Strangeness suppression and non-equilibrium effects in heavy-ion collisions

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Introduction

Strangeness production in heavy-ion collisions is a crucial phenomenon for understanding the properties of Quark Gluon Plasma (QGP) and the dynamics of strongly interacting matter. It refers to the production of strange quarks (s) during the early stages of A+A collisions in perturbative $2 \rightarrow 2$ partonic scattering processes by flavour creation and flavour excitation. The main processes which produce strangeness are flavour formation ($gg \rightarrow s\bar{s}$, $q\bar{q} \rightarrow s\bar{s}$) and quark-antiquark interactions ($gs \rightarrow gs$, $qs \rightarrow qs$). In the early stages of A+A collisions, such as Au+Au or Pb+Pb nuclei, the system is dominated by partonic interactions rather than hadronic interactions. The energy density (ϵ) is extremely high in this phase, which can lead to the formation of QGP. Strangeness in this phase is suppressed as quarks and gluons are not bound into hadrons, thus limiting the availability of strange quarks and the conditions needed for their formation into strange hadrons. The high energy densities and temperatures in these collisions create an environment conducive to the formation of strange quark-antiquark pair ($s\bar{s}$) [1]. However, we have found an increased production of strange quarks and hence strange hadrons theoretically compared to what is seen in p+p, p+A, or A+A collisions at the experiments like Relativistic Heavy Ion Collider (RHIC) and Large Hadron Collider (LHC). This enhancement is considered a signal of the formation of QGP, a state of matter where quarks and gluons are no longer confined within hadrons.

Therefore in this work, by taking the above effect into consideration, we analyzed the strange particle yields and their ratios which are important observables for understanding the origin, composition and production dynamics in heavy-ion collisions. In low center-of-mass collision energy ($\sqrt{s_{NN}}$) range, strange particles are rarely produced and can generally be neglected when evaluating the overall thermodynamic properties of the collision fireball. However in the high energy regime, production of strangeness content increases with the increase in temperature, overpredicting the entire RHIC to LHC energy spectrum in statistical thermal models. Thus modifying this deviation of strange particles from the chemical equilibrium by factor called as the strangeness suppression factor γ_s. This factor, γ_s modifies the strange and anti-strange hadron multiplicities, parameterizing any deviation from the chemical equilibrium by the equation $n_s^{mod} = \gamma_s n_s$, where n_s^{mod} is the modified number density of strange hadrons. The effect of γ_s is predominantly seen in all strange to non-strange ratios like K^-/π^-, K^+/π^+, Λ/π, Λ/p etc where we analyze these ratios with the center-of-mass collision energy $\sqrt{s_{NN}}$.

Theoretical Framework

The expression for the partition function of the i^{th} particle specie in the grand canonical ensemble can be written as [2, 3]

$$ln\mathcal{Z}_i^{id}(T,\mu,V) = \pm\frac{Vg_i}{2\pi^2}\int_0^\infty p^2dp\; ln\{1 \pm e^{-(E_i-\mu_i)/T}\} \quad (1)$$

where id refers to ideal i.e., non-interacting HRG model, V and T, g_i, $E = \sqrt{p^2+m^2}$ and m are the volume and temperature of the system, degeneracy, energy and mass of a particle respectively. Also $\mu_i = B_i\mu_B + S_i\mu_S + Q_i\mu_Q$ is the chemical potential where symbols have relevant meaning. In the above mentioned chemical potential B_i, S_i, Q_i are respectively the baryon number, strangeness and electric charge of the particle and $\mu_i' s$ are the corresponding chemical potentials. The ideal pres-

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sure p^{id} and number density n^{id} of thermal system are given as

$$p_i^{id}(T,\mu_i) = \pm\frac{Tg_i}{2\pi^2}\int_0^\infty p^2dp\ ln\{1\pm e^{-(E_i-\mu_i)/T}\}$$
$$n_i^{id}(T,\mu_i) = \frac{g_i}{2\pi^2}\int_0^\infty \frac{p^2dp}{1\pm e^{-(E_i-\mu_i)/T}} \quad (2)$$

The vdW equation of state is given as [4]

$$p(T,n) = \frac{TN}{V-bN} - \frac{aN^2}{V^2} = \frac{nT}{1-bn} - an^2 \quad (3)$$

where N is the number of particles, and a, b are vdW parameters, which are both positive. The value of $a = 329\,MeV\,fm^3$ and $n = N/V$ is the number density of the particles and $b = \frac{16}{3}\pi r^3$ is the proper volume of the particles, with r=0.59 fm being the corresponding radius [4].

The vdW equation of state in the grand canonical ensemble can be write as

$$p(T,\mu) = p^{id}(T,\mu^*)\ -\ an^2$$
$$\mu^* = \mu\ -\ bp(T,\mu) -\ abn^2 + 2an \quad (4)$$

where $n = n(T,\mu)$ is the particle number density of the vdW gas in Eq.(4) which is given as

$$n(T,\mu) = \frac{n^{id}(T,\mu^*)}{1+bn^{id}(T,\mu^*)} \quad (5)$$

Results and Discussions

We have numerically solved the aforementioned equations and obtained number density of various strange as well as non-strange hadronic species. While calculating the ratio of various strange to non-strange hadrons, we find that the theoretical value below $\sqrt{s_{NN}} \sim$ 10 GeV subceeds the experimental value then exceeds tremendously. This value then attains saturation after a fixed $\sqrt{s_{NN}}$. Considering this effect, we inserted an strangeness suppression factor "γ_s" to the hadrons containing strangeness (i.e., strange quarks). We find that there is a deviation in the strange particle production from the chemical equilibrium i.e., it is produced excessively compared to experiments. The γ_s lowers the excessive strangeness content of the system. Hence we find that the factor $\gamma_s < 1$, is more suppressed towards higher $\sqrt{s_{NN}}$. The values of T and μ_B have been extracted for $\sqrt{s_{NN}}$ as mentioned in [3].

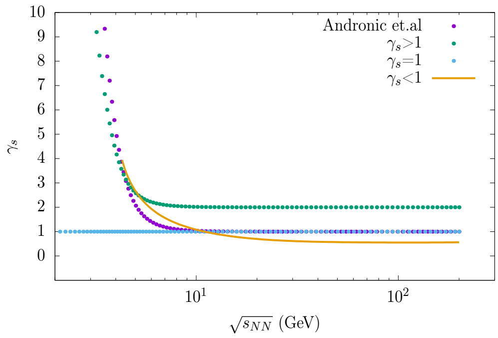

FIG. 1: γ_s dependence on $\sqrt{s_{NN}}$

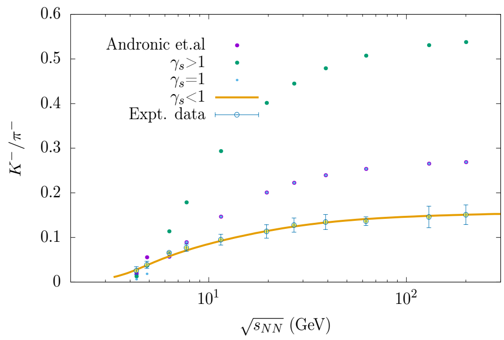

FIG. 2: K^-/π^- dependence on $\sqrt{s_{NN}}$

In Fig. 1 we show the trend γ_s follows with increasing $\sqrt{s_{NN}}$ for different cases and calculated the K^-/π^- ratio for these different cases and found that the experimental data is explained quite well for the case of $\gamma_s < 1$ as shown in Fig. 2.

References

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