] we have shown that at a beam energy of 158 AGeV, in collisions of lead-on-lead nuclei, the strangeness saturation continuously increases with centrality. However, strangeness is well below saturation. A preliminary analysis [3] of the centrality dependence at RHIC energy of \( \sqrt{s_{NN}} = 130 \) GeV points to a further increase of strangeness towards saturation for central collisions of gold nuclei. An independent analysis [4] confirms this finding.

In this paper, we compare the analyses of two data sets: (i) NA49 4\( \pi \) multiplicities of \( \langle \pi \rangle, K^\pm, \phi, N_{\text{part}} \) (taken as the sum over all baryons) and \( \bar{p} \) in 6 centrality bins in the reaction Pb (158 AGeV) + Pb [5,6] (our previous study [2] did not include the \( \phi \) multiplicities). It should be emphasized that protons are not included in our analysis since, particularly in non-central collisions, there may be a large spectator component in the quoted experimental yields. (ii) PHENIX mid-rapidity densities of \( \pi^\pm, K^\pm \) and \( p^\pm \) in the reaction Au + Au at \( \sqrt{s} = 130 \) AGeV in 5 centrality bins [7]. These yields were not corrected for weak decays. PHENIX estimates the probability for reconstructing protons from \( \Lambda \) decays as prompt protons at 32% at \( p_T = 1 \) GeV/c [8]. In the analysis of the PHENIX data, two fits were performed: with no feeding from weak decays, and with a 32% feed-down from \( \Lambda \) decay.

The use of 4\( \pi \) data at SPS energy is in the spirit of the fireball model, since many dynamical effects cancel out in ratios of fully-integrated hadron yields. In particular, effects
2. Analyses of Hadron Multiplicities

Hadron multiplicities can be described \([9,10]\) by the grand-canonical partition function 
\[
Z(V, T, \vec{\mu}_i) = \text{Tr}\{e^{-\frac{\hat{H}}{T} - \vec{\mu}_i \cdot \vec{Q}_i}\},
\]
where \(\hat{H}\) is the statistical operator of the system, \(T\) denotes the temperature, and \(\mu_i\) and \(Q_i\) represent the chemical potentials and corresponding conserved charges respectively. In the analysis of \(4\pi\) data, the net-zero strangeness and the baryon-to-electric charge ratio of the colliding nuclei constrain the components of \(\vec{\mu}_i = (\mu_B, \mu_S, \mu_Q)\). These constraints have to be relaxed when considering data in a limited rapidity window, increasing the number of free parameters. The particle numbers are given by

\[
N_i^{\text{prim}} = V(2J_i + 1) \int \frac{d^3p}{(2\pi)^3} \frac{1}{\gamma_s |S_i| e^\frac{\vec{p} \cdot \vec{Q}_i}{T} \pm 1} \text{BW}(m_i),
\]  

(1)

where we include phenomenologically a strangeness saturation factor \(\gamma_s\) with \(|S_i|\) the number of valence strange quarks and anti-quarks in species \(i\) \([11]\) (e.g. \(\gamma_s\) suppression for the kaons and \(\gamma_s^2\) for \(\phi\)) to account for incomplete equilibration in this sector, 
\(E_i = \sqrt{\vec{p}^2 + m_i^2}\), and BW is the Breit-Wigner distribution. The particle numbers to be compared with experiment are \(N_i = N_i^{\text{prim}} + \sum_j \text{Br}^{j\rightarrow i} N_j^{\text{prim}}\), due to decays of unstable particles with branching ratios \(\text{Br}^{j\rightarrow i}\). The results of our fits are displayed in figs. 1 and 2. The inclusion of weak decays in the PHENIX analysis lowers the temperature but does not appreciably affect either \(\gamma_s\) or \(\mu_B\). Both at SPS and RHIC, the number of kaons and antikaons increase with centrality relative to the charged pion and antiproton multiplicities. This is responsible for the increase of the strangeness saturation factor \(\gamma_s\). At RHIC energy the temperature also appears to increase with centrality, as shown in fig. 1.

The findings for central collisions at RHIC agree fairly well with the results in \([4]\), as do our extracted values of \(T\) and \(\mu_B\) in central collisions at SPS energy. In contrast to \([4]\), however, we find a pronounced strangeness under-saturation, as in \([4]\) at SPS energy (cf. also \([4]\) for other analyses with \(\gamma_s < 1\) at SPS). What is striking is the increase of \(\gamma_s\) with energy and centrality, and the tendency to approach full strangeness saturation at RHIC, i.e. \(\gamma_s \rightarrow 1\). The observed increase of \(\gamma_s\) with increasing centrality is in agreement with parton kinetics as described in \([12]\), for example.

The baryo-chemical potential is fairly constant at both SPS and RHIC, as shown in fig. 2. The apparent centrality independence of the temperature and baryo-chemical potential at SPS leads to the model prediction that the ratio \(\phi/K^+\) should increase like \(\gamma_s\) with centrality. This, however, does not agree with the experimentally observed centrality independence of this ratio. The trend can be reproduced by the model if the \(\phi\) is suppressed by a factor of \(\gamma_s\) (instead of \(\gamma_s^2\)), but this leads to higher values of \(\chi^2\) in all but the most peripheral bin. This is shown quantitatively in fig. 2 where the \(\phi/K^+\) ratio is plotted against the number of participants. As can be seen, if the \(\phi\) mesons are suppressed only by a factor \(\gamma_s\), one overestimates their number but the dependence as a
function of $N_{\text{part}}$ can be reproduced. If however, the $\phi$ has a quadratic suppression factor, $\gamma_s^2$, then the normalization is reproduced, at least in the three most central bins, but the shape of the curve does not match the observed dependence. It would be of interest to establish this point more clearly, since it touches on the precise way in which strangeness suppression occurs. A more accurate determination of the $\phi$ yield for small values of $N_{\text{part}}$, especially for 150 - 200 participants, would be extremely useful. Also at AGS energies, the $\phi/K^+$ ratio is centrality independent. The situation of the $\phi$ yield as a function of $N_{\text{part}}$ remains inconclusive.

3. Summary

In summary, we have shown that the analyses of full phase-space multiplicities at SPS energy and mid-rapidity densities at RHIC energy point to strangeness saturation in central collisions at still higher energies.

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Figure 2. Left panel: The baryo-chemical potential $\mu_B$ as a function of $N_{\text{part}}$. Squares (triangles) are for the full phase-space NA49 data [5,6] (mid-rapidity PHENIX [7]). Right panel: The $\phi/K^+$ ratio at SPS as a function of the number of participants. The dotted line corresponds to predictions of the model using a linear $\gamma_s$ suppression factor for $\phi$ mesons, while the solid line is obtained using $\gamma_s^2$.

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