# STRANGENESS ENHANCEMENT IN pA AND AA COLLISIONS IN THE FRAME OF INDEPENDENT SCATTERING SCHEME

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It is shown that the simple consecutive scattering scheme with strangeness yield in nucleon-nucleon pair collision dependent on the "composition" of the pair (*fresh–fresh*, *wounded–fresh* or *wounded–wounded*) can reproduce some aspects of strangeness enhancement observed in relativistic nuclear interactions.

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## 1. Introduction

An enhancement of strange particle production in relativistic heavy ion collisions over that expected from a superposition of nucleon-nucleon scattering has been suggested as one of the possible signals of quark-gluon plasma formation [1] and later observed at BNL AGS and CERN SPS energies as an increase of a $K/\pi$ ratio (see *e.g.* [2, 3]). However, this ratio rises not only in $AA$ but also in relatively low-energy $pA$ collisions which suggests a possible hadronic scenario. It has been shown recently that the observed yields of strange particles in 14.6 A GeV $AA$ collisions can be reproduced in terms of parametrized $pA$ yields [4], and the $K$'s and $\Lambda$'s enhancements observed at 200 A GeV — as a result of conventional strangeness production and rescattering *via* secondary interactions [5]. In the scheme presented below the strangeness enhancement is treated at the "wounded nucleon" level and then an attempt is made to reproduce both the AGS and SPS results.

## 2. Calculation scheme

We present here the results of slightly modified independent scattering scheme, ISS [6], in which a nucleus behaves like a bunch of weakly bounded objects spatially distributed according to Woods–Saxon density. The relativistic nuclear collision is reduced to a sequence of independent $NN$-scattering at gradually decreasing energy. Each participant in projectile and target nuclei behaves as "fresh" only in the first collision and as "wounded" in the consecutive ones. The average inelasticity of a fresh nucleon, $\langle K_1 \rangle = 0.5$ in the first collision, is about twice as large as in the $\nu$-th one ($\nu = 2,\ 3,\ \ldots$) [7]. In contrast with pure Wounded Nucleon Model [8], wounded nucleons can create here new particles in each above-threshold intranuclear scattering. The mean free path in nuclear matter remains unchanged for wounded objects in agreement with experimental observation [9]. In the case of $pA$ collisions we prove these assumptions on the basis of comparison with an experiment the calculated ratio of rapidity density in central region, $R = \left(\frac{d\sigma}{dy}\right)_{pA} \Big/ \left(\frac{d\sigma}{dy}\right)_{pp}$. Two available sets of 200 GeV $pA$ data, [10] and [11] are well described by the ISS for $\langle K_{\nu>1} \rangle = 0.20$ and $\langle K_{\nu>1} \rangle = 0.25$, respectively, whereas the possibility of constant inelasticity $\langle K_{\nu\geq 1} \rangle = 0.50$ should be definitely rejected.

## 3. Strange particle production

Furthermore, we have assumed that not only inelasticity, but also the composition of produced particles changes dramatically in the collisions of wounded participants. Consequently, the fresh and wounded nucleons contribute to the multiplicity of produced pions $\frac{\alpha\langle n^{pN\to\pi X}\rangle}{2}$ and $\frac{\beta\langle n^{pN\to\pi X}\rangle}{2}$ kaons, respectively. So, the $\frac{K}{\pi}$ fraction equals $\alpha$ in the first collision of the projectile nucleon inside the target nucleus and $\gamma_\nu = \frac{\alpha_\nu+\beta_\nu}{2}$ in the $\nu$-th collision ($\nu = 2, 3, \ldots$). Hence, the average multiplicity of kaons of specified charge in $pA$ collisions is given by

$$\left\langle n^{pA\to KX}\right\rangle = \alpha\left\langle n^{pN\to\pi X}\right\rangle + \sum_{\nu=2}^{\infty}\gamma_\nu\left\langle n_\nu^{pN\to\pi X}\right\rangle . \tag{1}$$

If $\alpha_w$ denotes the weight relative kaon yield

$$\alpha_w = \frac{\sum_{\nu=2}^{\infty}\gamma_\nu\left\langle n^{pN\to\pi X}\right\rangle}{\sum_{\nu=2}^{\infty}\left\langle n_\nu^{pN\to\pi X}\right\rangle} = \frac{\sum_{\nu=2}^{\infty}\gamma_\nu\left\langle n_\nu^{pN\to\pi X}\right\rangle}{\left\langle n^{pA\to\pi X}\right\rangle - \left\langle n^{pN\to\pi X}\right\rangle} , \tag{2}$$

then the average kaon multiplicity (1) can be written in the form

$$\langle n^{pA\to KX}\rangle = \alpha_w \langle n^{pA\to\pi X}\rangle + (\alpha - \alpha_w)\langle n^{pN\to\pi X}\rangle . \quad (3)$$

In the case of Gaussian-shaped rapidity the average multiplicity of newly produced particles in $NN$ collisions depends on the available energy $E^*_{a\nu} = \sqrt{s} - 2m_N$ as

$$\langle n_{\rm prod}\rangle = \langle K\rangle E^*_{a\nu} \exp\frac{-0.5\sigma^2}{\langle m_T\rangle},$$

where $\langle K\rangle$ and $\langle m_T\rangle$ denote the average inelasticity and transverse mass, respectively, and $\sigma \sim \ln(E^*_{a\nu})$ is the rapidity dispersion [6]. The global multiplicity after $\nu_p$ intranuclear collisions and also the central rapidity density in the $pA$ case rises then approximately as $\nu_p^{1/2}$, in a good agreement with 200 GeV $pA$ data [12]. The resulting power-type dependence on the target mass obtained after simple geometrical approximation $\langle\nu_p\rangle \sim A^{1/3}$

$$\frac{\langle n_-^{pA}\rangle}{\langle n_-^{pN}\rangle} = A^{1/6} \quad (4)$$

describes well the 200 GeV $pA(= p$, Mg, Ar, Ag, Xe, and Au) data [11–13] for $\langle n_-^{pN}\rangle = 2.94$.

Let

$$\kappa^{pA}_{K/\pi} = \frac{\langle n^{pA\to KX}\rangle}{\langle n^{pA\to\pi X}\rangle}$$

denotes the $\frac{K}{\pi}$ ratio (for specified charge) in nuclear collisions at a given energy. The strangeness enhancement can then be determined relatively to the $\kappa^{pp}_{K/\pi}$ value known from $pp$ collisions. After substituting the pion multiplicity ratio in $pA$ and $pN$ collisions by hadron relative multiplicity (4) we obtain a simple relation

$$\kappa^{pA}_{K/\pi} = \alpha_w + (\alpha - \alpha_w)\frac{\langle n^{pN\to\pi X}\rangle}{\langle n^{pA\to\pi X}\rangle} = \alpha_w + (\alpha - \alpha_w)A^{-1/6} \quad (5)$$

in good agreement with 14.6 GeV/$c$ data [2] as can be seen from Fig. 1 ($\kappa^{pA}_{K/\pi} = \alpha_w$ for infinitely large target nucleus). Thus, the "effective" value of the coefficient $\beta$ can be estimated: $\beta_{\rm eff} = 2\alpha_w - \alpha = 0.32$.

In principle strangeness can be distributed between different species of produced particles depending on available energy, mass of the colliding system, centrality of the collision, rapidity region *etc.* Experimental data suggests for example, (see *e.g.* [14–16]) that the strange hyperons are produced

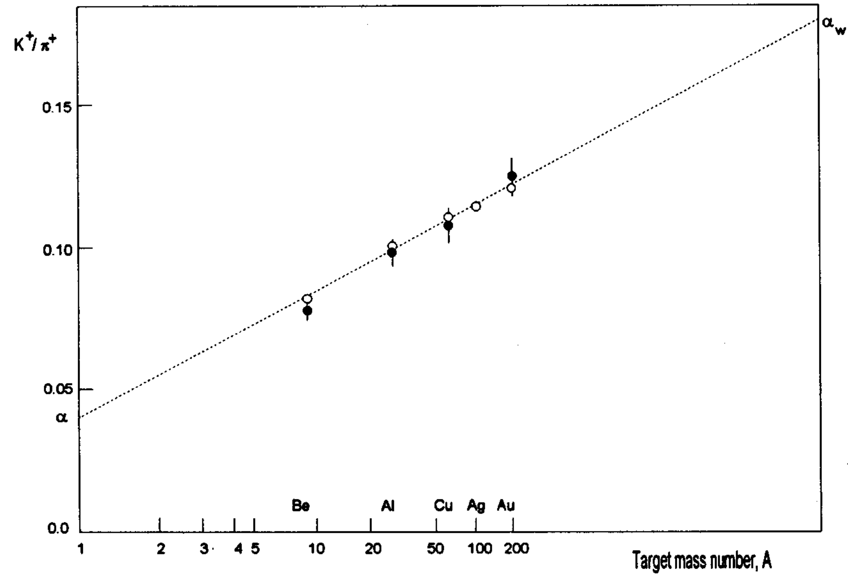


Fig. 1. The $K^+/\pi^+$ ratio in 14.6 GeV/$c$ minimum bias $pA$ collisions calculated in central rapidity region $1.2 \leq \gamma \leq 1.4$ (light circles). Experimental points are from Ref. [2] (full circles) and the straight line represents relation (5) in the form $\kappa^{pA}_{K/\pi} = 0.5(\alpha + \beta) + 0.5(\alpha - \beta)A^{-1/6}$ with $\alpha = 0.04$ and $\beta = 0.32$.

in two different mechanisms: "central" and "leading". The second contribution is born by a replacement of light quark in the $|uud\rangle$ or $|ddu\rangle$ system by a heavier $s$-quark. If the yield of leading hyperons (mostly lambdas) is proportional to the number of participants (exactly two in $pp$ collisions), then

$$n^{pp}_{\Lambda}(\text{leading}) = n^{pp}_{\Lambda} - n^{pp}_{\bar{\Lambda}} = 2\alpha\,, \tag{15}$$

where $n^{pp}_{\bar{\Lambda}}$ denotes the mean number of antilambdas, exclusively centrally produced in equilibrium with lambdas: $n^{pp}_{\bar{\Lambda}} = n^{pp}_{\Lambda}$ (central). The global yield of leading lambdas in 200 GeV $pp$ collisions [17] as estimated from (15) equals $n^{pp}_{\Lambda} = 0.07 \pm 0.02$. An observed production rate of leading hyperons relatively to the negative hadrons increases in 200 GeV $pA$ collisions with the multiplicity od identified protons in an event — a measure of the number of intranuclear scatterings [16]. If the multiplicity of produced lambdas (in both hemispheres) is simply proportional to the number of participants and the coefficient $\alpha$ remains unchanged in the wounded "remnants" collisions, then:

$$n^{pA}_{\Lambda\,(\text{leading})} = \alpha(\langle\nu\rangle + 1) = (n^{pp}_{\Lambda} - n^{pp}_{\bar{\Lambda}})\frac{\langle\nu\rangle + 1}{2}\,. \tag{16}$$

This value can be sufficiently greater, however, if the production rate (16) depends on the overall number of "wounds", $2\langle\nu\rangle$, rather than the number of participants, $\langle\nu\rangle+1$ (the average number of leading hadron collisions for nuclei shapes according to the Woods–Saxon density can be parameterized in our scheme as $\langle\nu\rangle = 0.84\ \mathrm{A}^{0.29}$).

Also in $AA$ collisions, where the $\bar{\Lambda}$ rapidity distribution exhibits the *central type*-shape whereas the $\Lambda$ one is much wider with very long plateau [16], dominates probably the leading production mechanism of hyperons. The rapidity losses distribution: $f(Y) = \frac{f(K)p_L}{E_0 - m_N}$ of leading nucleons with primary energy $E_0$ and final longitudinal momentum $p_L$ shows for uniformly distributed inelasticity $f(K)$ a distinct minimum at midrapidity, *i.e.* high degree of stopping, in symmetric $AA$ collisions. An analogous very large proton stopping was observed in 200 A GeV $SS$ collisions [18]. So, we can interpret the resulting $\Lambda$ distribution as a sum of two different contributions — the hollow typical for leading component is filled by the centrally produced particles. The ratio $\sim 0.37$ of the rapidity density for centrally produced antilambdas as estimated in the frame of the ISS, is similar to what is observed in the central region $2.2 \leq \eta \leq 3.5$, *i.e.* the (uncorrected) $\bar{\Lambda}/\Lambda$ ratio $0.305 \pm 0.004$ [19] and also to $\sim 0.4$, observed at midrapidity for various collision systems [16]. The consistence of presented indirect estimate with experiment supports our earlier assumption on equal multiplicities of hyperons and antihyperons in central production. This feature is in agreement with equal yields of lambdas and antilambdas extrapolated to $x = 0$ from 300 GeV/$c$ $pA$(=Be, Cu, and Pb) data [14]. So, in all types of nuclear collisions the dominant mechanism of lambda production is a "charge exchange" process in leading baryon regions.

## 4. Monte Carlo calculations

As an input we use data on hadron production in $NN$ collisions at 200 GeV/$c$, compiled in Ref. [17]. The yields of kaons and hyperons in wounded nucleon collisions are chosen to fit the 200 GeV $S+S$ data [20]. The same set of parameters was also applied to the heavy target reactions (see Table I). In our scheme only nucleons scatter multiply and, therefore, the lack of newly produced particles is present in $SS$ collisions and, more remarkably, in collisions with heavier targets. In low-energy scattering of secondaries practically only pions are produced, fully neglected in modelling. Therefore, in the case of full phase space data or in the limited rapidity intervals near the target or projectile fragmentation regions the absolute calculated kaon and lambda yields rather than $K/\pi$ and $\Lambda/\pi$ ratios should be compared with experimental data. This is not the case of $K^+/\pi^+$ ratio ($0.192 \pm 0.031$) measured in 14.6 A GeV Si+Au collisions, near midrapidity ($y_{NN} \approx 1.7$) [2]. This result is reproduced in our scheme ($K^+/\pi^+ = 0.22$) when the absolute kaon contribution in the interaction of a wounded nucleon relative to a fresh one, increases about 8 times, in agreement with an earlier estimate of relative kaon yield. In comparison with the lower energy results, the $K^+/\pi^+$ ratio in 200 GeV/$c$ $pA$ collisions depends relatively weak on the target mass (the coefficient $\beta_{\rm eff}$, as estimated from Fig. 2, equals $\sim 0.24$), in agreement with $\sim 1.3$ strangeness enhancement observed in $pW$ collisions [15]. No such enhancement was observed in broad scattered experimental data on strangeness production in 200 GeV/$c$ $pA$ collisions compiled in Ref. [21].

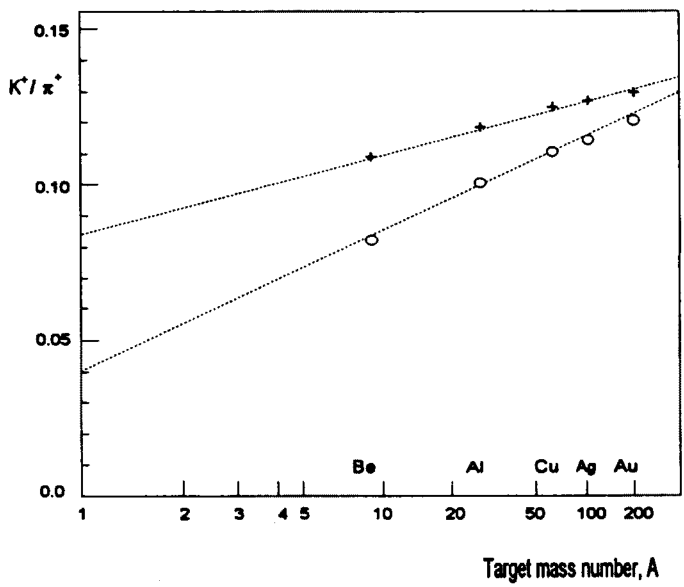


Fig. 2. The $K^+/\pi^+$ ratios in 14.6 GeV/$c$ minimum bias $pA$ collisions calculated in central rapidity region $1.2 \leq y \leq 1.4$ (circles) and full phase space 200 GeV/$c$ central collisions (crosses). The lines are guided on the eye.

The $K/\pi$ ratio is very sensitive to kinematical factors like available energy and rapidity. The strangeness enhancement in asymmetric systems, depends stronger than in symmetric ones on the rapidity acceptation region (wounded nucleon, shifted toward midrapidity, produces more and slower kaons than the fresh one). For example, the $K_s^0/h^-$ in $pS$ collision in two symmetrically located rapidity windows $1 \leq y \leq 2$ and $4 \leq y \leq 5$, equals 0.11 and 0.08, respectively. As it was pointed in [5], this effect can partly explain no additive strangeness yield in $pA$ collisions registered in NA35 acceptance region [3].

In the case of nuclear projectile we expect a strangeness enhancement greater than in $pA$ collisions as a result of the presence of $NN$-pairs in which both participants are wounded. Due to this effect ISS reproduces also an increase of the $K_s^0/h^-$ and $\Lambda/h^-$ ratios as a function of negative multiplicity (centrality of the collision) in 200 GeV/$c$ $SS$ reactions [3]. For extremely peripheral collisions, both calculated ratios have values known from $pp$ data [22], then monotonically increase and for impact parameter $b \approx 4$ fm saturate at the level characteristic for central $SS$ collisions.

TABLE I

Multiplicities in 200 A GeV central* nuclear collisions in full phase space. Experimental data (in brackets) are from Ref. [20]. The contribution of antiprotons was estimated on the assumption that the ratio $\bar{p}/h^-$ known from $pp$ data, remains unchanged in nuclear collisions.

| | $h^-$ | $\pi^-$ | $K_s^0$ | $K^+$ | $K^-$ | $\Lambda$ | $\bar{\Lambda}$ |
|---|---|---|---|---|---|---|---|
| S+S | 92 (95 ± 5) | 84 (88 ± 5) | 10.6 (10.5 ± 1.7) | 12.3 (12.5 ± 0.4) | 6.7 (6.9 ± 0.4) | 9.3 (9.4 ± 1.0) | 1.5 (1.5 ± 0.4) |
| S+Ag | 148 (160 ± 8) | 136 (149 ± 8) | 16.8 (15.5 ± 1.5) | 19.2 (17.4 ± 1.0) | 10.9 (9.6 ± 1.0) | 15.0 (15.2 ± 1.2) | 2.5 (2.4 ± 0.4) |
| S+Au | 177 | 163 | 21.1 | 23.8 | 13.3 | 19.6 | 3.0 |

* The selections imitated "central trigger" (3%, 3.2% and 6% of the geometrical cross sections for S+S, S+Ag and S+Au reactions, respectively [16]) by a cut in the impact parameter.

## 5. Summary

Nuclear collisions were considered in the frame of independent scattering scheme (ISS), as a sequence of $NN$-pair scatterings in three combinations: *fresh–fresh, wounded–fresh* and *wounded–wounded*. We conclude that it is possible to interpret the positive kaon enhancement observed in 14.6 A GeV $pA$ and SiAu and also strangeness enhancement in 200 A GeV $AA$ collisions in terms of the ISS when the ratio of strange to non-strange particles produced by wounded nucleons, reaches 0.2–0.3.

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