STRANGENESS AND ENTROPY PRODUCTION IN RELATIVISTIC NUCLEAR COLLISIONS

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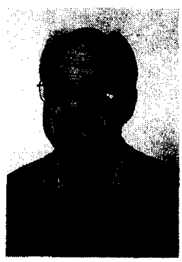

ABSTRACT

Assuming the formation of a thermal fireball in nuclear collisions, we analyze data on strange particle multiplicities from WA85 and NA35 for signs of chemical equilibration. Resonance decays and possible collective transverse flow effects are fully taken into account. We consistently find a vanishing strange quark chemical potential and nearly complete saturation of the strange quark phase space. We show that these findings are only compatible with a hadron resonance gas (HG) equation of state if the fireball temperature is very high ($\sim$ 210 MeV) and the $m_\perp$-spectra contain no transverse flow component, which contradicts an earlier analysis of those spectra. Furthermore, the HG model underpredicts the entropy of the fireball (extracted from measurements of the charged particle multiplicities) by more than a factor of 2. It can thus be excluded as an interpretation of the data. We point out that the above characteristics of the fireball result naturally if the collision proceeds through an early dense partonic phase with a dominantly gluonic $s - \bar{s}$ production mechanism (quark-gluon plasma).

Introduction. Enhanced production of strangeness, specifically of strange antibaryons, was suggested more than 10 years ago [1] as an (indirect) signature for quark-gluon plasma (QGP) formation in relativistic nuclear collisions. It arises as a result of enhanced strange quark production and a large strangeness density in the QGP phase. (Multi)strange antibaryons are most sensitive to these features and thus more specific than an enhancement of strange

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mesons. The argument rests basically on a comparison of time scales: while the time needed for saturation of the strange phase space in a QGP via gluon fusion ($g + g \rightarrow s + \bar{s}$) is only a few fm/$c$, the rate for strange pair production in conventional hadronic processes ($h_1 + h_2 \rightarrow h_3^s + h_4^{\bar{s}}$) is much slower (of order of a few 10 to 100 fm/c) [1]. Thus, while the typical lifetime of the hot and dense interaction region created in the collision appears to be long enough to reach nearly complete chemical equilibrium between light and strange quarks if a QGP is formed, its absence would indicate itself by a similar suppression of strange vs. nonstrange particle production as observed in usual hadron-hadron collisions. We parametrize the degree of chemical equilibrium by a strangeness saturation factor γ_s which is expected to be close to 1 if the collision proceeds through a QGP phase, while conventional hadronic dynamics would signal itself by a value $\gamma_s \ll 1$ as measured in p-p collisions [2].

Furthermore, if (via fast strangeness exchange processes) relative chemical equilibrium is reached between the available strange particle channels even though overall strangeness saturation is incomplete ($\gamma_s < 1$), a QGP distinguishes itself from the more conventional hadron resonance gas (HG) by another characteristic feature: The strangeness neutrality of the fireball as a whole (strangeness is conserved on the nuclear collision time scale) requires a vanishing strange quark chemical potential, $\mu_s = 0$ independent of the temperature T and the baryon chemical potential μ_B, if it is in the QGP phase where isolated strange quarks can exist. In a HG, on the other hand, strangeness neutrality requires the balance of various strange mesons and baryons whose abundances depend on the baryon chemical potential μ_B; this results in a generally complicated relation $\mu_s(\mu_B, T)$ to guarantee strangeness neutrality, with $\mu_s = 0$ being a natural solution only in a baryon-free environment ($\mu_B = 0$), which cannot be reached in nuclear collisions with present day energies, and otherwise requiring very special combinations of T and μ_B (see below).

A final distinguishing feature of a QGP compared to a conventional HG is its specific entropy S/A: due to the liberation of the abundant gluon degrees of freedom, its specific entropy is much larger at fixed T and μ_B, $(S/A)_Q(T, \mu_B) > (S/A)_H(T, \mu_B)$. As we will show, this quantity can be estimated from measured charged particle multiplicities and is indeed found to be much larger than predicted by a HG model for the strange particle data.

The data we will use refer to collisions at CERN energies (200 A GeV sulphur projectiles on various nuclear targets) and stem from the WA85 [3] and NA35 [4, 5] collaborations for strange particle production and from the EMU05 [6] and NA35 [5] collaborations for the measurement of charged particle rapidity distributions. Other existing data on strange particle production [7] are, for various reasons, less suitable for a systematic analysis as the one presented below.

Data interpretation. The model to be tested against the data is that of a thermalized fireball in relative chemical equilibrium (i.e. the strange phase space is not ncessarily assumed to be fully saturated, but strangeness is distributed among the available channels according to the law of maximum entropy). Note that the measured hadron abundances and spectra give information only about the freeze-out stage, and thermal and chemical equilibrium at freeze-out does not automatically imply the same at earlier stages. On the other hand, without thermalization at freeze-out the assumption of a possible early thermalized QGP phase appears unfounded, thus we are testing a necessary prerequisite in the search for QGP formation.

Local thermal equilibrium implies Boltzmann (or Fermi-Bose) momentum distributions, possibly with a superimposed collective flow component. A recent hydrodynamic analysis of measured y- and $m_\perp$-spectra showed consistency with thermalization at freeze-out [8]. However, on a purely phenomenological level, the thermal and flow components cannot be separated from the $m_\perp$-data which appear to be compatible both with a stationary or only longitudinally expanding fireball at $T \approx 210$ MeV and with a colder fireball at $T \approx 150$ MeV expanding with an average transverse flow velocity $\beta_f \simeq 0.32\,c$, yielding the same slope parameter in terms of a blueshifted temperature $T_{\rm eff} = T\sqrt{(1+\beta_f)/(1-\beta_f)}$. While only the latter set of parameters is consistent with the freeze-out criterium [8] and is thus the preferred explanation of the data, we will here also consider the former possibility, for reasons to become clear below.

The two independent chemical potentials $\mu_q = \mu_B/3$ (for the light quarks) and μ_s (for the strange quarks) as well as the strangeness saturation factor γ_s are extracted from strange and nonstrange particle ratios (for details see [9, 10]). Each hadron is assigned a combination of μ_q and μ_s according to its light and strange valence quark content, with $\bar\mu = -\mu$ for antiparticles, and a power of the strangeness saturation factor γ_s corresponding to its number of valence strange quarks plus antiquarks. There is also a spin-isospin degeneracy factor g. In principle the u and d quark flavors are conserved separately, and in addition to $\mu_q = (\mu_u + \mu_d)/2$ we would have to introduce $\delta\mu = \mu_d - \mu_u$ to describe the isospin asymmetry of the fireball if $Z/A \neq 0.5$. In practice we found $\delta\mu$ to be very small [9, 10], and we thus neglect it here.

For a constant transverse flow velocity $\beta_f = \tanh\rho$ the spectrum of a given hadron species i is thus given by

$$\frac{dN_i^{\rm flow}}{dy\, dm_\perp^2} = V\, g_i\, \gamma_i\, \lambda_i\, \Phi_i\left(\frac{m_\perp}{T}, \rho\right) , \tag{1}$$

where V is the unknown volume of the fireball, $\lambda_i = \exp(\mu_i/T)$ is the fugacity, and

$$\Phi_i\left(\frac{m_\perp}{T}, \rho\right) = m_\perp\, K_1\left(\frac{m_\perp \cosh\rho}{T}\right) I_0\left(\frac{p_\perp \sinh\rho}{T}\right) . \tag{2}$$

For $\rho \to 0$ (no flow) the combination of Bessel functions reduces to the usual Boltzmann distribution; it depends essentially only $m_\perp$ (and thus not explicitly on the rest mass) unless the flow becomes very strong. Thus at fixed $m_\perp$ or in a fixed $m_\perp$ window the momentum phase space factors Φ_i cancel to good accuracy from particle ratios, which (in the absence of resonance decay contributions, see below) thus depend only on the chemical potentials and degeneracy and saturation factors [9]:

$$\left.\frac{dN_i/dy}{dN_j/dy}\right|_{m_\perp^{\rm cut}} \simeq \frac{g_i\, \gamma_i\, \lambda_i}{g_j\, \gamma_j\, \lambda_j} . \tag{3}$$

This approximation becomes exact in the limit $\rho \to 0$. It yields, for example,

$$R_\Lambda = \frac{\overline{\Lambda}}{\Lambda} = e^{-(4\mu_q + 2\mu_s)/T} ; \qquad R_\Xi = \frac{\overline{\Xi}^+}{\Xi^-} = e^{-(2\mu_q + 4\mu_s)/T} , \tag{4}$$

from which μ_q/T and μ_s/T can be easily extracted with rather good accuracy:

$$\frac{\mu_s}{T} = \frac{1}{6}\ln\frac{R_\Lambda}{R_\Xi^2} ; \qquad \frac{\mu_q}{T} = \frac{1}{6}\ln\frac{R_\Xi}{R_\Lambda^2} . \tag{5}$$

(All particle ratios are to be understood at fixed y and in a common $m_\perp$ window.)

In the same approximation the strangeness saturation factor is given by

$$\gamma_s^2 = R_s \cdot R_{\bar s} = \frac{\Xi^-}{\Lambda} \cdot \frac{\overline{\Xi}^+}{\overline{\Lambda}} . \tag{6}$$

Here, however, before comparing to data one has to correct for the invisible decay $\Sigma^0 \to \Lambda + \gamma$ which implies that the experimental ratios include the Σ^0's in the denominator. The masses of Λ and Σ^0 being similar, their abundances will be roughly equal such that this correction amounts to about a factor 4 in eq. (6).

WA85 has measured the above ratios in 200 A GeV S+W collisions near central rapidity $2.3 \leq y \leq 3.0$ at $m_\perp \geq m_\perp^{\rm cut} = 1.72$ GeV [3]. From their result $R_\Lambda = 0.13 \pm 0.03$, $R_\Xi = 0.39 \pm 0.07$, $\Xi^-/\Lambda = 0.20 \pm 0.04$ (from which $\overline{\Xi}^+/\overline{\Lambda} = 0.60 \pm 0.20$ follows, which is larger by a factor 6–10 than the same ratio measured in e^+e^- and pp collisions [3] and shows most dramatically the strangeness enhancement in nuclear collisions) one extracts by this procedure (assuming $\Lambda^{\rm exp} = \Lambda + \Sigma^0 \approx 2\Lambda$) the values $\mu_{\rm q}/T = 0.53 \pm 0.1$, $\mu_{\rm s}/T = -0.018 \pm 0.05$, and $\gamma_{\rm s} = 0.7 \pm 0.1$. These results are perplexing: although we are clearly not dealing with a baryon-poor environment ($\mu_{\rm B}/T$ is larger than unity), the strange quark chemical potential vanishes with apparently very high accuracy, and the strange phase space appears to be saturated to about 70%! As explained in the introduction and further discussed below, this is exactly what is naively expected from a QGP source for the strange hadrons, whereas in a HG environment such a result has to appear as a rather accidental coincidence. Before jumping to further conclusions in this direction it is, however, wise to check the stability of these results against various explicit or implicit approximations in the above analysis.

The possibly most serious correction is expected from resonance decays: for fireball temperatures of the order of 150 - 220 MeV resonance production is significant[4]. Their relative contribution to the above ratios depends on T and is thus sensitive to the presence of flow in the $m_\perp$ spectra. Therefore we have performed a careful study of these effects [10]. We write

$$\left.\frac{dN_i}{dy}\right|_{m_\perp^{\rm cut}} = \int_{m_\perp^{\rm cut}}^{\infty} dm_\perp^2 \left[\frac{dN_i^{\rm flow}}{dy\, dm_\perp^2} + \sum_R b_{R\to i} \frac{dN_i^R(T)}{dy\, dm_\perp^2} \right] , \tag{7}$$

where the sum goes over all resonances decaying into the observed particle species i (with the corresponding branching ratios $b_{R\to i}$), and the spectrum of daughter particles $dN_i^R/dydm_\perp^2$ is calculated from the flow spectrum (2) for the resonance R as described in [11].

Splitting the sum over R into separate sums over resonances with identical baryon number and strangeness, we can extract the common fugacity and strangeness saturation factors from the latter and write (for details see [10])

$$R_\Lambda = \left.\frac{\overline{\Lambda}}{\Lambda}\right|_{m_\perp^{\rm cut}} = \frac{\gamma_{\rm s}\lambda_{\rm q}^{-2}\lambda_{\rm s}^{-1}\tilde{N}_\Lambda^{Y^*} + \gamma_{\rm s}^2\lambda_{\rm q}^{-1}\lambda_{\rm s}^{-2}\tilde{N}_\Lambda^{\Xi^*} + \gamma_{\rm s}^3\lambda_{\rm s}^{-3}\tilde{N}_\Lambda^{\Omega^*}}{\gamma_{\rm s}\lambda_{\rm q}^2\lambda_{\rm s}\tilde{N}_\Lambda^{Y^*} + \gamma_{\rm s}^2\lambda_{\rm q}\lambda_{\rm s}^2\tilde{N}_\Lambda^{\Xi^*} + \gamma_{\rm s}^3\lambda_{\rm s}^3\tilde{N}_\Lambda^{\Omega^*}} , \tag{8}$$

with similar expressions for the other ratios. $\tilde{N}_i^R$ denotes the contribution to particle species i (in the given y and $m_\perp$ window) from all resonances[5] with the quantum numbers of R, including their g_R factors. We have included all known resonances below 2 GeV.

Although the $\tilde{N}_i^R$ and their relative importance depend on T, usually the first terms in the numerator and denominator of ratios like (8) dominate. Since the excitation spectrum for particles and antiparticles is identical, $\tilde{N}_i^R = \tilde{N}_{\bar{i}}^{\bar{R}}$, this implies that particle-antiparticle ratios like (8) are only weakly affected by resonance decays. Since according to (5) $\mu_{\rm s}/T$ and $\mu_{\rm q}/T$

[4]For T=200 MeV about 70% of all pions come from the decay of unstable resonances after freeze-out [11].

[5]If i and R have the same quantum numbers, $\tilde{N}_i^R$ includes the direct contribution N_i.

involve only such ratios, the fugacities turn out to be quite stable against the inclusion of resonance decays and against changes in the freeze-out temperature (as implied by the flow scenario). On the other hand, Table 1 shows that the strangeness saturation factor γ_s depends crucially on the resonance decay contributions, since it is determined by the ratio $R_s = \Xi^-/\Lambda$ where the numerator and denominator have a different excitation spectrum. At lower temperatures higher resonances are exponentially suppressed and the ratio $\tilde{N}_\Xi/\tilde{N}_\Lambda$ decreases. A fixed Ξ/Λ ratio thus implies a relatively larger strangeness enhancement, resulting in a larger value for γ_s.

	thermal w/o reson. $T = 210$ MeV, $\beta_f = 0$ in brackets: incl. $\Sigma^0 = \Lambda$	thermal w. reson. $T = 210$ MeV, $\beta_f = 0$	thermal+flow w. reson. $T = 150$ MeV, $\beta_f = 0.32$
μ_s/T	-0.018	-0.027	-0.028
μ_s (MeV)	-3.9	-5.7	-4.2
μ_q/T	0.53	0.54	0.54
μ_q (MeV)	111.3	113.6	80.5
γ_s	0.35 (0.70)	0.76	0.90

Table 1: Thermal fireball parameters extracted from the WA85 data [3] on strange baryon and anti-baryon production, with and without resonance decay contributions, for two different interpretations of the measured $m_\perp$-slope.

Predictions for other particle ratios (Λ/p, Ω/Ξ, etc.) which allow to distinguish between the above scenarios can be found in [10] where we also discussed the sensitivity to $m_\perp^{\rm cut}$.

Strangeness neutrality. Since the strong interaction conserves strangeness, the fireball has to be strangeness neutral (up to small corrections from a possible strangeness asymmetry of surface radiation). In a QGP with liberated strange quarks this implies a vanishing strange quark chemical potential, μ_s=0, irrespective of T and μ_B, which agrees strikingly with the value extracted from the WA85 data. To see the consequences of strangeness neutrality for the chemical potentials in a hadron gas we have to study the strange particle partition function:

$$\ln \mathcal{Z}_s^{\rm HG} = \frac{VT^3}{\pi^2}\left[\gamma_s F_K \cosh\frac{\mu_s-\mu_q}{T} + \gamma_s F_Y \cosh\frac{\mu_s+2\mu_q}{T} + \gamma_s^2 F_\Xi \cosh\frac{2\mu_s+\mu_q}{T} + \gamma_s^3 F_\Omega \cosh\frac{3\mu_s}{T}\right]$$

where the phase space factors $F_i(T)$ are given by $F_i = \sum_R g_R (m_R/T)^2 K_2(m_R/T)$, the sum going over all resonances with the quantum numbers of i. The strangeness neutrality condition

$$0 = \langle s\rangle - \langle \bar{s}\rangle = \lambda_s \frac{\partial}{\partial\lambda_s} \ln \mathcal{Z}_s \qquad (9)$$

provides a non-trivial relationship between μ_s, T, and μ_q which is shown, for various values of T, in Fig. 1. One sees that at finite baryon density μ_s generally does not vanish, but that for temperatures near $T = 210$ MeV and for $\gamma_s = 0.7$ (parameters similar to those of the second column in Table 1) μ_s is accidentally close to zero in a rather large range of μ_B. This observation has led to the conclusion [12] that the WA85 data may be compatible with a chemically equilibrated HG if the $m_\perp$-slope is directly interpreted as the fireball temperature, i.e. if the flow component suggested by the analysis of [8] is excluded. With the parameters from the flow scenario [8] (3rd column in Table 1), on the other hand, the observation $\mu_s \simeq 0$ cannot be made compatible with strangeness neutrality in a HG, which according to Fig.

1 would rather require a strange chemical potential of about 40 MeV (even larger if one extrapolates the curve in the Figure from $\gamma_s = 0.7$ to 0.9). This is several standard deviations away from the experimental result[6].

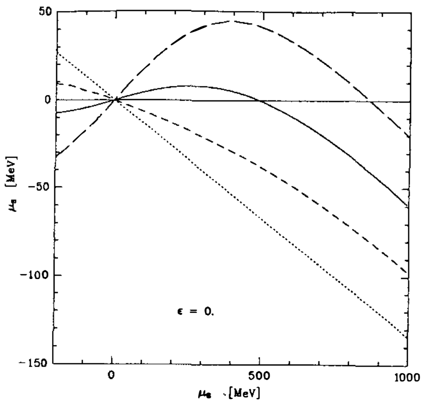

Figure 1: μ_s versus μ_B in a HG with $\gamma_s = 0.7$ at fixed temperature T (long-dashed: $T = 150$ MeV; solid: $T = 200$ MeV; dashed: $T = 300$ MeV; dotted: $T \to \infty$). The horizontal line at $\mu_s = 0$ shows the QGP value.

Entropy. However, the HG explanation of the WA85 data has several theoretical problems: at $T > 200$ MeV the hadrons in the gas overlap strongly, invalidating the assumption of an ideal gas mixture and even the often used naive proper volume correction. It is unlikely that this internal inconsistency can be qualitatively improved by including medium induced mass shifts and widths. This view receives support from lattice QCD calculations with one heavy and two light dynamical quark flavors which find a transition to quark matter at $T \simeq 150$ MeV at zero baryon density [7] (expected to drop slightly at $\mu_B \neq 0$).

But the most serious problem with the HG interpretation is an experimental one: we will now show that the data require a much larger specific entropy than provided by the HG scenario [13]. To this end we define the charge asymmetry ratio

$$D_Q = \frac{N^+ - N^-}{N^+ + N^-} \tag{10}$$

which can be easily measured (also as a function of rapidity) in any tracking detector in a magnetic field, without need for particle identification. The above HG at $T = 210$ MeV, $\mu_s = -5.7$ MeV, $\mu_B = 341$ MeV, $\gamma_s = 0.76$ yields $D_Q = 0.29$ at freeze-out; after resonance decays (which conserve the net charge, but produce additional charged pion pairs) this is diluted to $D_Q^{HG} = 0.18$. The EMU05 collaboration has measured D_Q for 200 A GeV S+Pb collisions [6, 10], a similar system as the one studied by WA85: in the same central rapidity window as WA85 they find $D_Q^{exp} = 0.088 \pm 0.007$, i.e. less then half the value predicted by the HG!

[6] Note that no contradiction with flow exists in the QGP scenario: since there strangeness neutrality implies $\mu_s = 0$ independent of T, the lower freeze-out temperature of the flow picture does not pose a problem.

Since the net charge reflects the number of participating protons in the fireball, while the total charged multiplicity is dominated by produced pions and thus measures the total fireball entropy, it is clear that D_Q is closely related to the specific entropy S/A. In [13, 10] we studied this relationship in detail and found that to very good approximation $D_Q \cdot (S/A) = \text{const.}$ The above discrepancy implies that the HG predicts only $(S/A)^{\text{HG}} \simeq 18$ while the EMU05 data require $(S/A)^{\text{exp}} \simeq 40$. Thus the measured final state contains much more entropy than provided by the HG model. This discrepancy cannot be easily remedied by reasonable changes to the HG equation of state.

It is amusing to observe [13, 10] that a specific entropy of about 40 to 50 units is exactly the value expected in a QGP with the measured μ_B/T (only this ratio enters, thus this conclusion is independent of the actual freeze-out temperature). Of course, the question arises how the QGP can hadronize without changing μ_q/T and μ_s/T, i.e. without violating the above analysis of the strange (anti)baryon ratios, while at the same time producing the excess particles (pions and other mesons) to carry away the entropy. No consistent dynamical hadronization scenario with such properties has been worked out yet; but we believe that a sudden disintegration of the QGP, where baryons are formed by quark coalescence (thus preserving μ/T) while the hadronization of gluons goes mostly into excess mesons, could provide such a scenario. The thermal phase space factors Φ_i in (2) must then be replaced by kinetic factors describing the coalescence mechanism which are likely to be quite different for mesons (with their gluonic contribution) and baryons. As long as they continue to depend mostly on $m_\perp$, they are expected to be similar for all baryons (and separately for all mesons) such that the above analysis of particle ratios (which requires their cancellation) continues to go through.

Such a picture implies that in order to minimize the sensitivity to the kinetic details of hadronization the chemical analysis should be based on particle ratios involving either only baryons or only mesons, but not on mixed ones (for example the Λ/π ratio is expected to be more sensitive to the entropy balance than to the chemistry of strangeness). We will carefully stick to this principle in the following analysis of the NA35 data.

More evidence from NA35. NA35 has studied strange particle production in central 200 A GeV S+S collisions [4, 5]. The symmetry of the collsion system allows them to extrapolate their strange particle yields to full phase space. They find $\overline{\Lambda}/\Lambda$=0.18 (contrary to WA85 this includes weak Ξ decays), K^+/K^-=1.81, and Λ/p^{exp}=0.30 (where $p^{\text{exp}}=p-\bar{p}$). From the first two ratios one determines [2] $\mu_q/T = 0.48$ and $\mu_s/T = 0.025$. Again these ratios are hardly sensitive to resonance decays and transverse flow. Once more μ_s is strikingly close to zero, while μ_B is finite (in accord with an observed significant baryon stopping) and only 10% smaller than in the larger S+W system of WA85. The value of γ_s is extracted from the Λ/p ratio and depends strongly on resonance decay contributions. If we take the measured slope of the $m_\perp$-spectra, $T_{\text{eff}} = 195$ MeV, as the fireball temperature (which would make the observed value of μ_s compatible with a strangeness neutral HG), we find $\gamma_s = 0.70$; lower freeze-out temperatures increase γ_s. Thus again the strange phase space is nearly saturated, in agreement with the observed rise of strangeness production with collision centrality [4] which appears to level off in very central collisions [14].

A HG with these parameters provides a charge asymmetry ratio $D_Q^{\text{HG}} = 0.15$. NA35 has measured the y-distributions of the net charge and of the negative charged multiplicity [5]. From these measurements we find that at central rapidity, where the fireball should be concentrated, $D_Q^{\text{exp}} = 0.065$. In terms of (S/A) we see again that the data require about twice the entropy provided by the HG explanation. Thus the latter is inconsistent.

Conclusions. The strange (anti)baryon data from WA85 (S+Pb) allow for an accurate determination of the parameters of a hypothetical thermal fireball formed in the collision. We find a vanishing strange quark chemical potential at rather large baryon density, combined with nearly complete strangeness saturation. These findings are insensitive to resonance decay and flow effects and are dramatically confirmed by strangeness production data from NA35 (S+S). They are natural consequences of QGP formation followed by sudden disintegration. A HG interpretation of these parameters requires unnaturally long fireball lifetimes and excessively high fireball temperatures and is inconsistent with the observed transverse flow effects in the $m_\perp$ spectra and with the large entropy measured by EMU05 (S+Pb) and NA35 (S+S) using charged multiplicity distributions. Our analysis points strongly towards an early, dense partonic phase with a gluonic $s - \bar{s}$ production mechanism in these collisions.

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