Strangeness to equilibrium entropy: A signal for the quark gluon plasma formation in the relativistic nuclear collisions

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Various signals have been proposed for the detection of quark gluon plasma (QGP) expected to be formed in the relativistic heavy ion collisions. The pros and cons of these signals are matter of intense debate. The strangeness productions and its ratio to equilibrium entropy is one such widely discussed signal. In this work we study the strangeness perticularly the kaon productions and estimate the ratio, $R^+ \equiv K^+/\pi^+$. R^+ is measured experimentally [1] as a function of centre of mass energy ($\sqrt{s_{NN}}$). It is observed that the R^+ increases with $\sqrt{s_{NN}}$ and then decreases beyond a certain value of $\sqrt{s_{NN}}$ giving rise to a horn like structure, whereas the ratio, $R^- \equiv K^-/\pi^-$ increases faster at lower $\sqrt{s_{NN}}$ and tend to saturate at higher $\sqrt{s_{NN}}$. The kaon prductions have been calculated for different center of mass energies($\sqrt{s}_{NN}$) ranging from 3 to 200 GeV. We consider the processes of gluon fusion and light quarks annihilation for the strangeness prduction (s,$\bar{s}$) in a partonic phase. For the production of K^+ and K^- an exhaustive set of reactions involving thermal baryons and mesons have been considered. The time evolution of the densities are governed by the Boltzmann equation. The possibility of formation of a fully equilibrated system in high energy nuclear collisions is still a fiercely debated issue because of the finite size and life time of system. In the present work we assume that the strange quarks or the strange hadrons (depending on the value of $\sqrt{s_{\rm NN}}$) are produced out of chemical equilibrium. We assume various scenarios to examine whether the K^+/π^+ experimental data can differentiate between different initial conditions. The system after the collision is assumed to be formed; (I) in the hadronic phase for all $\sqrt{s_{\rm NN}}$ or (II) in the partonic phase beyond a certain threshold in $\sqrt{s_{\rm NN}}$. Other possibilities like formation of strangeness in complete thermal equilibrium and evolution in space time (III) without and (IV) with secondary productions of quarks and hadrons have been considered. (V) Results for an ideal case of zero strangeness in the initial state will also be presented.

In the present work we use momentum integrated Boltzman equation to study the evolution of the strange quarks and anti-quarks in the QGP phase or kaons in the hadronic phase. The coupled equations describing the evolution of i (particle) and j (anti particle) with proper time τ is given by:

$$\frac{dn_i}{d\tau} = R_i(\mu_B,T)[1-\frac{n_in_j}{n_i^{eq}n_j^{eq}}]-\frac{n_i}{\tau}$$
$$\frac{dn_j}{d\tau} = R_j(\mu_B,T)[1-\frac{n_jn_i}{n_j^{eq}n_i^{eq}}]-\frac{n_j}{\tau}. \quad (1)$$

where, n_i (n_j) and ${n_i}^{eq}$ (${n_j}^{eq}$) are the non-equilibrium and equilibrium densities of i (j) type of particles respectively. R_i is the rate of production of particle i at temperature T and chemical potential μ_B, τ is the proper time. First term on the right hand side of Eq. 1 is the production term and the second term represents the dilution of the system due to expansion. The variation of temperature and the baryonic chemical potential with time is governed by the hydrodynamic equations. The indices i and j of Eq.1 are replaced by $s,\bar{s}$ quark in the QGP phase and by K^+,K^- in the hadron phase respectively. For higher colliding energies i.e., $\sqrt{s}\geq 8.76$ GeV an initial partonic phase is assumed. The hadrons are

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formed at a transition temperature, $T_c = 190$ MeV through a first order phase transition from QGP to hadrons. The fraction of the QGP phase in the mixed phase at a proper time τ is given by [3]:

$$f_Q(\tau) = \frac{1}{r-1}(r\frac{\tau_H}{\tau} - 1) \quad (2)$$

where τ_Q (τ_H) is the time at which the QGP (mixed) phase ends, r is the ratio of statistical degeneracy in QGP to hadronic phase. The evolution of the kaons are governed by [3]:

$$\frac{dn_{K^+}}{d\tau} = R_{K^+}(\mu_B, T_c)[1 - \frac{n_{K^+}n_{K^-}}{n^{eq}_{K^+}n^{eq}_{K^-}}] - \frac{n_{K^+}}{\tau} + \frac{1}{f_H}\frac{df_H}{d\tau}(\delta n_{\bar{s}} - n_{K^+})$$
$$\frac{dn_{K^-}}{d\tau} = R_{K^-}(\mu_B, T_c)[1 - \frac{n_{K^+}n_{K^-}}{n^{eq}_{K^+}n^{eq}_{K^-}}] - \frac{n_{K^-}}{\tau} + \frac{1}{f_H}\frac{df_H}{d\tau}(\delta n_s - n_{K^-}) \quad (3)$$

Similar equation exist for the evolution of s and $\bar{s}$ quarks in the mixed phase (see [3] for details). In the above equations $f_H(\tau) = 1 - f_Q(\tau)$ represents the fraction of hadrons in the mixed phase at time τ. The last term stands for the hadronization of $\bar{s}(s)$ quarks to $K^+(K^-)$ [3]. Here δ is a parameter which indicates the fraction of $\bar{s}(s)$ quarks hadronizing to $K^+(K^-)$. $\delta = 0.5$ indicates the formation of K^+ and K^0 in the mixed phase because half of the $\bar{s}$ form K^+ and rest hadronize to K^0.

The kaon productions have been calculated for different centre of mass energies ($\sqrt{s_{\rm NN}}$) ranging from AGS to RHIC. The ratio K^+/π^+ is displayed in fig. 1. We obtain a non-monotonic horn like structure for K^+/π^+ when plotted with $\sqrt{s_{\rm NN}}$ with the assumption of an initial partonic phase beyond a certain threshold in $\sqrt{s_{NN}}$. However, a monotonic rise of K^+/π^+ is observed when a hadronic initial state is assumed for all $\sqrt{s_{\rm NN}}$. Experimental values of K^-/π^- are also reproduced within the ambit of the same formalism. Results from scenarios where the strange quarks and hadrons are formed in equilibrium and evolves with and without secondary productions have also been presented. In similar formalism the production of Λ hyperons have also been calculated. For the production in the hadronic scenario different hadronic interactions such as $\pi N \to \Lambda K$, $\rho N \to \Lambda K$, $NN \to N\Lambda K$, $N\Delta \to N\Lambda K$ and $\Delta\Delta \to N\Lambda K$ have been considered.

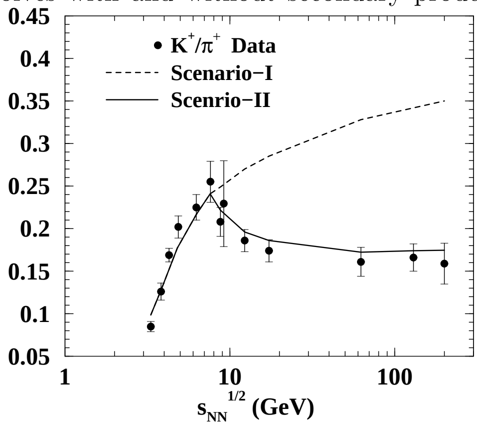

FIG. 1: Kaon to entropy ratio as a function of centre of mass energy. Scenario-I: when a hadronic initial state is assumed for all center of mass energies. Scenario-II: when an partonic initial state is assumed beyond $\sqrt{s_{NN}}$=7.6 GeV.

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