Strangeness enhancement and energy dependence in heavy ion collisions

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Abstract. The canonical statistical model analysis of strange and multistrange hadron production in central A–A relative to p–p/p–A collisions is presented over the energy range from $s^{1/2} = 8.73\,\text{GeV}$ up to $s^{1/2} = 130\,\text{GeV}$. It is shown that the relative enhancement of strange particle yields from p–p/p–A to A–A collisions substantially increases with decreasing collision energy. It is largest at $s^{1/2} = 8.7\,\text{GeV}$, where the enhancement of Ω, Ξ and Λ is of the order of 100, 20 and 3, respectively. In terms of the model these results are due to the canonical suppression of particle thermal phase space at lower energies, which increases with the strangeness content of the particle and with decreasing size of the collision fireball. The comparison of the model with existing data on the energy dependence of the kaon/pion ratio is also discussed.

1 Introduction

The production of strange particles is extensively studied in heavy ion experiments in a very broad energy range from GSI/SIS to BNL/AGS and from CERN/SPS up to BNL/RHIC [1]. The amount of data available for K^+ and K^- yields already allows a detailed analysis to be made of the kaon excitation function in A–A collisions [2–4] as well as an analysis of the relative enhancement of kaon production in A–A with respect to p–p collisions [3,5,6]. Of particular interest is here the behaviour of K^+ yield with energy, as this is the most abundantly produced particle with non-vanishing strangeness. The kaon excitation function at mid-rapidity, as the K^+/π^+ ratio, is a very abruptly increasing function of the collision energy between SIS up to top AGS. At higher energies it reaches a broad maximum between $10\,\text{AGeV}$ and $40\,\text{AGeV}$ [5] and then one finds a gradual decrease up to RHIC energy [7, 8]. In the microscopic transport models the increase of the kaon yield with collision energy is qualitatively expected, owing to a change in the production mechanism from associated to direct kaon emission. However, the hadronic cascade transport models are as yet not providing the quantitative explanation of the experimental data. The hadron string dynamics (HSD) model [9] severely underpredicts the top AGS results on the K^+/π^+ ratio, while RQMD [3] overpredicts the yield at lower energies and gives too small a yield at the SPS. The statistical model SM, on the other hand, provides quite a satisfactory description of the kaon excitation function and of the K/π mid-rapidity ratio in the whole energy range from SIS up to RHIC [10, 11]. A detailed analysis of the experimental data at SIS

[10], AGS [12,13], SPS [13,14] and recently also at RHIC [15–17] has shown that hadronic yields and their ratios resemble those of a population in chemical equilibrium. Most particle multiplicities measured in nucleus–nucleus collisions are well consistent with the thermal model predictions [13–15,18]. A similar analysis of particle yields in hadron–hadron collisions [19] also shows the consistency of the statistical model with the data.

Recently, it was argued [20] that SM can also describe a basic future of strangeness enhancement from p–A to A–A collisions measured by the WA97 Collaboration [21]: the enhancement pattern and enhancement saturation for a large number of participants N_{part}. The enhancement of (multi)strange baryons is of particular interest, since it was conjectured to be a signal for quark–gluon plasma formation in heavy ion collisions [22]. The centrality dependence of the (multi)strange baryon enhancement, increasing with the strangeness content of the particle, was shown to appear in the SM as a consequence of the canonical suppression of the particle phase space in a small system. Satisfactory agreement of the SM with the data confirmed that SM provides a tool to make a prediction for hadron production in A–A collisions.

In this paper we apply SM formulated in terms of the canonical ensemble [23,24] to a study of the energy dependence of the (multi)strange baryon enhancement from p–p to A–A collisions. We first show that the observed relative enhancement of the K^+/π^+ ratio in A–A to p–p collisions from top AGS up to top SPS energy can be quantitatively described by the SM. We then make a prediction for relative (multi)strange baryon enhancement at

$s^{1/2} = 8.73, 12.3, 17.3\,\mathrm{GeV}$ at SPS and $s^{1/2} = 130\,\mathrm{GeV}$ at RHIC energies. We show that at RHIC the enhancement of (multi)strange baryons is expected to be comparable with the one measured at the top SPS energy; however, it could be almost an order of magnitude larger at lowest ($s^{1/2} = 8.73\,\mathrm{GeV}$) SPS energy.

2 Statistical description of strangeness enhancement

Within the statistical approach, hadron production is commonly described by using the grand canonical GC partition function, where the charge conservation is controlled by the related chemical potential. In this description a net value of a given U(1) charge is conserved on the average. The GC approach can be valid only if the total number of particles carrying a quantum number related with this symmetry is very large. In the opposite limit of small particle multiplicities, conservation laws must be implemented exactly and locally, i.e. the canonical C ensemble for conservation laws must be used [23, 25, 26]. The local conservation of quantum numbers in the canonical approach severely reduces the thermal phase space available for particle production. The exact charge conservation is therefore of crucial importance in the description of particle yields in proton-induced processes [19, 20], in e^+–e^- [19] as well as in peripheral heavy ion collisions [27].

In the present analysis of the energy dependence of the strangeness enhancement, we adopt the statistical model, which has previously been used to analyse hadron productions in heavy ion collisions [20, 24]. This model is formulated in the canonical ensemble with respect to strangeness conservation, whereas baryon number conservation is controlled by the chemical potential. Within this framework particle multiplicity ratios depend only on two thermal parameters: the temperature T and the baryon chemical potential μ_B, as well as the correlation volume, which is assumed to scale with the number of participating projectile nucleons.

The canonical model description of strangeness conservation including multistrange particle contributions was described in detail in [20, 24, 27]. We quote here the final results [24] for particle density, which are relevant to our discussion of the energy dependence of the strangeness enhancement.

The number density n_i^s of particle i carrying strangeness s is found to be

$$n_i^s = \frac{Z_i^1}{Z_{S=0}^C} \sum_{n=-\infty}^{\infty} \sum_{p=-\infty}^{\infty} a_3^p a_2^n a_1^{-2n-3p-s}$$
$$\times I_n(x_2) I_p(x_3) I_{-2n-3p-s}(x_1), \qquad (1)$$

where

$$Z_{S=0}^C = \sum_{n=-\infty}^{\infty} \sum_{p=-\infty}^{\infty} a_3^p a_2^n a_1^{-2n-3p}$$
$$\times I_n(x_2) I_p(x_3) I_{-2n-3p}(x_1) \qquad (2)$$

is the canonical partition function for a system with total strangeness $S = 0$. The variables a_i and x_i are defined by $a_i = (S_i/S_{-i})^{1/2}$, $x_i = 2(S_i S_{-i})^{1/2}$, and $S_n = V \sum_k Z_k^1$ is the sum over all particles and resonances carrying strangeness n. For a particle of mass m_k, with degeneracy factor g_k, carrying baryon number B_k with the corresponding chemical potentials μ_B, the one-particle partition function in Boltzmann approximation reads

$$Z_k^1 \equiv \frac{g_k}{2\pi^2} m_k^2 T K_2\left(\frac{m_k}{T}\right) \exp(B_k \mu_B); \qquad (3)$$

here I_i and K_2 are the modified Bessel functions.

It can be shown that, in the limit of large x_1, that is for large strangeness multiplicity, the above formula coincides with the grand canonical result[1]. In the opposite limit, that of small x_1, the equilibrium density of (multi)strange baryons is strongly suppressed with respect to their grand canonical value [20].

To study the energy and centrality dependence of (multi)strange particle yields in terms of the above model, one needs to establish first the variation of thermal parameters with energy and centrality. From a previous analysis [28] one knows that temperature to a good approximation is only a function of the collision energy and is independent from the number of participating nucleons. For fully integrated 4π particle yields, one can also assume that the baryon chemical potential is weakly changing with centrality. The above assumption could be partly justified by the data since for $s^{1/2} = 8.73\,\mathrm{GeV}$ the total number of pions per participant in central Pb–Pb ($\langle\pi\rangle/\langle N_{\mathrm{part}}\rangle = 2.5$) and in p–p ($\langle\pi\rangle/\langle N_{\mathrm{part}}\rangle \sim 2.62$) almost coincide [29] (see also Fig. 1). In the SM and with the same temperature, the above can only be valid if the baryon chemical potential is weakly centrality dependent. For larger collision energies, such as at RHIC, $\langle\pi\rangle/\langle N_{\mathrm{part}}\rangle$ is seen in Fig. 1 to increase from p–p to central Au–Au collisions. Thus, here μ_B is decreasing with increasing centrality. With a freeze-out temperature $T \sim 175\,\mathrm{MeV}$ and $\mu_B \sim 50\,\mathrm{MeV}$ required to reproduce the RHIC data [24], this would correspond to an increase of μ_B from $50\,\mathrm{MeV}$ at most central Au–Au collisions to $70\,\mathrm{MeV}$ in p–p collisions. This change, however, will only weakly influence the relative enhancement of (multi)strange particles. We thus assume, for simplicity, that the baryon chemical potential is centrality independent[2].

Thermal parameters are, however, very sensitive to the collision energy. At the AGS [12] and SPS [14] we use the chemical freeze-out parameters as obtained from a detailed analysis of the experimental data. In particular at $s^{1/2} = 17.3\,\mathrm{GeV}$, $T \sim 168\,\mathrm{MeV}$ and $\mu_B \sim 266\,\mathrm{MeV}$. At RHIC we adopt the values from [24]. At 40 AGeV the

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[1] This can easily be seen for charges and the baryons' neutral system by making a large argument expansion of the Bessel functions in (1)

[2] In general in p–p collisions the baryon number should also be treated canonically [13]. However, since here the baryon number $B = 2$ the canonical suppression is much less effective than in the case of strangeness. The canonical corrections due to baryon number should not exceed 30% [31]
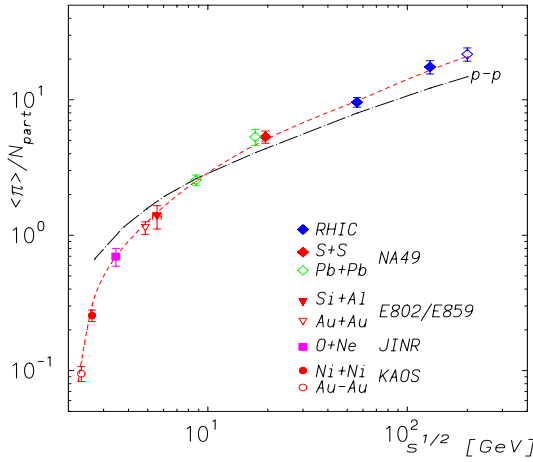
Fig. 1. Total number of pions per participant ($\langle\pi\rangle/N_{\mathrm{part}}$), 4π ratio versus energy. The data at lower energies in A–A as well as in p–p collisions are from [29]. On the origin of the RHIC results we note the following. The 4π results at $s^{1/2} = 56$ GeV were estimated from PHOBOS mid-rapidity data from [34], scaled by the same factor as required in p–p collisions when going from mid-rapidity to full phase space. The results at $s^{1/2} = 130$ GeV are from [33]. The 4π results at $s^{1/2} = 200$ GeV were estimated by multiplying the $s^{1/2} = 130$ GeV results by the same factor (modulo an increase in rapidity interval) as recently measured by PHOBOS at mid-rapidity [34]. The short-dashed and dashed lines represent the fit to the data

Fig. 2. K^+/π^+ ratio in $A+A$ relative to $p+p$ collisions. For the compilation of data, see [3,4,11]. The dashed line represents the statistical model results

available data are still not sufficient to make a precise determination of the freeze-out parameters [30]. To estimate these values we use the relation between T and μ_B as determined by the unified freeze-out conditions of fixed energy per particle [32] and the measured result on $\langle\pi\rangle/N_{\mathrm{part}} = 2.55 \pm 0.15$ for Pb–Pb collisions at 40 AGeV [4]. The Pb–Pb data at 80 AGeV for $\langle\pi\rangle/N_{\mathrm{part}}$ are still not known. Here we use instead the value extrapolated to 80 AGeV from Fig. 1, leading to $\langle\pi\rangle/N_{\mathrm{part}} \sim 3.4$. Thermal parameters for 40 and 80 AGeV extracted in this way are $T = 145 \pm 5$ MeV, $\mu_B = 370 \pm 20$ MeV and $T \sim 152$ MeV, $\mu_B \sim 280$ MeV respectively. Finally, the volume parameter appearing in (1) is assumed to be proportional to the number of projectile participants, $V \simeq V_0 N_{\mathrm{part}}/2$ where $V_0 \simeq 7\,\mathrm{fm}^3$ is taken as the volume of the nucleon.

In Fig. 2 we show the compilation of the data on the K^+/π^+ ratio in A–A relative to p–p collisions [3,4]. This double ratio could be referred to as the strangeness enhancement factor. The enhancement is seen in the data to be the largest at the smallest beam energy and is decreasing towards higher energy. The line is a smooth interpolation between the canonical model results for $s^{1/2} = 17.3, 12.3, 8.73, 5.56$ GeV, obtained with the parameters described above.

The enhancement seen in Fig. 2 is entirely due to the suppression of the K^+/π^+ ratio in p–p collisions with decreasing energy and not due to a dilution of this ratio by excess pions in the A–A system. The K^+/π^+ ratio is known experimentally not to vary within 30% in the energy range from $s^{1/2} \sim 5$ GeV at AGS up to $s^{1/2} = 130$ GeV at RHIC [3,4,11]. This behaviour is also de-
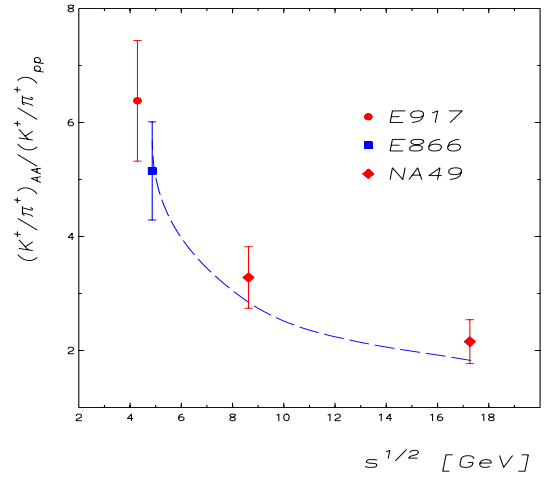
scribed by the statistical model as a consequence of particular distributions of the thermal parameters with collision energy [24][3].

The results in Fig. 2 show that in terms of the SM the energy dependence of the strangeness enhancement could be related with the suppression of the thermal phase space available for strangeness production in p–p collisions. Having in mind the above agreement, we apply this model to analyse the enhancement for multistrange baryons. Two relevant questions are here of particular interest:

(i) Is the enhancement pattern observed by WA97 a characteristic feature of the top SPS energy or can it also be seen at lower energies?
(ii) Is the enhancement for multistrange baryons a decreasing or increasing function of energy?

In Figs. 3 and 4 we show the results on relative (multi) strange baryon enhancement from p–p to Pb–Pb collisions at $s^{1/2} = 8.73$ GeV and at $s^{1/2} = 130$ GeV, respectively. It is clear that the same enhancement pattern as at the SPS is expected in the SM model to appear for all relevant energies.

To see the dependence of the strength of the enhancement with energy, we show in Figs. 5 and 6 the relative enhancement of Ξ and $(\Omega+\bar{\Omega})$ for different collision energies. The enhancement is the largest at lowest energy; for Ω, it can even be larger by a factor of almost 10 at 40 AGeV than observed at the SPS. This behaviour could already be partly deduced from the experimental data. Indeed, combing the Si–Pb results for Ξ^- production obtained by the E810 Collaboration [37] and the E802 value for pion or K^- yield in Si–Au collisions [38] at the top AGS energy, one can estimate that $\Xi^-/\pi^+ \sim 0.0076$; this within the errors coincides with the value of $\Xi^-/\pi^+ \sim 0.0074$ obtained by NA49 in Pb–Pb at $s^{1/2} = 17.3$ GeV [39], as seen

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[3] We have to point out that the NA49 data in the full phase space shows a depletion in the K^+/π^+ ratio from 40 AGeV to 160 AGeV. This behaviour was previously conjectured as a possible signal of deconfinement [35]
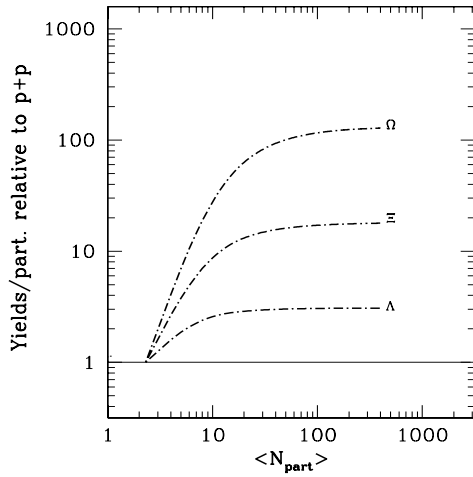
Fig. 3. Centrality dependence of the relative enhancement of particle yields/participant in central Pb–Pb to p–p collisions at fixed energy $\sqrt{s} = 8.73\,\text{GeV}$
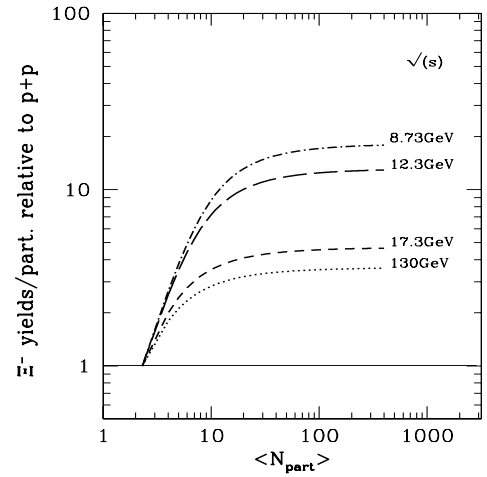

Fig. 5. Centrality dependence of relative enhancement of Ξ^- yields/participant in central Pb–Pb to p–A reactions at different collision energies
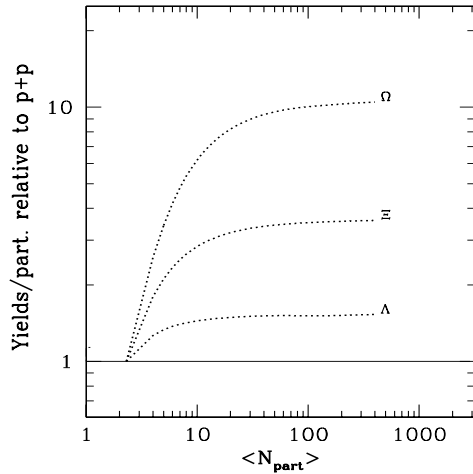

Fig. 4. Centrality dependence of the relative enhancement of particle yields/participant in central Pb–Pb to p–p collisions at fixed energy $\sqrt{s} = 130\,\text{GeV}$
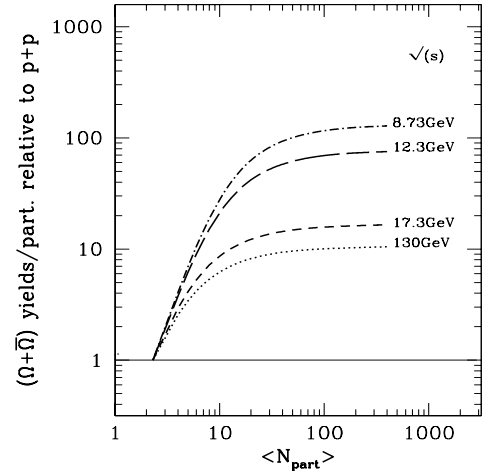

Fig. 6. Centrality dependence of relative enhancement of $(\Omega + \bar{\Omega})$ yields/participant in central Pb–Pb to p–p reactions at different collision energies

in Fig. 7. In p–p collisions the Ξ^-/π^+ ratio is obviously a strongly decreasing function of energy. From the above one could therefore expect that the relative enhancement of Ξ^- from p–p, p–A to A–A collisions should be larger at AGS than at SPS energy, which is seen in Fig. 5. In addition the ratio containing only newly produced particles such as e.g. Ξ^-/K^-, is also seen in Fig. 7 to be larger at AGS than SPS. The energy dependence of the Ξ^-/π^+ and Ξ^-/K^- ratios was calculated in Fig. 7 along the freeze-out curve [32] following the method described in [24].

The results of Figs. 5 and 6 show a saturation of the enhancement, which indicates that the grand canonical limit was reached. It is clear from these figures that this saturation is shifted towards larger centrality with decreasing energy.

In p-p collisions local strangeness conservation required that there be associated production of particles, e.g. Ξ has to appear together with two other strangeness 1 particles, to neutralize the strangeness. In high energy central A–

A collisions, there are already sufficiently many strange hadrons being produced for strangeness to be conserved on the average, which substantially increases thermal particle production. The associated production and locality of strangeness conservation is origin of the suppression of particle thermal phase space, which increases with the strangeness content of the particle as well as with decreasing collision energy. As a consequence the enhancement from p–A to A–A collisions with decreasing energy is seen in Figs. 5 and 6 to be stronger for Ω than for Ξ. At RHIC the freeze-out temperature was found to be consistent, within errors, with the one at the SPS as well as with the critical temperature found in the lattice gauge theory. As a consequence the enhancement of (multi)strange baryons at $s^{1/2} = 130\,\text{GeV}$ RHIC energy is seen in Fig. 4 to be comparable with that at the SPS. The change in baryon chemical potential from $266\,\text{MeV}$ to $50\,\text{MeV}$, evidently does not influence the strength of the enhancement. Thus, also an increase of the energy from 130 to $200\,\text{GeV}$ should
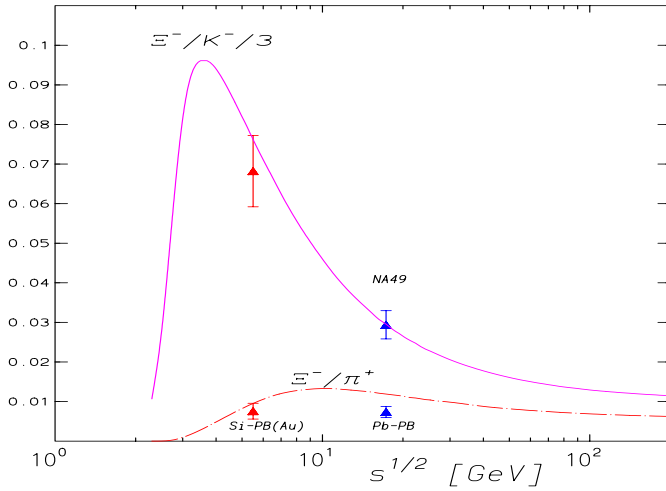
Fig. 7. Ratios of Ξ^-/π^+ and Ξ^-/K^- as a function of collision energy. The data at the SPS are fully integrated NA49 results. The corresponding ratio at the top AGS was obtained from E810 results on Ξ^- measured in Si–Pb collisions in the rapidity interval $1.4 < y < 2.9$ [37] normalized to the full phase space values of π^+ and K^- yield obtained in Si-Au collisions by E802 [38]

not change the above results much. These predictions are in obvious disagreement with UrQMD [36]. There, the production of strangeness is very sensitive to the initial conditions. In UrQMD the early stage multiple scattering may imply an increase of the colour electric field strength. Consequently, according to the Schwinger mechanism, this should increase the production of (multi)strange baryons. Under similar kinematical conditions as at the SPS, the UrQMD model predicts at RHIC an increase in relative strength of Ω yields from p–A to A–A by a factor of 4 [36].

The strangeness enhancement pattern measured by the WA97 Collaboration at the SPS [21] was predicted as a signal for quark–gluon plasma formation [22]. In the context of the considered SM model the enhancement pattern of (multi)strange baryons should be observed at all SPS energies, with increasing strength towards lower beam energy. Thus, the results of the above SM make it clear that strangeness enhancement and enhancement pattern are not a *unique* signal of deconfinement, since these features are expected to be there also at energies where the initial conditions are very unlikely for deconfinement.

The quantitative results shown in Figs. 3–6 contain some uncertainties. The magnitude of the enhancement is very sensitive to the temperature taken at a given collision energy. Changing T by $5\,\mathrm{MeV}$, a typical error on T in a thermal analysis, can change, for instance, the enhancement of Ω shown in Fig. 3 by a factor of 2. The N_{part} dependence of the strange hadron enhancement seen in Figs. 3–6 was obtained by assuming a linear dependence of a volume parameter V in (1) with N_{part}. In general, V could have a weaker dependence with centrality, which could be reflected with an only moderate increase of the enhancement, with centrality and saturation appearing at larger

volume. In addition, including the variation of the thermal parameters, in particular of the baryon chemical potential, with centrality, or extending the model to a canonical description of baryon number conservation [19], or finally including a possible asymmetry between the strangeness under saturation factors in p–p and A–A collisions [13,19], could change our numerical values.

However, independently of these uncertainties, the main results are always valid:

(i) enhancement decreasing with increasing collision energy, and
(ii) enhancement pattern being preserved at all SPS energies.

3 Summary and conclusions

In conclusion, we have shown that, in terms of the statistical model, the relative enhancement of (multi)strange baryons from proton–proton or proton–nucleus to nucleus-nucleus collisions is a decreasing function of the collision energy. Experimentally this fact already had been obtained for kaon yields and is shown to be expected for multistrange baryons. In addition, an increase of the enhancement with the strangeness content of the particle is a generic feature of our model, independent of the collision energy. On the qualitative level the only input being required in the model to make the above predictions is the information that freeze-out temperature is increasing with collision energy and that the chemical potential shows the opposite dependence. The above conditions are well confirmed by a very detailed analysis of particle production at different collision energies.

We have presented the quantitative predictions for a relative enhancement of Λ, Ξ and Ω yields in the energy range from $s^{1/2} = 8.7$ up to $s^{1/2} = 130\,\mathrm{GeV}$. We have discussed the possible uncertainties of the presented results. The relative enhancement at RHIC was found to be lower than at the SPS. This is in contrast with the UrQMD predictions, which are showing the opposite behaviour [36].

The statistical model applied here is also very unlikely to be capable of explaining an abrupt change of the $\bar{\Xi}/N_{\mathrm{part}}$ enhancement recently reported by the NA57 Collaboration [42].

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