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Strangeness production in heavy ion collisions

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Strangeness production in heavy ion collisions is discussed in a broad energy range from SIS to RHIC. In the whole energy range particle yields are showing high level of chemical equilibration which can be described by the unified freezeout conditions of fixed energy/particle $\simeq 1\text{GeV}$. The statistical model within the canonical formulation of strangeness conservation provides a framework to describe the observed enhancement of (multi)strange particles from p+A to A+A collisions measured at the SPS energy and predicts that this enhancement should be larger for decreasing collision energy. However, only at the SPS and RHIC chemical freezeout temperature is consistent within error with the critical value required for deconfinement and simultaneously strangeness is uncorrelated and distributed in the whole volume of the fireball.

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 high temperature [1–5]. 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 conditions [2–5] leads to an energy density of 2–3 GeV/fm³ and a baryon density of the order of 0.7/fm³. Lattice QCD at vanishing baryon density suggests that the phase transition from confined to the quark-gluon plasma (QGP) phase appears at the temperature $T_c = 173 \pm 8\text{ MeV}$ which corresponds to the critical energy density $\epsilon_c \sim 0.6 \pm 0.3\text{ GeV/fm}^3$ [6]. One could thus conclude that the required initial conditions for quark deconfinement are already reached in heavy ion collisions at the SPS energy. It will be discussed to what extent 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 content of the quark-gluon plasma - signal for deconfinement

An enhanced production of strange particles was long suggested as a possible signal of the QGP formation in heavy ion collisions [7,8]. In the QGP the production and equilibration of strangeness is very efficient due to a large gluon density and a low energy threshold for dominant QCD processes of $s\bar{s}$ production. In hadronic systems the higher thresh-

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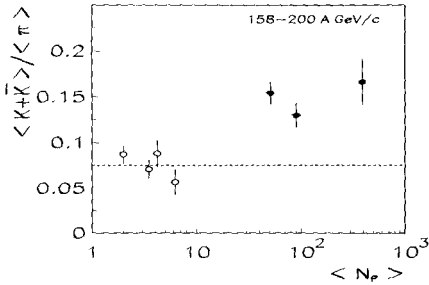


Figure 1. Ratio of total number of kaons per pions versus the number of participant in p+p, p+A and A+A collisions [10].

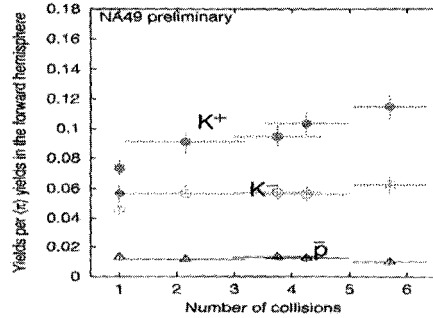


Figure 2. The multiplicity of K^+ , K^- and \bar{p} per pion multiplicity as a function of the number of collisions in p+A reactions [9].

old for strangeness production was argued [7] to make the strangeness yield considerably smaller and the equilibration time much longer.³

On the basis of the above strangeness QGP characteristics the following experimental implications are commonly quoted as the signal of deconfinement:

i) *global strangeness enhancement*: strangeness content of secondaries, measured by the total number of produced $\langle s\bar{s} \rangle$ quarks per participant A_{part} or per produced light quarks $\langle u\bar{u} + d\bar{d} \rangle$ should increase from pp, pA to AA collisions.

ii) *enhancement of multistrange baryons*: the specific enhancement (increasing with strangeness content) of multi-strange baryons and anti-baryons in central AA collisions, with respect to proton induced reactions follows deconfinement.

iii) *chemical equilibration of secondaries*: the appearance of the QGP being close to chemical equilibrium and subsequent phase transition should in general drive hadronic constituents produced from hadronizing QGP towards chemical equilibrium.

Heavy ion experiments at CERN SPS reported actually a global strangeness enhancement from p-p, p-A to A-A collisions [1,9–11]. In Fig. 1 we show full phase-space data of NA35 and NA49 collaboration on $\langle K + \bar{K} \rangle / \langle \pi \rangle$ ratio in S+S, S+Ag and Pb+Pb relative to p+p and p+A collisions. There is indeed a jump of factor of about two in strangeness content when going from p+p to heavy ion collisions. However, strangeness enhancement is already present in p+p [2] and in p+A collisions [9]. In Fig. 2 the $\langle K^+ \rangle / \langle \pi^+ \rangle$ ratio measured by the NA49 collaboration in p+Pb collisions in the forward hemisphere shows an increase with the number of collisions due to the secondary production. This effect is qualitatively similar to the one observed in Pb+Pb collisions. Strangeness enhancement from p+p to the most central p+A collisions can already account for more than 50% increase of strangeness seen in Fig. 1.

Large strangeness content of the QGP plasma should be reflected in a very specific hierarchy of multistrange baryons [7]: enhancement of $\Omega > \Xi > \Lambda$. Fig. 3 shows the yield/participant in Pb+Pb relative to p+Pb collisions measured by the WA97 and NA57

³In [39] it was argued, however, that multi-mesonic reactions could accelerate the equilibration time of strange antibaryons especially when the hadronic system is hot and very dense.

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 [8,20,21] and will be discussed in the next sections.

3. Equilibration and particle yields

One of the key questions in the description of particle production in heavy ion collisions is to what extent measured yields are showing equilibration. The level of equilibration of secondaries in heavy ion collisions can be tested on a different level: by analyzing (i) particle abundances or (ii) particle momentum distributions. In the first case one establishes the chemical composition of the system (*chemical freezeout*), while in the second an additional information on dynamical evolution and collective flow can be extracted (*thermal freezeout*).

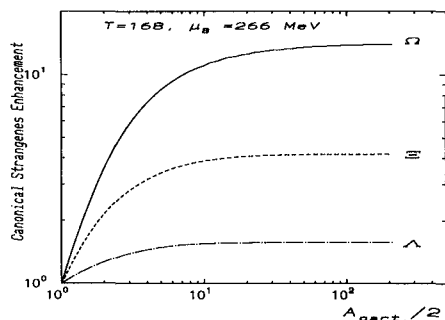


Figure 6. Particle multiplicities per participant normalized to its value in p+p system as a function of $A_{part.}$ calculated in statistical model in (C) ensemble [21].

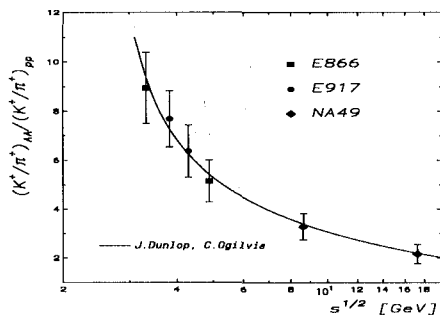


Figure 7. K^+/π^+ ratio at midrapidity in A+A relative to p+p collisions. For the compilation of data see [33,34]. The full line is the parameterization from [33].

The compilation of the experimental data for particle multiplicity ratios in central Pb+Pb collisions at the SPS is shown in Fig. 4. The relative hadron abundances are compared with the thermal model [20]. The model was formulated in the grand canonical (GC) ensemble with the partition function which contains the contributions of most hadrons and resonances and preserves the baryon number, strangeness and charge conservation. The particle ratios depend only on two parameters; temperature T and baryon chemical potential μ_B . It is clear from Fig. 4 that with $T \sim 170$ MeV, corresponding to the energy density $\epsilon_f \sim 0.6$ GeV/ $f m^3$, and with the baryon chemical potential $\mu_B \sim 270$ MeV the statistical model reproduces the experimental data.

In Fig. 5 we compare the recent data of STAR collaboration in Au+Au collisions at RHIC with the statistical model results. Also here the model is consistent with data [22,24].⁴ The crucial difference to the SPS is a much lower value of the baryon chemical potential μ_B of 45 MeV. This is to be expected as higher collision energy should lead to less stopping. The freezeout temperatures in central A+A collisions at the SPS and RHIC coincide within errors 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 established during hadronization [3-5].

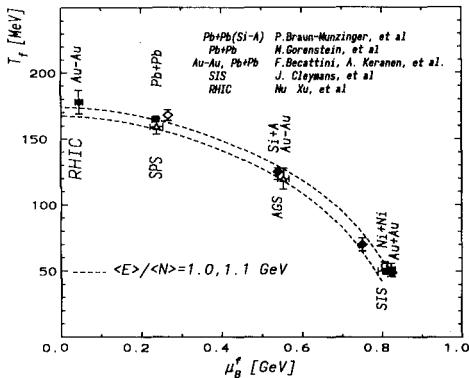


Figure 8. Average temperature and baryon chemical potential required to describe particle yields measured at GSI/SIS, AGS, and SPS [25,26]. The unified chemical freezeout curve (dotted line) is calculated from the condition that the ratio of the average energy $\langle E \rangle$ per average number of hadrons $\langle N \rangle$ is equal to 1 or 1.1 GeV.

Chemical equilibration of secondaries is, however, not a unique property of the SPS data [21,25-27]. It is also present at much lower incident energy or in peripheral high energy nucleus-nucleus collisions where the initial conditions required for deconfinement are not necessarily established. To discuss equilibration of strangeness in the above cases one needs, however, to formulate a statistical model in the canonical (C) ensemble with respect to the strangeness conservation [21,26,28,29].

4. Chemical equilibration - canonical description

Strangeness conservation in statistical models can be described in the (GC) ensemble only if the number of produced strange particles per event is much larger than one. In the opposite limit of rare particle production [30], strangeness conservation must be implemented locally on an event-by-event basis i.e., (C) ensemble of strangeness conservation must be used. The (C) ensemble is relevant in the statistical description of particle production in low energy heavy ion [25], or high energy hadron-hadron or e^+e^- reactions [29] as well as in peripheral heavy ion collisions [21]. The exact conservation of quantum numbers, that is the canonical approach, is known to reduce severely the phase-space available for particle productions. [28].

To illustrate the canonical suppression let us consider a simple example of K^+K^- production in the pionic thermal system of the volume V at temperature T . For large T , kaons are abundantly produced and the density of kaons reaches (GC) equilibrium

⁴A precise determination of T_f is not yet possible as fits with $170 < T_f < 190$ give similar value of χ^2 . Data like eg. $\bar{\Lambda}/\bar{p}$ are necessary to further determine T_f [24].

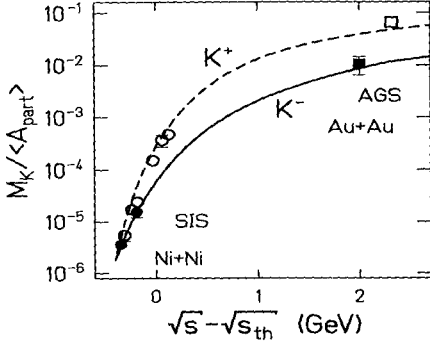


Figure 9. Statistical model results on the average number of kaons M_K per participant A_{part} [26]. Open (full) symbols represent measured multiplicities.

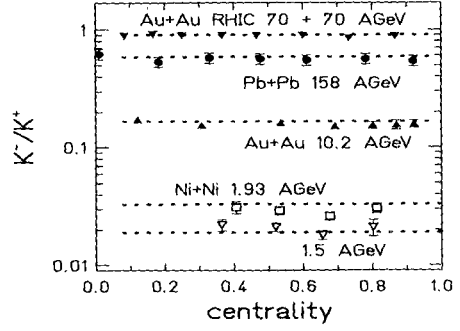


Figure 10. K^+/K^- data for different centrality at GSI/SIS [26], AGS [33], SPS [9] and RHIC [23]. The dotted lines are statistical model predictions [26].

value, $n_{K^+}^{GC} = (1/2\pi^2)m_{K^+}^2TK_2(m_{K^+}/T)$. In the limit of low temperature the K^+ , K^- are very rarely produced and in order to satisfy strangeness neutrality condition, kaons must appear in pairs in the near vicinity. In this case, the density of produced kaons reaches an equilibrium result of (C) ensemble. In the asymptotic limit with $\langle K \rangle \ll 1$ we have $n_{K^+}^C \sim [(1/2\pi^2)m_{K^+}^2TK_2(m_{K^+}/T)] \times [V_0(1/2\pi^2)m_{K^-}^2TK_2(m_{K^-}/T)]$. (1)

The first term coincides with (GC) value, the second describes the phase space suppression since with each K^+ a K^- has to appear in the near vicinity in order to conserve strangeness exactly. The parameter V_0 in Eq. 1 is introduced as a correlation volume where the K^+ and K^- should be created to fulfill locality of strangeness conservation. In heavy ion collisions V_0 was found to scale with A_{part} and in proton induced processes $V_0 \sim V_{proton}$. There are thus, two origins of canonical suppression of strangeness: first, particles are produced in pairs what restricts the available momentum phase-space and secondly they appear in the near vicinity in space to fulfill locality of the conservation laws.

4.1. Multistrange baryons - centrality dependence

The canonical suppression of thermal particle phase-space increases with strangeness content of the particle. The exact conservation of strangeness requires that each particle carrying strangeness \bar{s} has to appear e.g. with s other particles of the strangeness one to satisfy strangeness neutrality condition.

In Fig. 6 we calculate the multiplicity/participant of Ω , Ξ , and Λ relative to its value in a small system with only two participants. Thermal parameters were assumed here to be A_{part} independent. Fig. 6 shows that the statistical model in (C) ensemble reproduces the basic features of WA97 data: the enhancement pattern and enhancement saturation for large A_{part} indicating here that (GC) limit is reached. The quantitative comparison of the model with experimental data would require an additional assumption on the variation of μ_B with centrality to account for larger value of B/B ratios in p+A than in Pb+Pb

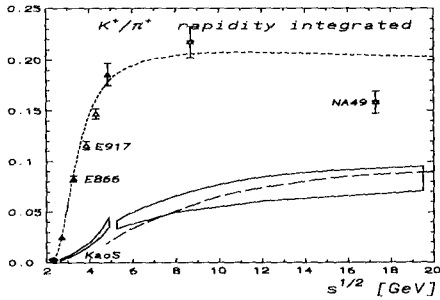


Figure 11. The K^+/π^+ , 4π ratio versus energy [34]. The short-dashed and dashed lines represent thermal model result for Pb+Pb and p+p respectively. The full lines are a parameterization of p+p data [33].

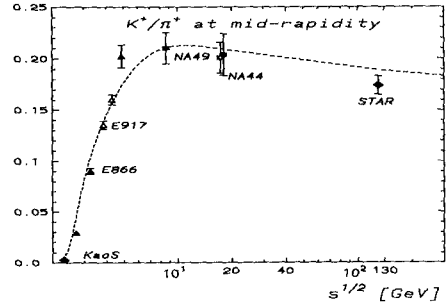


Figure 12. As in Fig. 11 but at mid-rapidity. The results at RHIC were estimated from STAR results on K^-/π^- and K^+/K^- ratios [23], assuming that the ratio of $\pi^+/\pi^- \simeq 1$.

collisions [11]. An abrupt change of the enhancement seen in the NA57 data for Ξ^- is, however, *very unlikely* to be reproducible in terms of this approach.

One of the consequences of the model is that the enhancement pattern seen in Fig. 6 should not be only a feature of the SPS data. In terms of (C) model strangeness enhancement and enhancement pattern should be also present there 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 [17].

In Fig. 7 we show a compilation of the data on K^+/π^+ ratio in A+A relative to p+p collisions. This double ratio could be referred to as a strangeness enhancement factor. The enhancement is seen to be the largest at the smallest 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 [31] the observed strangeness enhancement from p+p to A+A collisions as an *appropriate characteristics* of the deconfinement. To search for the QGP formation through the strangeness composition of secondaries one should rather look for a non-monotonic behavior of strange particle yields versus centrality or collision energy.

A detailed analysis of the experimental data in heavy ion collisions from SIS to SPS [20,25–27] has shown that most particle yields are reproduced by the statistical model.⁵ In Fig. 8 we present the compilation of chemical freezeout parameters required to reproduce measured particle yields at SIS, AGS, SPS and RHIC energies. The GSI/SIS results have the lowest freezeout temperature and the highest baryon chemical potential. As the beam energy is increased a clear shift towards higher T and lower μ_B occurs. There is a common feature of all these points namely that the average energy per hadron is approximately 1 GeV. *Chemical freezeout* in A+A collisions is thus reached *when the energy per particle drops below 1 GeV* at all collision energies [25]. Figs. 9–12 are showing different particle multiplicity ratios along unified freezeout curve in comparison with experimental data.

⁵Statistical models, however, failed e.g. to describe the yield of η at SIS or $\bar{\Lambda}/\bar{p}$ ratio at AGS.

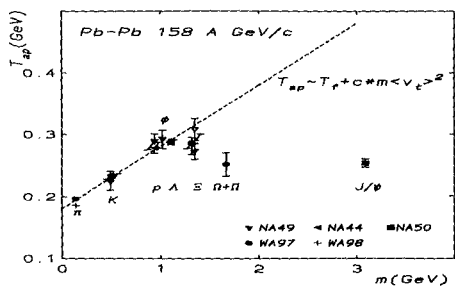


Figure 13. Dependence of the transverse mass inverse slope parameters on the particle rest mass [32,40].

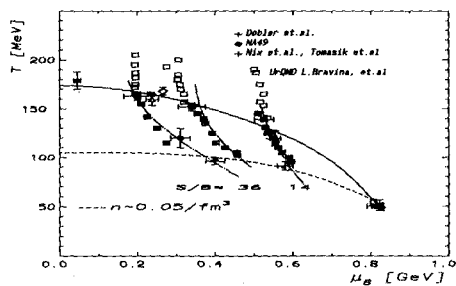


Figure 14. Thermal [5,37] and chemical freezeout conditions [25,26] compared with the evolution path from UrQMD [15].

In all cases the energy dependence of data is well reproduced by the statistical model. The canonical strangeness suppression in central A+A collisions is very relevant at SIS energies. At the top AGS the (GC) treatment of strangeness conservation is already adequate.

Specific features of K^+ and K^- excitation functions shown in Fig. 9 are appearing in the model as a consequence of different dependence of K^+ and K^- yields on baryon number density [26]. Also here, the increase of the canonical correlation volume from the size of the colliding nucleus at SIS up to the macroscopic volume of a thermal fireball at SPS is of crucial importance. Furthermore, the independence of the K^+/K^- ratio on the number of participating nucleons seen in Fig. 10 from SIS to RHIC is a natural result of the statistical model as a particle and its antiparticle have the same centrality dependence as well as in (GC) and in (C) formulation. A consistent description of the energy or centrality dependence of kaon yields in A+A collisions within microscopic transport models is still missing [35].

Of particular interest are experimental results represented in Fig.11 where the 4π data on K^+/π^+ ratios [34] are showing a maximum at $\sqrt{s} \sim 6 - 8\text{GeV}$ and drop at the SPS. The suppression of this ratio disappears, however, at midrapidity [34] as seen in Fig. 12. Statistical model favors the behavior seen in Fig. 12. The description of fully integrated data at the top SPS energy is only possible in terms of the statistical model when introducing an extra parameter which accounts for strangeness undersaturation [27]. The suppression of K^+/π^+ ratio seen in Fig. 11 was predicted as a possible signal for deconfinement [36].

5. From chemical to thermal freezeout

Transverse mass distribution of strange and non strange particles clearly indicates in addition to the thermal one also the collective transverse flow component [4,5,37]. In Fig.13 the resulting increase of the transverse mass slope parameter T_{app} with the rest mass of the particle is typical for transversely expanding source. Deviations of Ω [32] and J/Ψ seen in Fig.13 most likely reflect their earlier decoupling from the system due to a small rescattering cross section with the surrounding medium.

The compilation of thermal freezeout parameters from SIS to SPS, extracted from

particle spectra and two particle momentum correlation are shown in Fig. 13. The system seems to expand transversely from the chemical to thermal freezeout following the path of constant entropy (S) per baryon (B) [25]. The abundances of secondaries during this evolution are frozen in. In the statistical approach this can only happen if the phase space of particles like e.g. pion, kaon and nucleon are over-saturated [38] by an effective chemical potentials with typical values of 60-120 MeV at $T_{th} \sim 110$ MeV. The evolution path and the moment of dynamical decoupling of the fireball is seen in Fig. 14 to coincide with UrQMD description [14,15]. The chemical freezeout curve of constant $\langle E \rangle / \langle N \rangle \simeq 1$ GeV appears in UrQMD [15] when the system reaches the kinetic equilibrium (full squares in Fig. 14).

6. Conclusions

One of the most puzzling results in heavy ion collisions is presumably an observation that particles seem to be produced according to the principle of maximal entropy. In a very broad energy range from $\sqrt{s} \sim 2.5$ up to 130 GeV hadronic yields and their ratios observed in heavy ion collisions resemble chemical equilibrium population along unified freezeout curve determined by the conditions of fixed energy/hadron $\simeq 1$ GeV. Strangeness follows this systematics and since their production mechanism is quite different at low and at high energies it seems that particle yields are losing information about dynamics. However, there are some characteristic features of the system at chemical freezeout in central A+A collisions being only present at SPS and RHIC: i) chemical freezeout temperature is within errors consistent with the critical temperature and ii) strangeness is un-correlated and redistributed in the whole volume of a thermal fireball. Although the condition i) is also there in peripheral nucleus-nucleus and even in p+p collisions, the property ii) is obviously not valid any more. Here, the thermal phase space available for strange particles is strongly suppressed since, for only a few particles being produced per event, strangeness is strongly correlated in the volume $V_0 \sim V_{proton}$ and thus has to be conserved exactly and locally (canonical description). In high energy A+A reactions, there are already sufficiently many strange particles being produced per event such that strangeness is conserved on the average and is distributed in the whole volume of the fireball (grand canonical description).

If thermal description of particle productions is correct, strangeness enhancement from p+p to A+A collisions appears naturally as a transition from the canonical to the grand canonical regime. Hence strangeness enhancement does not necessarily require deconfinement and should also be observable at lower collision energies where the conditions for deconfinement are not satisfied. However, a specific, non-monotonic behavior of strangeness versus centrality or collision energy could be of interest in this context. Recent results of NA57 and NA52 showing an abrupt change with centrality of Ξ and K^+ , respectively, as well as the observed by NA49 drop of K^+/π^+ ratio seen in Fig. 11 could signal a new dynamics.

Acknowledgments

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