KAON PRODUCTION IN ULTRARELATIVISTIC NUCLEAR COLLISIONS [1,2]

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A model for the description of the $\sqrt{s_{NN}}$ dependence of $\langle K^+ \rangle / \langle \pi^+ \rangle$ ratio at the CERN SPS and upper AGS energies is proposed. It uses hadronic degrees of freedom and the amount of produced strangeness is mainly controlled by the total lifetime of the fireball. Decreasing lifetime with increasing collision energy is conjectured.

Production of strangeness was among the first observables studied in ultrarelativistic nuclear collisions in the search for *quark-gluon plasma* (QGP). Transition to the plasma phase was expected to facilitate strangeness production and lead to its enhancement [1]. It is energetically rather costly to produce strangeness in a hadronic system; the lowest threshold, which is about 530 MeV above the incoming masses is realised in the $\pi N \to \Lambda K$ channel. On the other hand, production of a $s\bar{s}$ pair of quarks in the QGP requires only some 300 MeV. Thus the production rates should be bigger in the deconfined (QGP) phase than in the hadronic gas.

A decisive role in strangeness production is also played by the lifespan of the fireball. Smaller or larger production rates lead to longer or shorter times, respectively, to produce the same amount of strangeness.

At present, perhaps the most exciting result of the energy scan with nuclear collisions at the CERN SPS is the excitation function[4] of the $\langle K^+ \rangle / \langle \pi^+ \rangle$ multiplicity ratio (see Figure 1) [2, 3]. So far, the sharp decrease of the ratio above the peak position at beam energy of 30 GeV per nucleon was successfully interpreted only in the so-called *Statistical Model of Early Stage* [4]. This model assumes that primordial[5] production of secondaries leads immediately to chemically equilibrated system where the amount of strangeness is given by the governing temperature and the phase the system finds itself in. The sharp decrease of the $\langle K^+ \rangle / \langle \pi^+ \rangle$ ratio above $E_{\text{beam}} = 30 \, A$GeV is put in connection with the mixture of the hadronic and the QGP phase.

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[2]Based on work done in collaboration with E.E. Kolomeitsev
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[4]Excitation function is, in general, the dependence of a studied quantity on the energy of the collision.
[5]Primordial production is due to collisions of incoming nucleons/partons.
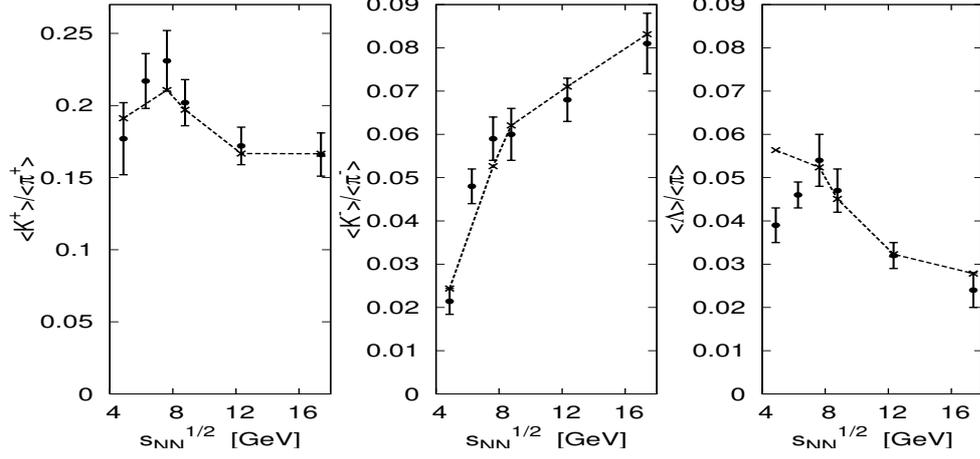
Fig. 1. Comparison of model calculations with data [3] for all collision energies.

An important task in the hunt for QGP is the exploration of alternative models which make *no* plasma assumptions. Such models must be falsified if the identification of QGP is to be claimed. Therefore, we propose [5] a model aimed for interpretation of the $\sqrt{s_{NN}}$ dependence of strangeness production exclusively using hadronic degrees of freedom.

It is assumed that the $\langle K^+\rangle/\langle\pi^+\rangle$ peak appears due to two effects. Firstly, the rise of positive kaon production is due to increasing energy which is at disposal for particle creation. The second effect is stopping and its weakening towards higher collision energies. This leads to shorter lifetimes. As a consequence, fewer kaons are produced during a shorter lifespan.

We focus on densities of various hadronic species and calculate their evolution. In particular, we evolve the kaon densities in time according to the master equation

$$\frac{dn_K}{dt} = n_K\left(-\frac{1}{V}\frac{dV}{dt}\right) + \sum_{ij}\langle v_{ij}\sigma^+_{ij}\rangle n_i\,n_j - \sum_j\langle v_{Kj}\sigma^-_{Kj}\rangle n_K\,n_j\,. \tag{1}$$

The first term on the right-hand side includes the expansion rate. It corresponds to the density change due to the increasing fireball volume. We shall adopt an ansatz for this term expressed via a parametrisation of the energy density and baryon density as functions of time below in eq. (2). The second term on the right-hand side of eq. (1) is the kaon production rate; the term in angular brackets denotes momentum-averaged cross-sections multiplied by relative velocity of the interacting species i and j. The last term gives the annihilation rate and has a similar structure to the second term.

The ansatz for density of energy and conserved quantum numbers B and I_3, reads

$$\rho(t) = \begin{cases} \rho_0(1 - at - bt^2)^\delta & \text{for}\quad t < \tau_s, \\ \frac{\rho'_0}{(t-\tau_0)^{\alpha\delta}} & \text{for}\quad t > \tau_s, \end{cases} \tag{2}$$

where a, b, α, δ, ρ_0, ρ'_0, τ_0, and τ_s are model parameters [5]; $\delta = 1$ for energy density and it assumes a value $3/4 < \delta < 1$ (depending on the equation of state) for baryon density and
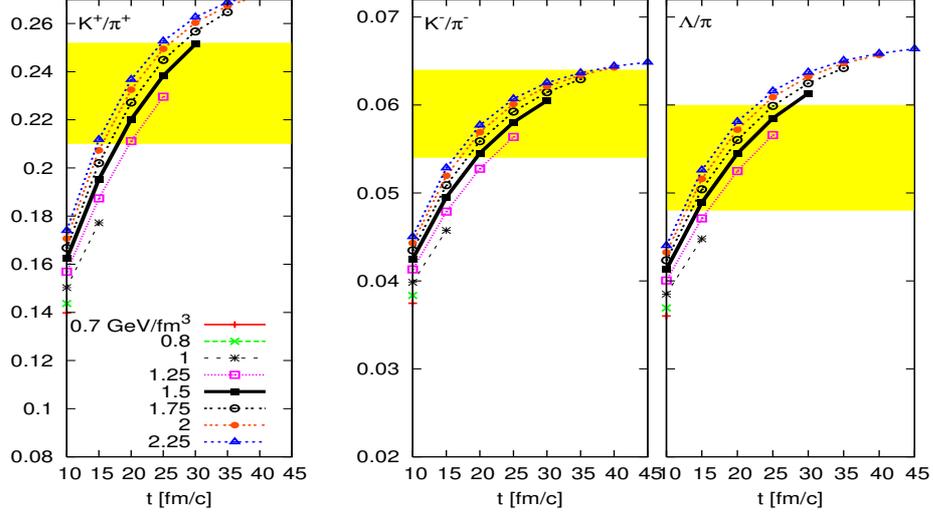
Fig. 2. Dependence of the multiplicity ratios $\langle K^+ \rangle / \langle \pi^+ \rangle$, $\langle K^- \rangle / \langle \pi^- \rangle$, $\langle \Lambda \rangle / \langle \pi \rangle$ on the total lifetime of the fireball calculated for Pb+Pb collisions at projectile energy of 30 AGeV. Different curves show scenarios with different initial energy densities. Horizontal bands indicate measured values.

I_3 density. The ρ's stand for any kind of density here. The first part of the parametrisation corresponds to acceleration and the second part is a power-law expansion suggested by intensity interferometry data (see e.g. [6, 7] for review). We shall explore a range of parameters in this parametrisation and investigate their impact on the results.

From eq. (2) we determine the energy density and the densities of all *non-strange* species at any time. Non-strange particles are assumed to be in *chemical equilibrium* since the reaction rates among them are large. Densities of K^+, K^0, K^{*+}, K^{*0} are calculated via eq. (1). Negative kaons are of different kind than K^+. In baryon-rich environment, as produced in nuclear collisions at these energies, the latter are produced in associated production with hyperons, $\pi N \rightarrow YK$, while the former can only be produced together with another kaon, e.g. $\pi\pi \rightarrow K\bar{K}$. On the other hand, reactions which just swap the strange quark from one species to another are quick (e.g. $\pi\Lambda \leftrightarrow \bar{K}N$), thus the $S < 0$ sector is in *relative* chemical equilibrium: the *ratios* of these densities are given by temperature and chemical potentials. Of course, the *total* strangeness of the system must vanish.

Thus, the final density of $S > 0$ species is mainly determined by the lifespan and a bit less by the temperature. The total amount of negative K's and Λ's is such that the whole $S < 0$ sector balances the $S > 0$ densities. The density of K^- *relative* to Λ is given by the final temperature.

The parametrisation (2) is tuned in such a way that it ends in a final state corresponding to chemical composition as obtained in the fits by Becattini *et al.* [8]. Primordial content of strangeness is estimated from pp, pn, and nn collisions [5]. We are studying dependence of the resulting multiplicity ratios on initial energy density and total lifetime of the system.

An example of the results is shown in Fig. 2. One observes that strangeness production mainly depends on the lifetime and not so much on the initial energy density. This feature is
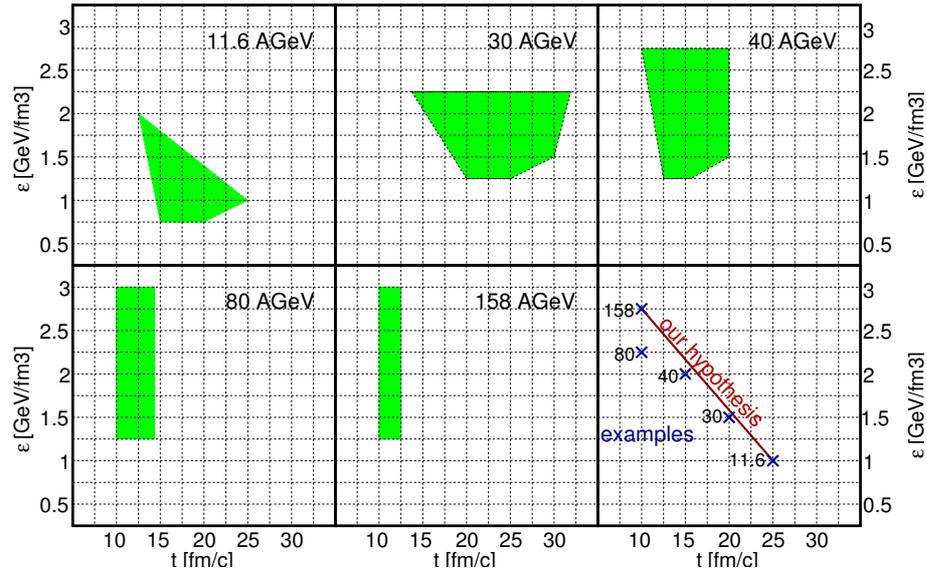
Fig. 3. Summary of lifespans and initial energy densities allowed by comparison with data. Crosses in the lower right panel show the parameters of calculations which are compared to data in Fig. 1.

even more pronounced at higher collision energies.

In Fig. 3 we see that at SPS strangeness production is accommodated by our hypothesis: with increasing collision energy the lifetime is shorter and the initial energy density can be higher. There may be some problems with collisions at 11.6 *A*GeV (AGS energy); a possible resolution might be in changing the type of parametrisation for the time-dependence of densities. The calculated results are compared with data in Fig. 1.

The underlying idea of the model works. We were able to describe the data using a hadronic scenario. Whether or not this scenario is indeed applicable can be decided after a careful cross-check with freeze-out analysis of spectra, HBT, abundances, and with the dilepton spectra.

References

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