Kaon and Lambda productions in relativistic heavy ion collisions

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Abstract

A microscopic approach has been employed to study the kaon and Λ productions in heavy ion collisions. The productions of K^+ and Λ have been studied within the framework of Boltzmann transport equation for various beam energies. We find a non-monotonic horn like structure for K^+/π^+ and Λ/π when plotted against centre of mass energies ($\sqrt{s}_{\rm NN}$) with the assumption of initial partonic phase for $\sqrt{s}_{\rm NN}$ beyond a certain threshold. However, the ratio K^+/π^+ shows a monotonic nature when a hadronic initial state is considered for all $\sqrt{s}_{\rm NN}$. Experimental values of K^-/π^- for different $\sqrt{s_{\rm NN}}$ are also reproduced within the ambit of the same formalism.

Key words: Heavy ion collision, quark gluon plasma, strangeness productions.
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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 particularly the kaon and Λ productions and estimate the ratio, $R^+(\equiv K^+/\pi^+)$, $R^-(\equiv K^-/\pi^-)$ and $R^\Lambda(\equiv \Lambda/\pi)$ for various collision energies. The ratios are measured experimentally [1] as a function of centre of mass energy ($\sqrt{s}_{NN}$) and observed that the R^+ and R^Λ increase with $\sqrt{s}_{NN}$ and then decrease beyond a certain value of $\sqrt{s}_{NN}$ giving rise to a horn like structure, whereas the ratio, R^- increases monotonically, faster at lower $\sqrt{s}_{NN}$ and tend to saturate at higher $\sqrt{s}_{NN}$. Various models [2] have been proposed in the literature to explain the data. In this work the kaon and Λ productions have been calculated for various $\sqrt{s}_{NN}$, ranging from 3.32 to 200 GeV and examine whether the K^+/π^+ experimental data can differentiate the following scenarios of the system that is assumed to be formed after collision. The system is 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

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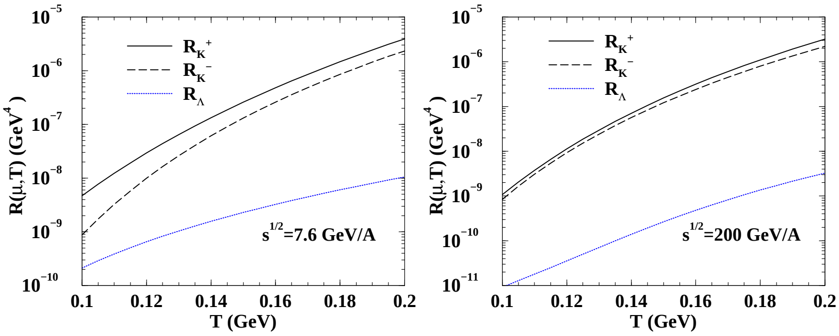

Fig. 1. Rate of production of K^+, K^- and Λ for $\sqrt{s_{\rm NN}}$=7.6 (left) and 200 GeV (right).

like formation of the system with strangeness in complete thermal equilibrium and the evolution in space time (III) without and (IV) with secondary productions of quarks and hadrons have been considered. (V) Results for an extreme case of zero strangeness in the initial state is also discussed.

We consider the processes of gluon-gluon fusion and light quarks annihilation for the strangeness production (s,$\bar{s}$) in the partonic phase. For the strangeness production (K^+, K^- and Λ) in hadronic phase an exhaustive set of reactions involving thermal baryons and mesons have been considered [3,4]. 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 the system. In scenario-I & II 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 and the non-strange quarks and hadrons are in complete thermal equilibrium. Therefore, the evolution of the strange sector of the system is governed by the interactions between the equilibrium and non-equilibrium degrees of freedom. In such cases the time evolution of the densities of the strange quarks and hadrons can be evaluated by the momentum integrated Boltzmann equation which reads,

$$\frac{dn_{i,j}}{d\tau}=R_{i,j}(\mu_B,T)\left[1-\frac{n_in_j}{n_i^{eq}n_j^{eq}}\right]-\frac{n_{i,j}}{\tau}. \qquad (1)$$

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 net production term and the second term represents the dilution of the system due to expansion. The indices i and j in Eq.1 are replaced by $s,\bar{s}$ quark in the QGP phase and by K^+,K^- in the hadron phase respectively. For $\sqrt{s_{NN}}\leq$ 7.6 GeV an initial hadronic states and for $\sqrt{s_{NN}}>$ 7.6 GeV an initial partonic phase is assumed (scenarios-II,III,IV and V). In these scenarios the hadrons are assumed to be formed at a transition temperature, $T_c=190$ MeV through a first order phase transition. In case of a first order transition the evolution of kaons in the mixed phases is given by;

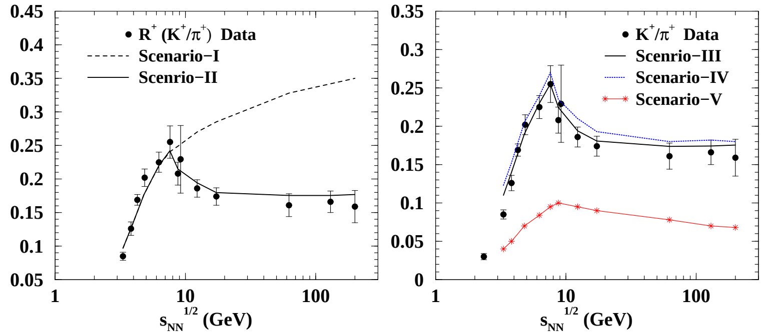

Fig. 2. The variation of R^+ with $\sqrt{s}_{\rm NN}$ for different scenarios (see text).

$$\frac{dn_{K^\pm}}{d\tau}=R_{K^\pm}(\mu_B,T_c)[1-\frac{n_{K^\pm}n_{K^\mp}}{n^{eq}_{K^\pm}n^{eq}_{K^\mp}}]-\frac{n_{K^\pm}}{\tau}+\frac{1}{f_H}\frac{df_H}{d\tau}\left(\delta n_{\bar{s}(s)}-n_{K^\pm}\right) \qquad (2)$$

The last term in the Eq. 2 is the hadronisation term and $f_H(\tau)=1-f_Q(\tau)$ represents the fraction of hadrons in the mixed phase at time τ. $f_Q(\tau)=(1/(r-1))(r\tau_H/\tau-1)$, is the fraction of the QGP phase. τ_Q (τ_H) is the time at which the QGP (mixed) phase ends, r is the ratio of the statistical degeneracies in QGP to hadronic phase. Similar equations exist for the evolution of s and $\bar{s}$ quarks in the mixed phase [5]. The δ in Eq. 2is a parameter which indicates the fraction of $\bar{s}(s)$ quarks hadronizing to $K^+(K^-)$. In the same approach the Λ productions have also been calculated for all the $\sqrt{s}_{NN}$. The rates of production for K^+, K^- and Λ for $\sqrt{s}_{NN}$=7.6 and 200 GeV are displayed in Fig. 1 (for the strange quark productions we refer to [6]). The rate of productions of K^+ and K^- are similar at large $\sqrt{s_{\rm NN}}$ (low μ_B) although at smaller $\sqrt{s_{\rm NN}}$ (high μ_B) K^- production is smaller because of the larger K^--nucleon absorption cross section at non-zero baryon density. The Λ yield is much smaller because of smaller production cross section. The baryonic chemical potential at freeze-out are taken from the parametrization of μ_B with $\sqrt{s_{\rm NN}}$ (see the table in [6] and the references there in) and its value at the initial state is obtained from the net baryon number conservation equation. The variation of temperature and net baryon density has been obtained from the solution of boost invariant relativistic hydrodynamics [7].

Results on K^+/π^+ for scenarios-I and II are displayed in Fig. 2 (left panel). In scenario-I a monotonic rise of R^+ for all $\sqrt{s_{\rm NN}}$ is observed. Whereas in scenario-II a non-monotonic horn like structure for R^+ is observed which describes the experimental data reasonably well. Now we consider the scenarios III, IV and V (Fig. 2, right). On one hand when the strangeness evolve from the initial state till the freeze-out stage in complete thermal equilibrium and the secondary productions of strange quarks and hadrons are off (III) the data is reproduced well. On the other hand the same equilibrium scenario overestimates the data slightly at high $\sqrt{s}_{NN}$ if the secondary production is switched on (IV). This indicates that the deficiency of strangeness below its equilibrium value as considered in (II) is compensated by the secondary productions. In scenario V we assume that vanishing initial strangeness and observed that the production of strangeness throughout the evolution is not

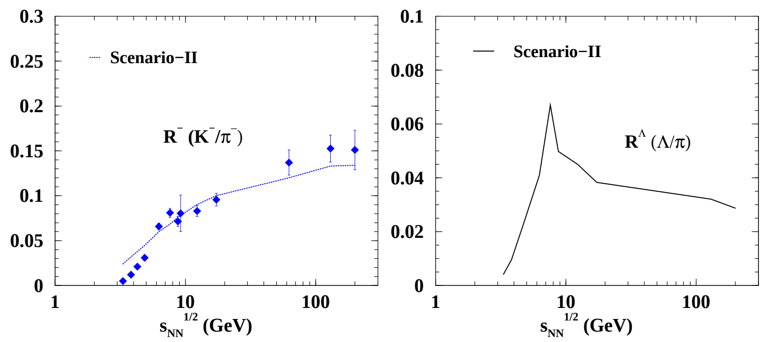

Fig. 3. Variation of R^- (left) and R^Λ (right) for scenario-II.

sufficient to reproduce the data. In Fig. 3 the R^- has been displayed as a function of $\sqrt{s}_{\rm NN}$ in the left panel of the curve for scenario-II. In the right panel the R^Λ is shown for the same scenario of initial condition. Theoretically a horn like structure is obtained for Λ which resembles the experimental data [8].

In summary, we have studied the kaon and Λ production in heavy ion collisions for various collision energies. The analysis of the experimental data indicates the formation of a partonic state for $\sqrt{s_{\rm NN}}$ beyond 7.6 GeV.

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