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Strangeness Production in Relativistic Nuclear Collisions

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A review of strange particle production in heavy ion collisions from AGS to SPS energies is presented. Implications of the newest developments in understanding the collision dynamics and the role of strange particle production in the search for a new phase of matter, in both experimental and theoretical sectors, are discussed.

1. INTRODUCTION

While there is still ultimate hope that a definite conclusion on the formation of a new phase of nuclear matter, the Quark Gluon Plasma (QGP), will eventually arise from analysis of direct lepton signals, most of the experimental effort is directed towards hadronic observables. This is due to many practical reasons, including a wide range of possible signatures, stronger signals, better understanding of background sources and their magnitudes, etc.

An enhanced production of strange hadrons in heavy ion collisions when compared to nucleon-nucleon or nucleon-nucleus collisions at the same energy as a consequence of plasma formation was predicted by Rafelski et al. more than a decade ago [1]. It was argued that the high parton density and lower energy threshold for $s\bar{s}$ pair production in the quark gluon plasma, compared to a hadron gas, may lead to increased strangeness content in the final state. Additionally, in an environment of high baryon density, the production of $s\bar{s}$ pairs should be favored if the lowest available u and d quark levels have energies above $2m_s$. These expectations were soon confirmed by QCD calculations [2].

Experimentally, strangeness enhancement in heavy ion collisions was observed for the first time in S+S collisions at 200 GeV/c per nucleon (the NA35 experiment at the CERN SPS) and in Si+Au at 14.6 GeV/c per nucleon (the E802 experiment at the AGS) in 1987, and the results were presented at one of the preceding conferences of this series [3], [4]. Since then, the strangeness signal has become one of the most discussed and speculated on candidates for messenger of the plasma phase. Strong interest in this field motivated a series of topical meetings, with the first one held in Tucson, Arizona, in 1995.

Note that, even if a phase transition does not take place and the QGP is not formed in the collision, strangeness itself remains one of the most interesting and powerful probes of nuclear reaction dynamics. In fact, the entire strangeness observed in the final state of a nuclear collision originates from the interaction (since there is no strangeness in the initial state). Moreover, strangeness is conserved in strong interactions. Its equilibrium value (as well as the entropy equilibrium value) is directly sensitive to properties of matter: the effective number of degrees of freedom and their effective masses. It is believed that

strangeness (and entropy) production freezes out in the early stage of system evolution, when energy density is the highest. Finally, strangeness presents a link between the partonic and hadronic phases of the collision, since the signal is well defined in both phases. However, strangeness enhancement may not necessarily arise exclusively from the partonic phase formation; it may also result to some extent from rescattering in the hadronic fireball formed in A+A collisions (e.g.: π+N $\rightarrow$ Λ+K, $\pi+\pi \rightarrow$ K+$\overline{K}$, $\pi+\pi \rightarrow \Omega+\overline{\Omega}$, etc).

The state of the art model of strongly interacting matter, lattice QCD, predicts the phase transition to quark-gluon plasma phase at a critical temperature of $\sim$ 150–160 MeV where the energy density $\epsilon_c \approx 1$ GeV/fm^3 [5]. Recent data indicate that, while 11 GeV/c Au on Au collisions at the AGS have an energy density approching the critical value of $\sim$ 1 GeV/fm^3 [6], at the CERN SPS (the higest energy available in the laboratory: $\sqrt{S}$ $\sim$20 GeV) the energy density far exceeds the ϵ_c value calculated within the QCD framework. Analysis of central Pb on Pb collisions indeed shows that matter with an energy density of several GeV/fm^3 is created in the early stages of the collision [7]. Thus, we expect to see some "new physics" emerging from the data, perhaps even evidence of a new phase of matter.

In the next section a brief summary of experimental results from the AGS, along with their interpretation, is presented. Section 3 discusses strangeness production at the CERN SPS with a particular emphasis on measurements from the CERN SPS lead beam program. Comparison to some of the models is included. Section 4 contains a short summary of the field.

2. STRANGENESS PRODUCTION AT THE AGS

Strangeness enhancement at AGS energies was originally observed by the E802 experiment in Si-induced central collisions at 14.6 GeV/c per nucleon as an increase in the K$^+$ yield relative to that of π^+ [8]. Ten years later, when Au beams became available at the

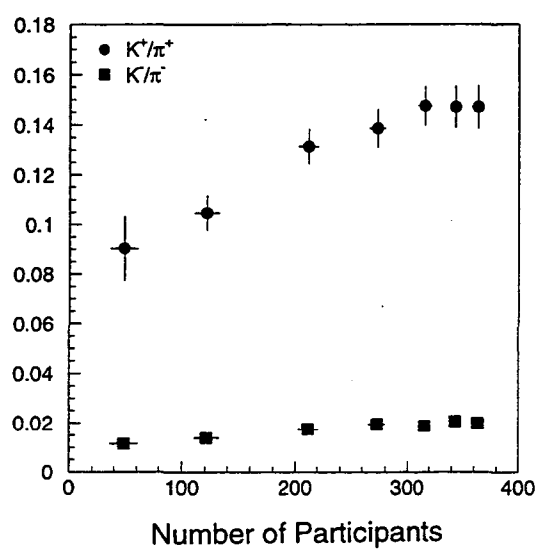

Figure 1. The K$^+/\pi^+$ and K$^-/\pi^-$ ratios in Au+Au collisions at 11.1 GeV/c.

AGS, this effect was studied in great detail in the much larger Au+Au system, but at a slightly lower energy. The K^+/π^+ and K^-/π^- ratios for Au+Au collisions at 11.1 GeV/c per nucleon, obtained by the E866 experiment, are shown in Fig.1 as a function of the number of participants (~centrality) [9].

Both ratios increase with centrality in peripheral collisions, and seem to saturate for more central interactions. The average K^+/π^+ ratio from minimum bias Au+Au data is a factor of ~5 higher than in pp collisions whereas the K^-/π^- ratio roughly agrees with that for pp [10]. As the K^+/π^+ ratio is very sensitive to baryon density, the observed enhancement must be largely a reflection of the high baryon density reached in the Au+Au system. The similarity of K^-/π^- ratios in Au+Au and pp colisions should not be misinterpreted as an implication of similarity of the systems; high baryon density is created in Au+Au collisions at the AGS (where $\overline{u}$ and $\overline{d}$, but not $\overline{s}$, quarks are suppressed due to Pauli blocking), whereas the pp system is basically baryon free. The similar K^-/π^- ratios in pp and Au+Au might be caused by an interplay of two processes: enhanced K^- production and enhanced K^- absorption through exchange channels [9]. Early results on K^+/π^+ ratio enhancement, together with the observation of nearly full stopping and high baryon density at AGS energies, created a lot of interest, and, consequently, the majority of the AGS collaborations included strangeness studies in their experimental programs. E866/917's systematic approach allowed an investigation of the excitation function of produced particles. By changing centrality, the size of the colliding system was selected, and by varying the beam energy, the baryon density was chosen. Figure 2 shows the rapidity density of π^+ and K^+ on a "grid" of beam energy vs centrality. We see that an order of

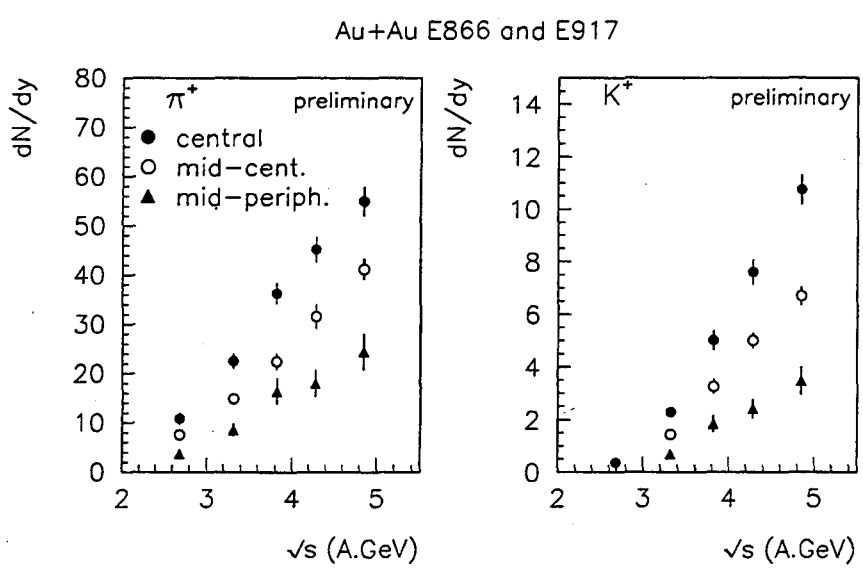

Figure 2. dN/dy of π^+ and K^+ in Au+Au collisions at mid-rapidity vs beam energy and centrality.

magnitude more kaons are produced at the highest AGS energy than at 2 GeV/c, and

that the rise is very smooth. In the case of pions, the rise is significantly smaller, but equally smooth. While not as numerous as pions, kaons, in general provide much more reliable information on produced particles and, therefore, on collison dynamics, than do pions, because their spectra have almost no contamination from resonance decays; only two rare channels ($K^* \rightarrow K\pi$ and $\phi \rightarrow K^+K^-$) can contribute. Figure 3 shows the behavior of total K^+ and K^- yields as a function of centrality. An increase of a factor ~9 between peripheral (60% of σ_{inel}) and central (4% of σ_{inel}) collisions, is seen. Unlike Si+Al and

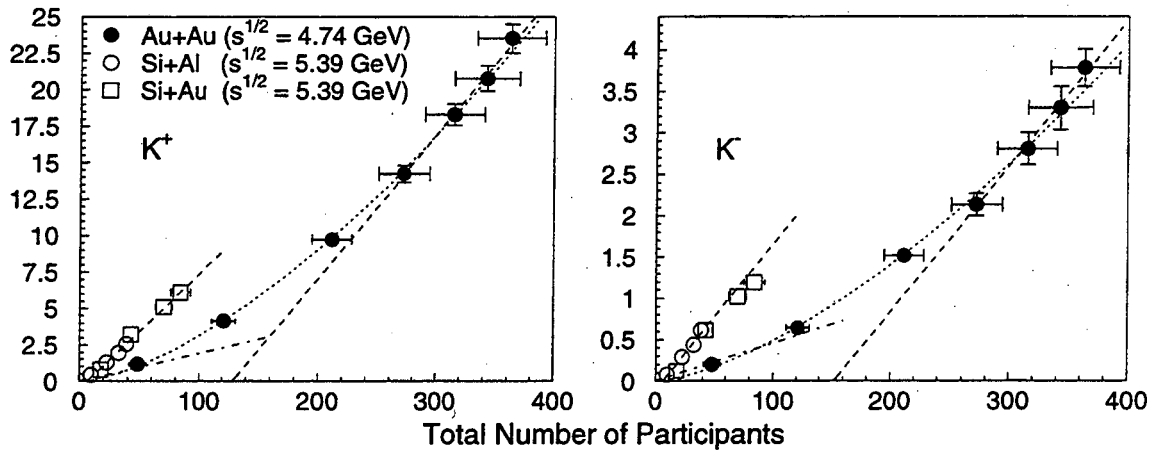

Figure 3. Estimated total K^+ (left) and K^- (right) yields versus total number of participants in Au+Au, Si+Al and Si+Au collisions. See text for details.

Si+Au collisions in which the total K^+ and K^- yields depend linearly on the total number of participants, the total K^+ and K^- yields in Au+Au collisions increase quadraticly. For comparison, the dot-dashed line shows the total K^+ and K^- yield in pp collisions at 11 GeV/c, multiplied by half the number of participants. Kaon yields in the most peripheral Au+Au collisions appear to follow this line, suggesting that peripheral Au+Au interactions behave like single nucleon-nucleon collisions with respect to kaon production (the so-called "corona" effect). With increasing centrality (higher N_{part}), the succesive nucleon-nucleon collisions and rescattering gradually take over, and, for the most central Au+Au collisions, the slopes of the K^+ and K^- yields are consistent with those from central Si+A data. Thus, the difference between K^+ and K^- yields vs centrality in Si+A and Au+Au is attributed to the collision geometry.

The rapidity distributions (not shown) for both K^+ and K^- peak at mid-rapidity and are approximately Gaussian. The dN/dy distributions are narrower for K^- than for K^+. This difference, common to all centralities, reflects the general trend in pp collisions, where $K\overline{K}$ pair production causes K^- to peak in the mid-rapidity region, while K^+ has a much broader range due to associated production contribution ($NN \rightarrow N\Lambda K^+$, $N\Sigma K^+$, etc.).

Another very interesting feature of kaon production is observed in AGS data: inspite of the very different K^+ and K^- production mechanisms, their ratio appears to be constant over the entire range of centrality. The K^+/K^- ratio vs the total number of participants

is plotted in Fig.4 for Au+Au collisions. For comparison, the ratios for Si+Al and Si+Au

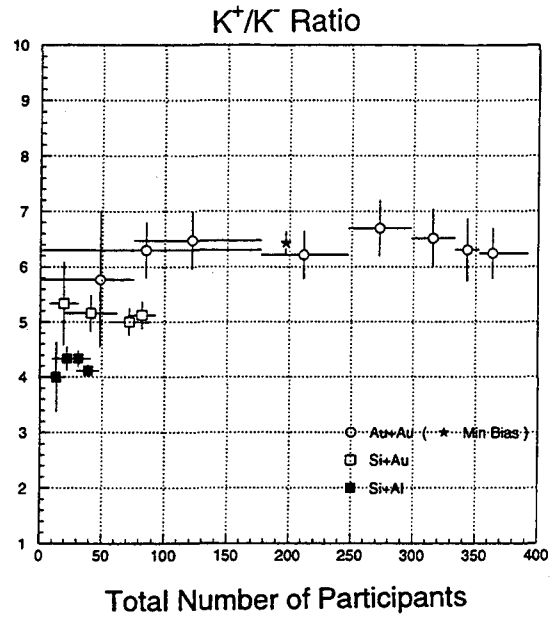

Figure 4. The K^+/K^- ratio in Au+Au and Si+A_T collisions vs the total number of participants.

collisions are shown on the same plot. The overall K^+/K^- ratio increases from the light system of Si+Al to the medium system of Si+Au, and to the large system of Au+Au. However, it stays the same from peripheral to central collisons for each of the systems, indicating that the increase is not driven by the changing system size, but most likely indicates that the baryon density increases from the lighter systems (Si+Al, Si+Au) to the heavier one (Au+Au).

Out of the wealth of the data obtained by the AGS experiments, only a small sample was sketched above. As it was shown, the interpretation of the strangeness production mechanisms, based entirely on kaon analysis, is consistent with the superposition of nucleon-nucleon collisions and hadronic re-interactions. All experimental dependencies are quite smooth, with no indication of any offset, jump or sharp turn to suggest a phase transition. Thus, the data support the assumption that the collision dynamics stay within the hadronic phase throughout, and are well understood without invoking the formation of a QGP. However, the AGS program lacks in a comprehensive analysis of hyperon production, and this is essential for drawing final conclusions. Once new data are available, we will need to reassess the situation.

3. STRANGENESS PRODUCTION AT THE SPS

Recent results from Pb on Pb collisions at the CERN SPS have confirmed [11], beyond any doubt, previous "hints" of new physics emerging from the analysis of strange particle production in S+A_T interactions at 200 GeV/c per nucleon. Most experiments using

heavy ion beams at the SPS have included strange particle production measurements in their program. Due to space limitations, we will discuss here only the most typical results. For details, see the references to the original publications below.

An important, and greatly appreciated, advantage of strangeness is the large variety of strange particle species. The long lifetime against weak decays, enhanced by the γ factor at CERN energies, has allowed measurements of ten different strange hadrons (K^+, K^-, K^0, ϕ, Λ, $\overline{\Lambda}$, Ξ^-, $\overline{\Xi}^-$, Ω, $\overline{\Omega}$) in heavy ion interactions.

From early results of CERN experiments with S beams, we learned that a significant fraction of the individual longitudinal energy becomes degraded during the interaction (due to elastic and inelastic collisions at the microscopic level) and deposited into the reaction volume. This became even more apparent with heavier beams. The net baryon distribution measured by NA49 for central Pb+Pb collisions as a function of rapidity (G.Roland and NA49 Coll. in this proceedings and [20]) together with the net baryon distribution for central S+S collisions measured by the NA35 experiment [12], show that the Pb+Pb system exhibits considerably greater stopping than S+S. Naturally, the energy deposited into the interaction volume increases the energy density there. The estimate of the energy density based on the boost-invariant dynamics of the Bjorken picture [13] and the measured energy density in rapidity space, $dE/d\eta$ [14], results in $\epsilon \approx 2.8$ GeV/fm^3 for Pb+Pb. This far exceeds the critical value set by lattice QCD calculations for the phase transition, even allowing for the uncertainty related to the τ_0 parameter in the Bjorken formula (at present, τ_0=1 fm/c is used rather arbitrarily). Thus, this high energy density interaction volume of Pb+Pb collisions could, in principle, contain the plasma state indicated by lattice QCD.

Strangeness production in heavy ion collisions has long been regarded as a sensitive probe of the proximity to chemical equilibrium that the system may achieve [1],[15]. To calculate the estimate reliably, one has to use a "4π" measurement of particle ratios and yields; otherwise, the results are strongly dependent on kinematical regions of the phase space, and conclusions are not model independent.

So far, only pion and kaon multiplicities (in 4π) are available for Pb+Pb collisions [17]. Figure 5 shows the $\langle K+\overline{K}\rangle/\langle\pi\rangle$ ratio for various systems. $\langle\pi\rangle = 3*\langle h^-\rangle$ denotes the multiplicity of pions of all charges. One observes from Fig. 5 that the data points cluster around 0.075 for pp and pA collisions, whereas they lie at about 0.13 for central S+S, S+Ag and Pb+Pb reactions. This represents an enhancement of strangeness production by about a factor 2 in nucleus-nucleus collisions. Note, that kaons represent over 70% of the total strangeness produced during a collision; therefore, this measurement represents the strangeness content of the system quite well. Strangeness production is known to be suppressed in pp and pA collisions at this energy. Central nuclear collisions appear to remove this suppression. In fact, a partonic state at T$\geq$200 MeV is expected to produce nearly equal abundances of the three light flavours, in spite of the strange quark being heavier. If it simply coalesces into hadrons during hadronization, the resulting $\overline{\Lambda}/\overline{p}$ ratio should be ≈ 1; indeed, we see a somewhat "corresponding" signal in the data [16]. Figure 6 presents the $\overline{\Lambda}/\overline{p}$ ratio in central heavy ion collisions from NA35 (S+S, S+Ag, S+Au) and NA49 (Pb+Pb), compared with pp and pA data. Whereas the pp and pA data stay below about 0.4, the S+S, S+Ag, and S+Au ratios average about unity. The Pb+Pb point, while very preliminary and with a large error bar, is consistent with the

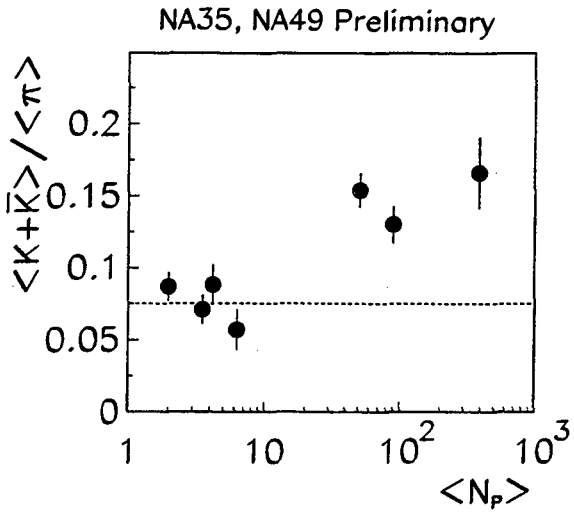

Figure 5. Multiplicity ratio $\langle K+\overline{K}\rangle/\langle\pi\rangle$ in full phase space for pp, pA and AA collisions plotted versus the average number of participating nucleons.

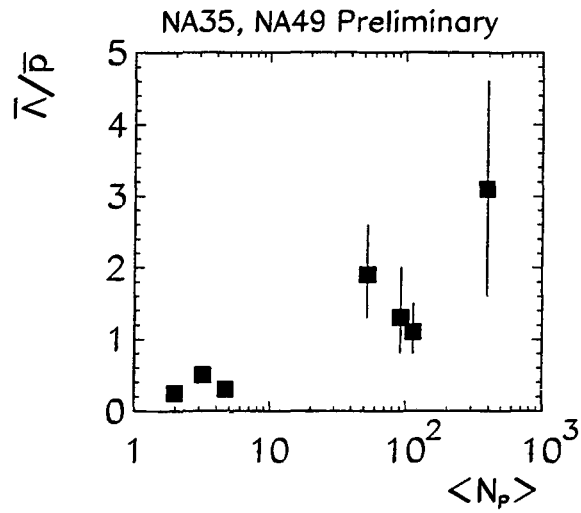

Figure 6. Ratio of the rapidity densities of $\overline{\lambda}$ and $\overline{p}$ at midrapidity for various target-projectile systems as a function of the number of participants.

rest of the A+A values. The ratio is plotted against the mid-rapidity negative hadron multiplicity density. From the flavour composition of $\overline{\Lambda}$ and $\overline{p}$, one intuitively expects that the production ratio reflects the flavor density in the source as it only refers to newly created antiquarks: $\overline{s}$ and $\overline{u}$.

With the observation that $\overline{\Lambda}/\overline{p} \approx 1$ in heavy ion collisions, the crucial question arises: are we seeing a signal of flavour equilibration in the source? So far, there is no definite answer to this question. However, the strangeness enhancement (Λ, $\overline{\Lambda}$, K^0) reported originally by NA35 was confirmed by the multistrange hyperon yields studied at mid-rapidity in S- and Pb-induced reactions by the WA85/94/97 [18] and NA35/49 [19] collaborations. Figure 7 shows a comparison of the Ξ/Λ and $\overline{\Xi}/\overline{\Lambda}$ ratios in heavy ion reactions with available pp, $p\overline{p}$, e^+e^- and pA data. It is clear that multistrange particle production in heavy ion collisions is further enhanced over elementary and pA data. In fact, this effect is indeed dramatically manifested in the newest WA97 analysis of the p+Pb and Pb+Pb data (I.Kralik and WA97 Coll. in this proceedings). The enhancement of triply strange hyperons ($\Omega+\overline{\Omega}$) in Pb+Pb over p+Pb reaches a factor ~10, doubly strange ($\Xi+\overline{\Xi}$) a factor ~6-8 and singly strange ($\Lambda+\overline{\Lambda}$) a factor ~2-3. Such results are seen for the first time, and certainly, even though very preliminary, deserve a lot of attention. In spite of the extremely high mass thresholds, multistrange hyperon multiplicities are unprecedentedly high and present a particular challenge to any hadronic kinetic model. Morover, of particular interest is the fact that the Ω and Ξ enhancements are higher than that observed in the Λ yield. Multi-strange hyperons are more "difficult" to produce than Λ in the hadronic scenario, so one would expect Λ to be significantly more enhanced than Ω and Ξ. It appears that the opposite is true in analyzed Pb+Pb collisions. Note that the Pb+Pb data points (Fig. 7), though still preliminary and with large error bars, are compatible with S+A_T measurements. We will come back to this very important observation shortly.

Let us turn now to the hidden strangeness vector meson ϕ. If a QGP was formed,

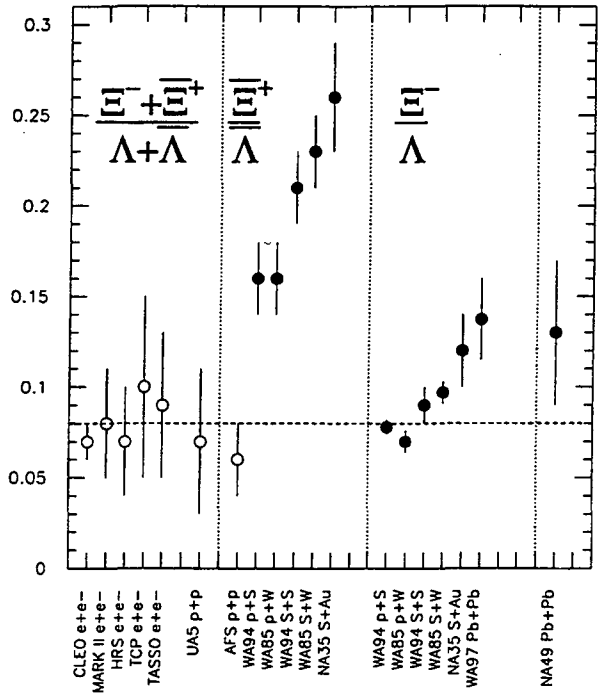

Figure 7. Ξ/Λ and $\overline{\Xi}/\overline{\Lambda}$ ratios for different experiments.

the abundant s and $\bar{s}$ quarks present in the plasma could coalesce to form ϕ mesons, overriding the strong suppression of ϕ present in nucleon-nucleon and nucleon-nucleus reactions. Indeed, the NA38/50 experiment (D.Jouan and NA38/50 Coll. in this proceedings) measuring vector meson production via the $\mu^+\mu^-$ decay mode, and the NA49 experiment reconstructing ϕ from the hadronic K^+K^- decay channel [21], report a significant ϕ enhancement in nucleus-nucleus collisions. NA49's preliminary estimate of this enhancement in Pb+Pb collisions, relative to the yield in pp, is $\sim$ 2.6 (F.Puhlhofer and NA49 Coll. in this proceedings).

Thus, the large observed difference ($\sim$ 2−3 times for S=1; and larger for S=2,3) between strange particle yields in central S+A_T and Pb+Pb collisions, and the scaled yields in the reference interactions (N+N, p+S and p+Pb), illustrating the enhanced production of strangeness (relative to π^- mesons) in central nucleus-nucleus collisions is present in all investigated strangeness production channels.

In order to quantify the total strangeness production and its enhancement, we follow a procedure introduced by NA35, and use the E_S ratio defined as [22]

$$E_S \equiv \frac{\langle \Lambda \rangle + \langle K + \overline{K} \rangle}{\langle \pi \rangle}$$

where $\langle K + \overline{K} \rangle$ is the mean multiplicity of neutral and charged kaons, and $\langle \pi \rangle$ is the mean multiplicity of pions produced by strong interactions. The E_S ratio is closely related (approximately two times smaller) to the strangeness suppression factor λ_s, commonly used in elementary particle physics [22].

To illustrate the increase of the total yield of $s\bar{s}$ quark pairs relative to that of non-strange quark-antiquark pairs when comparing central AA (or pA) with NN interactions

at the same collision energy per nucleon, we show in Fig. 8 the difference between E_S for central A+A (circles) or p+A_T (squares) collisions [23] and E_S for N+N interactions [24]. The solid line ($\equiv$0) represents N-N collisions. No strangeness enhancement is observed in p+A_T interactions; all corresponding E_S differences are close to zero. They seem to be independent of the target mass number. As previously discussed, strong strangeness enhancement occurs in central S+A_T and Pb+Pb collisions. Note that the strangeness enhancement is about the same in S+S, S+Ag and Pb+Pb, contradicting a secondary processes scenario, occuring in the high energy density regions of the collisions. In this case, one would rather expect higher strangeness enhancement in S+Ag and Pb+Pb, than in S+S, where low density "corona" surface interactions play an important role.

Numerous attempts were undertaken to modify string-hadronic approaches in order to reproduce the data. In addition to the standard string scenario, the models included additional processes, such as secondary hadronic interactions, fusion of strings, collective gluon emission, etc. Following the procedure proposed by NA35 [25], we compare the data in Fig. 8 with the published model results for central S+S, S+Ag and Pb+Pb collisions (VENUS [26], RQMD [27], UrQMD [28], LEXUS [29], HIJING [30], QGSM [31], FRITIOF [32], LUCIAE [33], MCSFM [34] and DPM [35]). All models, except one (DPM+fsi), fail to describe the experimentally observed strangeness enhancement, because they cannot simultaneously describe strange and non-strange particle production in nucleon-nucleon interactions and central nucleus-nucleus collisions. Interestingly enough, most of them approximately reproduce the absolute strangeness yields in nucleus-nucleus collisions.

The Dual Parton Model with final state interactions (DPM+fsi) seems to agree with the experimental data. However, this is due to the fact that, in this model, the strangeness content of the nucleon was already increased by a factor of $\sim$2 above the value observed in elementary collisions [36]. This leads to a prediction of strangeness enhancement in pA collisions that is not observed experimentally (e.g., see Fig.7), and in high energy pp collisions that is similarly contradicted by measurements.

Thus, the hadronic scenario that worked so well at AGS energies, does not hold in the CERN SPS energy domain. We are seeing here something entirely new. We will get back to it after a few remarks concerning current theoretical efforts.

Simulations of QCD on the lattice can provide, in principle, predictions (e.g. [2]) of the strangeness content in a QGP. These predictions, however, require a hadronization model to relate them to the experimentally accessible strange particle yields. Results, of course, strongly depend on the chosen model. Numerous studies have been tried, yet none have been able to reproduce all of the measured particle abundances quantitatively [37], [38].

Hadron gas models, assuming full equilibration of all hadronic species, were found to be equally unsuccessful in describing strange particle ratios in S+A_T collisions at 200 GeV/c (for a review, see [39]). They could only reproduce the measurements qualitatively within a factor of two. The agreement of the data with the off-equilibrium version of the hadron gas model, allowing for partial strangeness saturation (strangeness suppression factor $\gamma_S < 1$), is significantly better. Beccatini et al. [40] used the same formulation of the ideal hadron gas model for the analysis of data from e^+e^- and p+p to central Pb+Pb collisions with γ_S treated as a free parameter. They fit the data on hadron abundances measured in (or extrapolated to) the full phase space. The comparison between E_S calculated with fitted and measured multiplicities for S+S, S+Ag and Pb+Pb, and

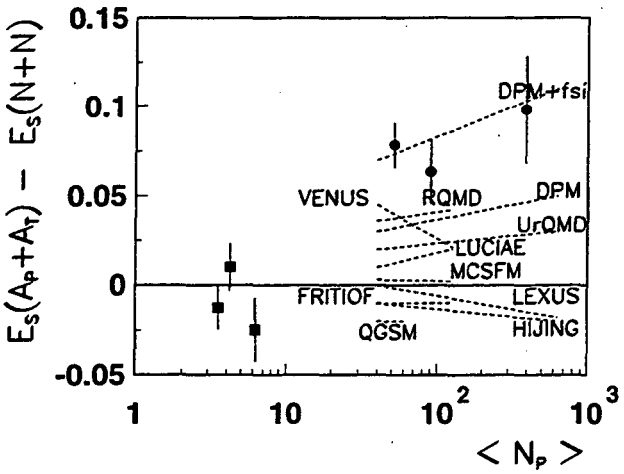

Figure 8. The difference between E_S value determined for central S+S, S+Ag and Pb+Pb collisions and E_S value for N+N interactions as a function of the target nucleus mass. See text for the description of lines.

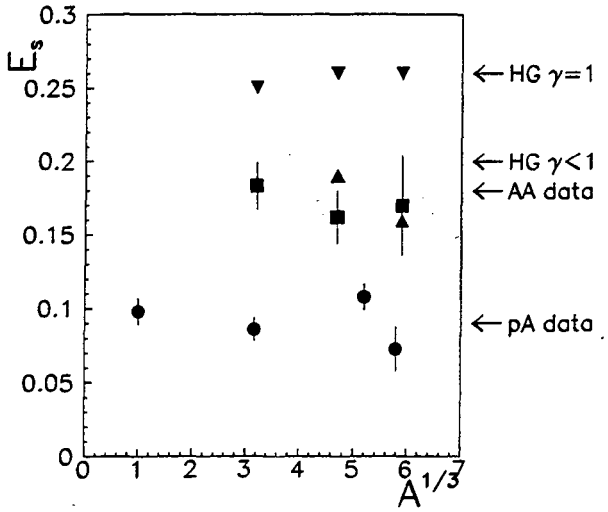

Figure 9. The E_S values for central S+S, S+Ag, Pb+Pb and p+A collisions compared to the predictions of the ideal gas model in equilibrium and off-equilibrium

for p+p and p+A (measured only) is shown on Fig. 9. Experimental points are represented by circles (p+p, p+A_T) and squares (A+A); Beccatini's et al. calculations are represented by triangles. The obtained temperatures and baryon chemical potentials are quite compatible with common values for p+p and A+A collisions. Of particular interest is the strangeness saturation factor γ_S, which turns out to be definitely smaller than one even in central Pb+Pb collisions. It was found that γ_S increases from about 0.45 in p+p interactions to about 0.7 in central A+A collisions, with no significant change from S+S to Pb+Pb systems. Similarly, the quark strangeness suppression factor λ_S was found to go up by a factor of ~2 for heavy ion collisions ($\lambda_S^{A+A} \approx 0.4$, whereas $\lambda_S^{elem.coll.} \approx 0.2$), also independent of the colliding system type. This agrees with the values obtained in [23], based on a quark counting method [36]. In order to illustrate the magnitude of strangeness undersaturation in the hadron gas, the E_S values for the case of full strangeness equilibration are plotted in Fig. 9 (upper row of triangles, ∇). The points are calculated by multiplying the E_S values obtained from the off-equilibrium version of the model by a factor $1/\gamma_S$; i.e., they correspond to the equilibrium values for T and μ_B obtained from a fit to the off-equilibrium model. The data points for A+A lie between the p+p and p+A data points and the predictions of the ideal hadron gas model in equilibrium. Thus, there is significantly more strangeness present in the AA final state than one would expect by extrapolation from p+A_T; however, there is still not enough to match the full-equilibrium thermal model scenario.

The fact that light (S+S) and heavy (Pb+Pb) colliding systems have the same values of λ_S and γ_S factors (illustrated also by Fig.5) may imply very serious consequences: one can picture a scenario in which quark flavor is already saturated in the pre-hadronic phase of collisions for both light and heavy systems. In this case, assuming that the

hadronization processes preserve this information, one would expect similar values of λ_S (or γ_S) in the hadronic phase. (Note that γ_S of the partonic and hadronic phases may have different values even in the case that strangeness and entropy are conserved during the hadronization process [43].) It appears that secondary hadron scattering, expected to be much more abundant in Pb+Pb collisions, is of minor importance for strangeness production.

The strangeness enhancement in AA, together with the saturation of the λ_S (γ_S) factors and undersaturation of strangeness in the hadron gas framework was interpreted within the Generalized Landau Model (GLM) as a signal of the QGP formation in the pre-hadronic phase of S+S, S+Ag and Pb+Pb collisions [42], [41]. Note that, contrary to the NA38/50 findings that seem to indicate possible QGP formation only in Pb+Pb collisions, strangeness production analysis suggests that the flavor equilibration in the pre-hadronic, partonic phase takes place already in the light system of S+S. The ball is back in the quarter of our colleagues from theory: is this the only plausible interpretation of the presented results?

4. SUMMARY

Recent data resulting from the CERN and AGS nuclear beam programs employing, in particular, the lead and gold beams, appear to imply two different strangeness production mechanisms. While the AGS measurements seem to be consistent with nucleon-nucleon superposition and hadronic re-interactions, the CERN SPS data definitely say farwell to the hadronic scenario. Strangeness enhancement in AA collisions, and its absence in pA systems, points us in a new direction. Whether the Quark Gluon Plasma is the ultimate answer to the new results - remains to be seen.

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