Strangeness Enhancement in $p + A$ and $S + A$
Interactions at SPS Energies

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The systematics of strangeness enhancement is calculated using the

HIJING and VENUS models and compared to recent data on $pp$, $pA$ and

$AA$ collisions at CERN/SPS energies (200 $A GeV$). The HIJING model is

used to perform a linear extrapolation from $pp$ to $AA$. VENUS is used to

estimate the effects of final state cascading and possible non-conventional

production mechanisms. This comparison shows that the large enhance-

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ment of strangeness observed in $S + Au$ collisions, interpreted previously as possible evidence for quark-gluon plasma formation, has its origins in non-equilibrium dynamics of few nucleon systems. A factor of two enhancement of $\Lambda^0$ at mid-rapidity is indicated by recent $pS$ data, where on the average one projectile nucleon interacts with only two target nucleons. There appears to be another factor of two enhancement in the light ion reaction $SS$ relative to $pS$, when on the average only two projectile nucleons interact with two target ones.

$I. INTRODUCTION$

The search for new states of dense nuclear matter is one of the most active areas of research in nuclear physics [1], [2]. Enhanced strangeness production in ultra-relativistic heavy ion collisions was suggested long ago [3] as a signal for quark-gluon plasma formation [4], [6], and has been observed at both the AGS and SPS. There is extensive data from both the SPS at CERN [7]- [38] and the AGS at BNL [39]- [45] on strangeness yields from reactions ranging from elementary $p + p$ to $p + A_T$ and $A_B + A_T$ for targets ranging up to $A_T \approx 200$ and beams up to $A_B = 30$. Detailed rapidity and transverse momentum spectra of ($K^+, K^-, K^0_s, \Lambda, \bar{\Lambda}$) are available and spectra of $\Xi^-$ and even $\Omega^-$ are becoming available. In all cases their yield relative to pions or negative hadrons are larger in nucleus-nucleus than expected from geometrically scaled proton-proton collisions. New experiments with truly heavy ion projectiles are in progress with Au beams at BNL [46], [47] and with Pb beams at CERN ($Pb(170AGeV) + Pb$) [8] and will soon extend considerably the data base.

These and other data on nuclear reactions have stimulated the development of many hadronic transport models to address the problem of multi-particle production in nuclear collisions. These include Dual Partons Models(DPM) [48]- [54], Quark Gluon String Models(QGSM) [55]- [59], VENUS [60], FRITIOF [61]- [62], ATTLA [63], HIJING [64]-
RQMD models [69]- [74], Parton String Model (PSM) [72], HIJET [76], Parton Cascade Model (PCM) [77]- [79]. An excellent review and detailed comparison of the models is given by Werner in Ref. [60].

At present no conventional explanation of the large enhancement of hyperons or anti-hyperons has been found. The Pomeron exchange picture has motivated the development of many of the above models with the Pomeron modeled in terms of colored strings. However, the string picture itself suggests the possibility of new dynamical mechanisms ranging from string fusion to color rope formation. Some of the above transport models like RQMD [74] and VENUS [60] include such non-conventional mechanisms as default options. These proposed novel *non-equilibrium* dynamical mechanisms were shown to be able to reproduce many features of the observed strangeness enhancement [80]- [82], [72], [73], [60]. On the other hand, there have been many attempts (see, e.g., review by Heinz in [1] p. 205c and references therein) to attribute the strangeness enhancement to the formation of an equilibrated fireball containing a quark-gluon plasma state [1], [5].

Therefore it appears that either non-conventional multi-particle mechanisms or the existence of a new form of matter seems to be indicated by the observed strangeness enhancement. Either case is of basic interest. The goal of the present study is to clarify which of these alternatives is more compelling. We use the HIJING model [64]- [68] to perform a *linear* extrapolation of strangeness production dynamics from *pp* to *AA* taking into account essential nuclear geometry and kinematical constraints. At higher collider energies it includes pQCD semi-hard processes, but in the SPS range it reduces essentially to a hybrid version of the FRITIOF and DPM models. We use the VENUS model [60] to estimate possible effects of final state cascading and new mechanisms of strangeness production in few nucleon processes. The non-conventional mechanism in VENUS4.13 is the occurrence of “double strings” which may form when one projectile nucleon interacts with two or more target nucleons. A double string is defined as a color singlet baryon configuration consisting of one projectile quark connected to two different valence quarks in the target via a three gluon vertex. In earlier versions of the model the parameterization of the vertex kinematics led to anomalously large baryon stopping power. In the present
version, the double string phenomenology is constrained to reproduce the \( pA \rightarrow pX \) data. However, the new feature, see eq. 15.52 in ref. [60], is the assumption that the probability for hyperon production in the fragmentation regions is enhanced by a factor of two relative to the single string rates. This enhanced strangeness production mechanism due to double strings is similar to that postulated in the color rope model [83] and incorporated into the RQMD model. The hyperon enhancement in VENUS is however more confined to the fragmentation regions.

Both HIJING and VENUS have been compared to a wide variety of data in \( pp, pA \) and AA collisions [60], [67], [60]. However, no systematic study of strangeness production at SPS-CERN energies were performed up to now. In addition, there have been substantial changes in the final published data [18] relative to earlier comparisons to preliminary data [1], [8]. In this paper, we calculate the rapidity and transverse momentum spectra of strange particles for \( pp \), minimum bias collisions of \( pS, pAg, pAu \) and central collisions of \( S + S, Ag, Au, W \) at the energy of 200 \( AGeV \) and \( Pb + Pb \) at the energy of 170 \( AGeV \). We focus special emphasis on the comparison with the data on \( pp, pS, \) and \( SS \) from Alber et al. [18]. That comparison reveals that much of the enhancement of strangeness in heavy ion collisions can be traced back to the enhancement of strangeness in the lightest nontrivial ion collisions, \( p + S \). Our main conclusion based on these data is that the enhancement of strangeness observed in \( S + Au \) is therefore most likely due to new non-equilibrium multi-particle production mechanisms in processes involving few nucleon systems.

This paper is organized as follows: A brief description of the HIJING Monte Carlo model and theoretical background are given in Section II. For a detailed discussion of the VENUS model, we refer to the review in [60]. In Section III, detailed numerical results with HIJING and VENUS for \( pp, pA \) and AA reactions at CERN-SPS energies \( (\sqrt{s} \simeq 20A GeV) \) for strangeness production are compared to experimental data and other model predictions. Section IV concludes with a summary and discussion of results.
A detailed discussion of the HIJING Monte Carlo model was reported in references [64]-[68]. The formulation of HIJING was guided by the LUND-FRITIOF and Dual Parton Model (DPM) phenomenology for soft nucleus-nucleus reactions at intermediate energies ($\sqrt{s} < 20 \text{ GeV}$) and implementation of perturbative QCD (PQCD) processes in the PHythia model [84] for hadronic interactions. We give in this section a brief review of the aspect of the model relevant to hadronic interaction:

1. Exact diffuse nuclear geometry is used to calculate the impact parameter dependence of the number of inelastic processes [83].

2. Soft beam jets are modeled by quark-diquark strings with gluon kinks along the lines of the DPM and FRITIOF models. Multiple low $p_T$ exchanges among the end point constituents are included.

3. The model includes multiple mini-jet production with initial and final state radiation along the lines of the PYTHIA model and with cross sections calculated within the eikonal formalism.

4. Hadronization is performed via the JETSET7.2 algorithm [84] that summarizes data on $e^+e^-$. 

5. HIJING does not incorporate any mechanism for final state interactions among low $p_T$ produced particles nor does it have color rope formation.

The rate of multiple mini-jet production in HIJING is constrained by the cross sections in nucleon-nucleon collision. Within an eikonal formalism [83] the total elastic cross sections $\sigma_{el}$, total inelastic cross sections $\sigma_{in}$ and total cross sections $\sigma_{tot}$ can be expressed as:

$$\sigma_{el} = \pi \int_0^{\infty} db^2 (1 - \exp(-\chi(b, s)))^2$$  \hspace{1cm} (1)

$$\sigma_{in} = \pi \int_0^{\infty} db^2 (1 - \exp(-2\chi(b, s)))$$  \hspace{1cm} (2)
\[
\sigma_{\text{tot}} = 2 \pi \int_0^\infty \! db \, 2(1 - \exp(-\chi(b, s)))
\] (3)

Strong interactions involved in hadronic collisions can be generally divided into two categories depending on the scale of momentum transfer \(q^2\) of the processes. If \(q^2 < \Lambda_{QCD}^2\) the collisions are nonperturbative and considered *soft* and modeled by beam jet fragmentation via the string model. If \(q^2 \gg \Lambda_{QCD}^2\) the subprocesses on the parton level are considered *hard* and calculated via pQCD [67].

In the limit that the real part of the scattering amplitude is small and the eikonal function \(\chi(b, s)\) is real, the factor

\[
g(b, s) = 1 - \exp(-2 \chi(b, s))
\] (4)

can be interpreted in terms of semi-classical probabilistic model as *the probability for an inelastic event of nucleon–nucleon collisions at impact parameter \(b\) which may be caused by hard, semi-hard or soft parton interactions*.

To calculate the probability of multiple mini-jet, the main dynamical assumption is that they are independent. This holds as long as their average number is not too large as is the case below LHC energies [67]. When shadowing can be neglected, the probability of no jets and \(j\) independent jet production in an inelastic event at impact parameter \(b\), can be written as :

\[
g_0(b, s) = (1 - \exp(-2 \chi_s(b, s))) \exp(-2 \chi_h(b, s))
\] (5)

\[
g_j(b, s) = \left[\frac{2 \chi_h(b, s)}{j!}\right]^j \cdot \exp(-2 \chi_h(b, s)) \quad j \geq 1
\] (6)

where \(\chi_s(b, s)\) –is the eikonal function for soft interaction, \(2 \chi_h(b, s)\) –is the average number of hard parton interactions at a given impact parameter, \(\exp(-2 \chi_s(b, s))\) –is the probability for no soft interaction. Summing eqs.(5) and (6) over all values of \(j\) leads to :

\[
\sum_{j=0}^\infty g_j(b, s) = 1 - \exp(-2 \chi_s(b, s) - 2 \chi_h(b, s))
\] (7)

Comparing with eq.(4) one has :
\[ \chi(b, s) = \chi_s(b, s) + \chi_h(b, s) \] (8)

Assuming that the parton distribution function is factorizable in longitudinal and transverse directions and that the shadowing can be neglected the average number of hard interaction \(2\chi_h(b, s)\) at the impact parameter \(b\) is given by:

\[ \chi_h(b, s) = \frac{1}{2} \sigma_{jet}(s) T_N(b, s) \] (9)

where \(T_N(b, s)\) is the effective partonic overlap function of the nucleons at impact parameter \(b\).

\[ T_N(b, s) = \int d^2b' \rho(b') \rho(|b - b'|) \] (10)

with normalization \(\int d^2b T_N(b, s) = 1\) and \(\sigma_{jet}\) is the pQCD cross section of parton interaction or jet production \([66],[67]\). Note that \(\xi = b/b_0(s)\), where \(b_0(s)\) provides a measure of the geometrical size of the nucleon \(\pi b_0^2(s) = \sigma_s(s)/2\) assuming the same geometrical distribution for both soft and hard overlap functions

\[ \chi_s(\xi, s) \equiv \frac{\sigma_s}{2\sigma_0} \chi_0(\xi) \] (11)

\[ \chi_h(\xi, s) \equiv \frac{\sigma_{jet}}{2\sigma_0(s)} \chi_0(\xi) \] (12)

\[ \chi(\xi, s) \equiv \frac{1}{2\sigma_0} [\sigma_s(s) + \sigma_{jet}(s)] \chi_0(\xi) \] (13)

We note that \(\chi(\xi, s)\) is a function not only of \(\xi\) but also of \(\sqrt{s}\) because of the \(\sqrt{s}\) dependence on the jet cross section \(\sigma_{jet}(s)\). Geometrical scaling implies on the other hand that \(\chi_s(\xi, s) = \chi_0(\xi)\) is only a function of \(\xi\). Therefore, geometrical scaling is broken at high energies by the introduction of \(\sigma_{jet}(s)\) of jet production.

The cross sections of nucleon - nucleon collisions can in this case be expressed as:

\[ \sigma_{el} = \sigma_0(s) \int_0^\infty d\xi^2 (1 - \exp(-\chi(\xi, s)))^2 \] (14)

\[ \sigma_{in} = \sigma_0(s) \int_0^\infty d\xi^2 (1 - \exp(-2\chi(\xi, s))) \] (15)
\[ \sigma_{\text{tot}} = 2\sigma_0(s) \int_0^\infty d\xi^2 (1 - \exp(-\chi(\xi, s))) \] (16)

The calculation of these cross sections requires specifying \( \sigma_s(s) \) with a corresponding value of cut-off momenta \( p_0 \approx 2 \text{ GeV/c} \).

In the energy range \( 10 \text{ GeV} < \sqrt{s} < 70 \text{ GeV} \), where only soft parton interactions are important, the soft cross section \( \sigma_s(s) \) is fixed by the data on total cross sections \( \sigma_{\text{tot}}(s) \) directly. In and above the \( \text{SppS} \) energy range \( \sqrt{s} \geq 200 \text{ GeV} \), a fixed \( \sigma_s(s) = 57 \text{ mb} \) and a mini-jet cutoff scale \( p_0 = 2 \text{ GeV/c} \), leads to observed energy dependence of the cross sections and inclusive distributions. Between the two regions \( 70 \text{ GeV} < \sqrt{s} < 200 \text{ GeV} \), a smooth extrapolation for \( \sigma_s(s) \) is used.

In HIJING, a nucleus-nucleus collisions is decomposed into a sequence of binary collisions involving in general excited or wounded nucleons. Wounded nucleon are assumed to be \( q - q \) string like configurations that decay on a slow time scale compared to the collision time of the nuclei. In the FRITIOF scheme wounded nucleon interactions follow the same excitation law as the original hadrons. In the DPM scheme subsequent collisions essentially differ from the first since they are assumed to involve sea partons instead of valence ones. The HIJING model adopts a hybrid scheme, iterating string-string collisions as in FRITIOF but utilizing DPM like distributions. In the SPS range the HIJING results for nuclear collisions are very similar to those of FRITIOF. However, HIJING provides an interpolation model between the nonperturbative beam jet fragmentation physics at intermediate CERN-SPS energies and perturbative QCD mini-jet physics at the highest collider energies (RHIC, LHC).

### III. NUMERICAL RESULTS

#### A. STRANGENESS IN PROTON - PROTON INTERACTION

We used the program HIJING with default parameters: IHPR2(11)=1 gives the baryon production model with diquark-antidiquark pair production allowed, initial diquark treated as unit; IHPR2(12)=1, decay of particle such as \( \pi^0, K^0_s, \Lambda, \Sigma, \Xi, \Omega \) are
allowed; IHPR2(17)=1 - Gaussian distribution of transverse momentum of the sea quarks;
IHPR2(8)=0 - jet production turned off for theoretical predictions denoted by HIJING
model, and IHPR2(8)=10-the maximum number of jet production per nucleon-nucleon
interaction for for theoretical predictions denoted by $HIJING^{(j)}$ for comparison.

In Table I the calculated average multiplicities of particle at $E_{\text{lab}} = 200 \, GeV$ in
proton-proton($pp$) interaction are compared to data. The theoretical values $HIJING$
and $HIJING^{(j)}$ are obtained for $10^5$ generated events and in a full phase space. The
values $HIJING^{(j)}$ include the very small possibility of mini jet production at these low
SPS energies. The experimental data are taken from Gazdzicki and Hansen [15].

The small kaon to pion ratio is due to the suppressed strangeness production basic
to string fragmentation. Positive pions and kaons are more abundant than the negative
ones due to charge conservation. We note that the integrated multiplicities for neutral
strange particle $< \Lambda >, < \bar{\Lambda} >, < K^0_s >$ are reproduced at the level of three standard
deviations for $pp$ interactions at $200 \, GeV$. However the values for $< \bar{p} >$ and $< \bar{\Lambda} >$
are significantly over predicted by the model. This is important since as we shall see the
$\bar{\Lambda}$ in $S + S$ is significantly underestimated by HIJING.

For completeness we include a comparison of hadron yields at collider energies $\sqrt{s} =
546 \, GeV$ ($Sp\bar{p}S$-energies), for $\bar{p}p$ interactions, where mini-jet production plays a much
more important role. From different collider experiments Alner et al. (UA5 Collaboration))
[86] attempted to piece together a picture of the composition of a typical soft event at the
$Sp\bar{p}S$ [87]. The measurements were made in various different kinematic regions and have
been extrapolated in the full transverse momenta($p_T$) and rapidity range for comparison
as described in reference [86]. The experimental data are compared to theoretical values
obtained with $HIJING^{(j)}$ in Table II. It was stressed by Ward [87] that the data show
a substantial excess of photons compared to the mean $\pi^+ + \pi^-$. It was suggested
as a possible explanation of such enhancement a gluon Cerenkov radiation emission in
hadronic collision [88]. Our calculations rules out such hypothesis. Taking into account
decay from resonances and direct gamma production, good agreement is found within
the experimental errors. The experimental ratio $\frac{K^+}{\pi^+} = 0.095 \pm 0.009$ is also reproduced.
by HIJING\(^{(j)}\) model (0.099). We note that a detailed study of the ratios of invariant cross sections of kaons to that of pions as a function of transverse momenta in the central region was presented in [67].

In the following plots the kinematic variable used to describe single particle properties are the transverse momentum \( p_T \) and the rapidity \( y \) defined as usual as:

\[
y = \frac{1}{2} \ln \frac{E + p_3}{E - p_3} = \ln\frac{E + p_3}{m_T}
\]

with \( E, p_3, \) and \( m_T \) being energy, longitudinal momentum and transverse mass \( m_T = \sqrt{m_0^2 + p_T^2} \) with \( m_0 \) being the particle rest mass.

In Fig. 1a, 3a, 4a, and 6a, we show rapidity and transverse momentum distributions for \( \Lambda \)'s (Fig. 1a, 4a) and \( K_0^0 \)'s (Fig. 3a, 6a) produced in \( pp \) scattering at 200 GeV. The theoretical histograms obtained with HIJING (solid) and VENUS-4.13 (dashed) are compared with experimental data taken from Jaeger et al. [89]. The HIJING spectra for \( \Lambda, K_0^0 \) are close to the data at mid-rapidity [89], although the dip in the \( K_0^0 \) yield at mid-rapidity and the \( \Lambda \) peak in the fragmentation regions are not well reproduced (see also ref. [60]). Unfortunately, more precise data are not available in \( pp \) interactions and those features could reflect experimental acceptance cuts. Similarly no detailed \( \bar{\Lambda} \) spectra are as yet available in \( pp \).

In comparison with VENUS (taking \( 10^4 \) events) we note that this version seems to over-predict the \( pp \rightarrow \Lambda^0 \) rapidity density at mid-rapidity by \( 50 \) – \( 100\% \) in Fig. 1a, even though the rapidity integrated transverse momentum distribution in Fig 4a seems closer to the data. The \( K_0^0 \) yields in Figs. 3a and 6a are similar to those of HIJING with the dip structure in the data absent.

The very sparse data base on \( pp \) strangeness production at SPS energies should be expanded in the future to improve the test of dynamical models before they are applied to the more complex nuclear collision case. Without \( \bar{\Lambda} \) spectra in \( pp \), for example, the need for the new dynamical mechanisms in that channel cannot be confirmed.
B. Multiplicities in \( pA \) and \( AA \) collisions

In this section, we compare strange particle production in the HIJING and VENUS models to \( pA \) and \( AA \) data. Again we limit the study to \( \Lambda, \bar{\Lambda}, K^0_s \) to compare with recent data from Alber et al. [18]. First we consider the average integrated multiplicities for negative hadrons \( < h^- > \), negative pions \( < \pi^- > \) and neutral strange particles \( < K^0_s > \), \( < \Lambda > \), \( < \bar{\Lambda} > \) in \( pp, pS, pAg, pAu \) (minimum bias collisions) and \( SS, SAg, SAu \) (central collisions) at 200 AGeV. The default parameters of HIJING were used without mini-jet production (IHPR2(8)=0). The number of Monte Carlo generated events was \( 10^5 \) for HIJING and \( 10^4 \) for VENUS for \( pp, pA \) interactions and \( 5 \cdot 10^3 \) for \( SS \), and \( 10^3 \) for \( S + Ag, W, Au \) and \( PbPb \) collisions.

The mean multiplicities are compared in Table III (for \( pp \) and \( pA \) interactions) and in Table IV (for \( AA \) interactions) with experimental data from Alber et al. [18]. Note that while the HIJING model describes well the integrated neutral strange particle multiplicities (except for \( < \bar{\Lambda} > \)) in \( pp \) and \( pA \) interactions, there is a large discrepancy already for the light ion \( S + S \) reaction.

It is worthwhile to mention that theoretical calculations have been done for \( pA \) 'minimum bias' collisions and the experimental data are for the events with charged particle multiplicity greater than five, which contain a significant fraction (about 90 %) of the 'minimum bias' events [18].

In Table III and IV the data are compared also with other theoretical values obtained in some models: VENUS (as computed here), RQMD [18], QGSM [59], [18] and DPM models. The theoretical values \( DPM^1 \) are from the Mohring et al. [49], version of DPM which include additionally \( (qq) - (\bar{q}\bar{q}) \) production from the sea into the chain formation process and the values \( DPM^2 \) are from the Mohring et al. [50], version of DPM which include chain fusion, as a mechanism to explain the anomalous antihyperon production.

Alber et al. [18] have considered that the total production of strangeness should be treated in a model independent way using all available experimental information for ratio \( E_S \) expressed as:
\[ E_S = \frac{< \Lambda > + 4 < K^0 >}{3 < \pi^- >} \]  

(18)

We have calculated this ratio in HIJING approach for the above interactions and the corresponding numerical predictions are shown in Table V. We note that there is much less discrepancy between HIJING and the data for this particular ratio. We conclude from this that such ratio is insensitive to the underlying physics and therefore should NOT be used for any further tests of models! This ratio hides very effectively the gross deficiencies of the HIJING model in SS reactions pointed out later in the comparison to the rapidity and transverse momentum distributions. We include Table V only to prove the futility of studying the systematics of such ratios in the search for novel dynamics in nuclear collisions!

C. Single inclusive distributions for neutral strange particles in \( pA \) and \( AA \)

The main results of the present study are contained in Figs. 1-6. Figure 1 is our most important result revealing the systematics of \( \Lambda \) enhancement from (a) \( pp \) to (d) \( SAu \). In part (a) the \( pp \) data at mid rapidity are seen to be well reproduced by HIJING. However, the new minimum bias \( pS \) data [18] in Fig. 1b clearly shows a factor of 2 – 3 discrepancy with respect to the linear extrapolation from \( pp \) as performed by HIJING. The effect of double string fragmentation and final state cascading, as modeled with VENUS is seen on the other hand to account for the observed \( \Lambda \) enhancement. We note, however, that in \( pp \), VENUS over-predicts the \( \Lambda \) yield at mid rapidity. Some fraction of the agreement in \( pS \) with VENUS may be due to this effect. The overprediction of midrapidity \( \Lambda \)'s in \( pp \) by VENUS was shown in Fig. 10.20b of ref. [50], but was not emphasized there. If both the \( pp \) and \( pS \) data on \( \Lambda \) production are correct, then the most striking increase of hyperon production therefore occurs between \( pp \) to \( pS \) reactions.

The strangeness enhancement in minimum bias \( p + S \) is striking because the number of target nucleons struck by the incident proton is on the average only two! The step from single \( p+p \) to triple \( p+p+p \) reactions therefore apparently leads a substantial enhancement
of midrapidity Λ’s which obviously cannot have anything to do with equilibrium physics.

In central $S + S$ reactions shown in Fig. 1c, the discrepancy relative to HIJING grows by another factor of two. We note that the new data [18] shown here have increased substantially relative to earlier data [7, 8] due to inclusion of lower transverse momentum regions and Λ’s originating from the decay of Σ, Ξ in the analysis. Including these decay channels, VENUS is seen to reproduce the new data as well. We note that with RQMD the excess Λ’s is also reproduced with the introduction of rope formation (see Table IV). For heavier targets, $Ag, Au$, in Fig. 1d, the discrepancy relative to HIJING is in fact less dramatic than in $S + S$.

In central $S + S$, on the average each projectile nucleon interacts with only two target one, but each target nucleon also interacts with two projectile ones. In effect, then $S + S$ reactions probe strangeness production in four nucleon interactions $p + p + p + p \to \Lambda + X$. Such reactions appear to be approximately four times as efficient in producing midrapidity Λ’s as two nucleon interactions in part (a). Our main conclusion therefore is that strangeness enhancement is a nonequilibrium dynamical effect clearly revealed in the lightest ion interactions.

Further support for this conclusion is shown in Figs. 4a,b,c, where the transverse momentum distributions are compared. We see that there is an enhancement of the Λ transverse momentum relative to $pp$ in $pS$. Comparing to VENUS we can interpret Fig. 4b as evidence that the enhanced transverse momentum of Λ in $pS$ is due cascading. The discrepancy in Fig. 4c between VENUS and the data in $SS$ may be due to the rapidity cuts in the data, which we have not included in the calculated spectra. In all cases the deficiency of the linear extrapolation via the HIJING model is clearly evident. For heavier targets, $S + Ag, Au$, the transverse momentum distribution predicted by VENUS is close to the data.

The same general conclusion emerges from the systematics of $\bar{\Lambda}$ and $K_s^0$ productions in Figs 2,3 and in Figs 5,6 respectively. In Fig.2a, the agreement between HIJING and VENUS and the data on the $p + S \to \bar{\Lambda}$ must be viewed with caution since as shown in Table III, both models overpredict the integrated $\bar{\Lambda}$ multiplicity by a factor $2 - 3$. Given
the absence of more detailed rapidity and transverse momentum distributions for $\bar{\Lambda}$, it is not possible to determine whether the $pp$ and $pA$ data are compatible. However, at least the step form $pS$ to $SS$ in Fig 2b indicates a possible factor of two enhancement of $\bar{\Lambda}$ similar to the comparison of Fig. 1b,1c for $\Lambda$. As in the case of $\Lambda$ production, there appears to be no further $\bar{\Lambda}$ enhancement from $SS$ to $SAu$. As regards to the transverse momentum distributions in Fig. 5, we note that as in Fig. 4 the $\bar{\Lambda}$ emerge with higher $p_\perp$ in $pS$ than in $pp$ in accord with the VENUS model. We note that in Figs 5 c,d, the norm theoretical curves is obtained integrating over the full rapidity interval, while the norm data are limited to a smaller domain as shown in Fig. 2 b,c.

In the case of $K^0_s$ production in Figs 3, 6, the same general trends are seen but in a less dramatic form.

We conclude that the new data indicate that the origin of strangeness enhancement in heavy ion collisions may be traced back to non-conventional and necessarily non-equilibrium dynamical effects that arise in collisions of three or more nucleons. However, this conclusion is forced upon us by the systematics of the new light ion data on $p+S$ and $S+S$ reported in [18]. As shown in Figs 1b, 2a, and 3b, those systematics, especially in $pA$, differ considerably from the trends of earlier NA5 data [14] and preliminary NA36 data [19]-[26]. Those data for heavier target nuclei incidate substantially less enhancement of midrapidity $\Lambda, \bar{\Lambda}, K^0_s$ than do the NA35 data on $p+S$. Part of the difference between these data sets may be due to different acceptance cuts and the inclusion or rejection of fragments from decay of higher mass hyperons. Obviously, the difference between these data sets must be resolved. Until then, the NA36 data must be regarded as an important caveat on our conclusions.

For completeness we show also in Figs 7 the linear extrapolations of HIJING to $Pb+Pb$ at 170 AGeV for all positives (Fig 7a) and all negatives charges (Fig 7b), for $\Lambda$ (Fig 7c) and for $\bar{\Lambda}$ (Fig 7d). It will be interesting to compare these extrapolations with upcoming data to test if the strangeness enhancement increases from $SS$ to $PbPb$.

We include the two dimensional distributions in Fig. 8 to emphasize that strangeness enhancement analyses restricted to narrow rapidity and transverse momentum cuts, es-
especially with simplistic fireball models, may completely miss the global non-equilibrium character of the data.

**IV. CONCLUSIONS**

In this paper we performed a systematic analysis of strange particle production in $pp, pA$ and $AA$ collisions at SPS CERN-energies using the HIJING and VENUS models. The most surprising result is that the breakdown of the linear extrapolation from $pp$ data to nucleus-nucleus in the strangeness channel already occurs in minimum bias $pS$! The apparent enhancement of $\Lambda$, $\bar{\Lambda}$ and $K^0_S$ at midrapidities in $pS$ reactions by a factor of 2 indicates that the mechanism for strangeness enhancement in heavier ion collisions must be associated with non-equilibrium dynamics involving multiparticle production and not with equilibrium quark-gluon fireball. In minimum bias $pS$ one projectile nucleon interacts on the average with only two target ones. The data [18] on $pS$ therefore indicate the existence of new dynamical mechanisms for strangeness production that becomes operative in $p+p+p$ collisions. The new data [18] on central $S+S$ show another factor of 2 enhancement of strangeness production relative to $pS$. This light ion reaction basically probes multiparticle production in $p+p+p+p$. The strangeness enhancement in heavier target systems apparently saturates at the $S+S$ level. We also showed that traditional analysis of strangeness enhancement in terms of ratios of integrated multiplicities is very ineffective since those ratios hide well defects of the detailed rapidity and transverse momentum distributions predicted by models.

The agreement with VENUS and RQMD results suggests color rope formation as a possible mechanism. However, to clarify the new physics much better quality data on elementary $p+p$ as well as on other light ion $p+\alpha, C, S$ and $\alpha+\alpha, C, S$ reactions will be needed. Especially, the discrepancy between NA35 and NA36 must be resolved. Only then can strangeness enhancement systematics used meaningfully in the search for signatures of quark-gluon plasma formation in future experiments with $Au+Au$ and $Pb+Pb$. 

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FIG. 1. Rapidity distributions of $\Lambda^0$ produced in $pp$ interactions at 200 GeV (Fig.1a). The data for $pp$ (black small circles) are from Jaeger et al. Rapidity distributions of $\Lambda^0$ produced in minimum bias $pS$ (Fig.1b) and central $SS$ (Fig.1c), $SAg$ (Fig.1d) and $SAu$ (Fig.1d) collisions at 200 AGeV. HIJING and VENUS results are shown by solid and dashed histograms (for $pp$, $pS$, $SS$, $SAu$). The new NA35 data ($pS$, $SS$-full circles; $SAg$ - stars; $SAu$-full triangle) are from Alber et al. The open circles show the distributions for $SS$ collisions reflected at $y_{lab} = 3.0$. In Fig 1b, earlier NA5 data on $p+Ar$ (open diamond) from ref. and preliminary data on $p+Pb$ (open squares) from NA36 are shown for comparison. In Fig1c NA36 data on $S+S$(open squares) are also shown for comparison.

FIG. 2. Rapidity distributions of $\bar{\Lambda}$ produced in minimum bias $pS$ (Fig.2a) and central $SS$ (Fig.2b), $SAg$ (Fig.2c) and $SAu$ (Fig.2d) collisions at 200 AGeV. Solid and dashed histograms are as in Fig.1. The NA35 data (full circles) are from Alber et al. The open circles show the distributions for $SS$ collisions reflected at $y_{lab} = 3.0$. In Fig. 2a, the open squares correspond to preliminary $p+Pb$ data from NA36.

FIG. 3. As in Fig.1 but for $K^0_s$ particles.

FIG. 4. Transverse momentum distributions of $\Lambda^0$ produced in $pp$ interactions at 200 AGeV (Fig.4a). The data (black small circles) for $pp$ interactions are from Jaeger et al. Transverse kinetic energy distributions of $\Lambda^0$ produced in minimum bias $pS$ (Fig.4b) and central $SS$ (Fig.4c), $SAg$ (Fig.4d) and $SAu$ (Fig.4d) collisions at 200 AGeV. HIJING and VENUS results are shown by solid and dashed histograms resp. (for $pp$, $pS$, $SS$, $SAu$). The NA35 data ($pS$, $SS$-full circles; $SAg$ - stars; $SAu$-full triangle) are from Alber et al.

FIG. 5. Transverse kinetic energy distributions for $\bar{\Lambda}$ particles produced in minimum bias $pS$ (Fig.5a) and central $SS$ (Fig.5b), $SAg$ (Fig.5c) and $SAu$ (Fig.5d) collisions at 200 GeV per nucleon. Solid and dashed histograms are as in Fig.4. The experimental data (full circles) are from Alber et al.
FIG. 6. As in Fig.4, but for $K^0_s$ particles.

FIG. 7. Predicted rapidity distributions for central ($b = 0 - 1$ fm) $PbPb$ collisions at 170 AGeV with the HIJING model for all positive charges (Fig.7a), all negative charges (Fig.7b), $\Lambda$ (Fig.7c) and $\bar{\Lambda}$ (Fig.7d).

FIG. 8. Unnormalized rapidity $y$ and transverse momentum $p_T$ distributions for $\Lambda$ (Fig.8a,b) and $\bar{\Lambda}$ (Fig.8c,d) for central $PbPb$ at 170 AGeV from HIJING.
TABLE I. Particle multiplicities for \( pp \) interaction at 200 GeV are compared with data from Gazdzicki and Hansen [15].

| \( pp \)  | Exp.data | HIJING | HIJING\(^{(j)}\) |
|----------|----------|--------|-----------------|
| \( < \pi^- > \) | 2.62 ± 0.06 | 2.61 | 2.65 |
| \( < \pi^+ > \) | 3.22 ± 0.12 | 3.18 | 3.23 |
| \( < \pi^0 > \) | 3.34 ± 0.24 | 3.27 | 3.27 |
| \( < h^- > \) | 2.86 ± 0.05 | 2.99 | 3.03 |
| \( < K^+ > \) | 0.28 ± 0.06 | 0.32 | 0.32 |
| \( < K^- > \) | 0.18 ± 0.05 | 0.24 | 0.25 |
| \( < \Lambda + \Sigma^0 > \) | 0.096 ± 0.015 | 0.16 | 0.165 |
| \( < \bar{\Lambda} + \bar{\Sigma}^0 > \) | 0.013 ± 0.01 | 0.03 | 0.037 |
| \( < K^0_s > \) | 0.17 ± 0.01 | 0.26 | 0.27 |
| \( < p > \) | 1.34 ± 0.15 | 1.43 | 1.45 |
| \( < \bar{p} > \) | 0.05 ± 0.02 | 0.11 | 0.12 |
| Particle type | \(< n \) | Exp.data | HIJING\(^{(j)}\) |
|---------------|--------|---------|-----------------|
| All charged   | 29.4 ± 0.3 | 86       | 28.2            |
| \(K^0 + \bar{K}^0\) | 2.24 ± 0.16 | 86       | 1.98            |
| \(K^+ + K^-\) | 2.24 ± 0.16 | 86       | 2.06            |
| \(p + \bar{p}\) | 1.45 ± 0.15 | 87       | 1.55            |
| \(\Lambda + \bar{\Lambda}\) | 0.53 ± 0.11 | 86       | 0.50            |
| \(\Sigma^+ + \Sigma^- + \bar{\Sigma}^+ + \bar{\Sigma}^-\) | 0.27 ± 0.06 | 87       | 0.23            |
| \(\Xi^-\) | 0.04 ± 0.01 | 86       | 0.037           |
| \(\gamma\) | 33 ± 3 | 86       | 29.02           |
| \(\pi^+ + \pi^-\) | 23.9 ± 0.4 | 86       | 23.29           |
| \(K_s^0\) | 1.1 ± 0.1 | 86       | 0.99            |
| \(\pi^0\) | 11.0 ± 0.4 | 87       | 13.36           |
TABLE III. Average multiplicities for negative charged hadrons and neutral strange hadrons in \( pp \) and \( pA \) interactions. HIJING and VENUS model results are compared with others recent estimates using RQMD, QGSM, DPM and with data from Alber et al. [18].

| Reaction | \(< h^- >\) | \(< \Lambda >\) | \(< \bar{\Lambda} >\) | \(< K^0_s >\) |
|-----------|--------------|----------------|-----------------|----------------|
| \( pp \)  | DATA 2.85 ± 0.03 | 0.096 ± 0.015 | 0.013 ± 0.005 | 0.17 ± 0.01 |
|          | HIJING 2.99 | 0.16 | 0.030 | 0.26 |
|          | VENUS 2.79 | 0.181 | 0.033 | 0.27 |
|          | RQMD 2.59 | 0.11 | 0.21 |
|          | QGSM 2.85 | 0.15 | 0.015 | 0.21 |
|          | DPM\(^1\) 3.52 | 0.155 | 0.024 | 0.18 |
|          | DPM\(^2\) 3.52 | 0.155 | 0.024 | 0.18 |
| \( p + S \) | DATA 5.7 ± 0.2 | 0.28 ± 0.03 | 0.049 ± 0.006 | 0.38 ± 0.05 |
| \( 'min.bias' \) | HIJING 4.83 | 0.255 | 0.046 | 0.400 |
|          | VENUS 5.40 | 0.340 | 0.065 | 0.510 |
|          | QGSM 5.87 | 0.240 | 0.023 | 0.340 |
|          | DPM\(^1\) 5.53 | 0.300 | 0.043 | 0.360 |
|          | DPM\(^2\) 5.54 | 0.32 | 0.060 | 0.360 |
| \( p + Ag \) | DATA 6.2 ± 0.2 | 0.37 ± 0.06 | 0.05 ± 0.02 | 0.525 ± 0.07 |
| \( 'min.bias' \) | HIJING 6.28 | 0.34 | 0.054 | 0.505 |
| \( p + Au \) | DATA 9.6 ± 0.2 |  |  |  
| \( 'central' \) | HIJING 11.25 | 0.67 | 0.090 | 0.88 |
TABLE IV. Average multiplicities for negative charged hadrons and neutral strange hadrons in AA interactions. HIJING and VENUS model results are compared with others recent estimates using RQMD, QGSM, DPM and with data from Alber et al. [18].

| Reaction  | < h^- >  | < Lambda > | < Lambdabar > | < K^0_s >  |
|-----------|----------|------------|---------------|------------|
| S + S 'central' | DATA 95 ± 5 | 9.4 ± 1.0 | 2.2 ± 0.4 | 10.5 ± 1.7 |
|           | HIJING 88.8 | 4.58 | 0.86 | 7.23 |
|           | VENUS 94.06 | 8.20 | 2.26 | 11.94 |
|           | RQMD 110.2 | 7.76 | 10.0 |
|           | QGSM 120.0 | 4.70 | 0.35 | 7.0 |
|           | DPM^1 109.8 | 6.83 | 0.80 | 10.6 |
|           | DPM^2 107.0 | 7.18 | 1.57 | 10.24 |
| S + Ag 'central' | DATA 160 ± 8 | 15.2 ± 1.2 | 2.6 ± 0.3 | 15.5 ± 1.5 |
|           | HIJING 164.35 | 8.61 | 1.48 | 13.20 |
|           | RQMD 192.3 | 13.4 | 18.30 |
|           | DPM^1 195.0 | 13.3 | 1.45 | 19.40 |
|           | DPM^2 186.90 | 14.06 | 3.65 | 15.73 |
| S + Au 'central' | HIJING 213.2 | 11.3 | 1.81 | 16.55 |
|           | VENUS 201.6 | 14.0 | 3.01 | 21.52 |
| S + W 'central' | HIJING 210.0 | 10.64 | 1.71 | 16.05 |
| Pb + Pb 'central' | HIJING 725.15 | 36.44 | 5.93 | 54.86 |
TABLE V. The mean multiplicities of negative pions and $E_S$ ratios (see the text for definition) for nuclear collisions at 200 AGeV. The data are from Alber et al. [18] and the $NN$ data are from Gazdzicki and Hansen [16].

| Reaction | DATA | HIJING | $< \pi^- >$ | $< E_S >$ |
|----------|------|--------|-------------|-----------|
| $p + p$  |      |        | 2.62 ± 0.06 | 0.153     |
| N + N    |      |        | 3.06 ± 0.08 | 0.100 ± 0.01 |
| $p + S$  |      |        | 5.26 ± 0.13 | 0.086 ± 0.008 |
| 'min.bias' | DATA | HIJING | 4.3         | 0.144     |
| $p + Ag$ |      |        | 6.4 ± 0.11  | 0.108 ± 0.009 |
| 'min.bias' |      |        | 5.59        | 0.141     |
| $p + Au$ |      |        | 9.3 ± 0.2   | 0.073 ± 0.015 |
| 'central' |      |        | 10.22       | 0.136     |
| S + S    |      |        | 88 ± 5      | 0.183 ± 0.012 |
| 'central' |      |        | 79.6        | 0.140     |
| S + Ag   |      |        | 149 ± 8     | 0.173 ± 0.017 |
| 'central' |      |        | 147.8       | 0.138     |
$P + P, P + S(200 \text{ GeV}), S + S, S + Au(200 \text{ AGeV})$ HIJING(−) vs. VENUS(−−)

(a) $P + P \rightarrow \Lambda + X$

(b) $P + S \rightarrow \Lambda + X$ NA35

(c) $S + S \rightarrow \Lambda + X$ NA35

(d) S+Ag(★), S+Au(△) → \Lambda+X

rapidity $y$
$P+S(200 \text{ GeV}), S+S, S+\text{Ag}, S+\text{Au}(200 \text{ AGeV})$ HIJING(−) vs. VENUS(−−)

(a) $P+S \rightarrow \text{ANTI} \Lambda + X$ NA35
(b) $P+\text{Pb} \rightarrow \text{ANTI} \Lambda + X$ NA36
(c) $S+\text{Ag} \rightarrow \text{ANTI} \Lambda + X$
(d) $S+\text{Au} \rightarrow \text{ANTI} \Lambda + X$
\[ \frac{dN}{dy} \]

**P+P, P+S (200 GeV), S+S, S+Au (200 AGeV) HIJING(--) vs. VENUS(--)**

(a) \( P+P \rightarrow K_0^S + X \)

(b) \( P+S \rightarrow K_0^S + X \) NA35

(c) \( S+S \rightarrow K_0^S + X \)

(d) \( S+Ag(\ast), S+Au(\triangle) \rightarrow K_0^S + X \)
$P + P, P + S(200 \text{ GeV}), S + S, S + Au(200 \text{ AGeV})$ HIJING(−) vs. VENUS(−−)
$P + S(200 \text{ GeV}), S + S, S + Ag, S + Au(200 \text{ AGeV})$ HIJING(−) vs. VENUS(--)

**Diagram (a)**: $P + S \rightarrow \text{ANTI} \Lambda + X$

**Diagram (b)**: $S + S \rightarrow \text{ANTI} \Lambda + X$

**Diagram (c)**: $S + Ag \rightarrow \text{ANTI} \Lambda + X$

**Diagram (d)**: $S + Au \rightarrow \text{ANTI} \Lambda + X$
$P+P, P+S(200 \text{ GeV}), S+S, S+Au(200 \text{ AGeV})$ HIJING (−) vs. VENUS (−−)

1. $P+P \rightarrow K^0_0 + X$ (a)

2. $P+S \rightarrow K^0_0 + X$ (b)

3. $S+S \rightarrow K^0_0 + X$ (c)

4. $S+Ag(\ast), S+Au(\Delta) \rightarrow K^0_0 + X$ (d)

Graphs showing the distributions of $1/2\pi \frac{1}{p_T} \frac{dn}{dp_T} (\text{GeV}/c)^2$ for different reactions.
Pb+Pb ($E_{\text{Lab}} = 170$ AGeV) HIJING(−)

\[ \frac{dN}{dy} \]

- **Pb+Pb → all pos. + X** (a)
- **Pb+Pb → all neg. + X** (b)
- **Pb+Pb → Λ + X** (c)
- **Pb+Pb → \text{ANTIΛ} + X** (d)
