Kaons and Antikaons in Multi-Phase Transport Model

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Abstract. We investigate the impact of medium modifications of kaons and antikaons on their rapidity distribution and production ratio using A Multi-Phase transport (AMPT) model. The medium modified masses of kaons and antikaons, which are used as input in AMPT model, are calculated using the chiral SU(3) mean field model. Usually in chiral SU(3) models along with the Weinberg Tomozawa term, the contribution of explicit symmetry breaking term and three range terms are considered to evaluate in-medium masses of kaons and antikaons. In the present work, we have considered Weinberg Tomozawa term and two range terms to study their impact on the above listed experimental observables. The repulsive contribution to the mass of $K^+$ meson from the Weinberg term dominates over the attractive contribution from two range terms. For the $K^-$ meson Weinberg term as well as two range terms give attractive contribution. Considering all these features from chiral effective model on properties of $K^+$ and $K^-$ mesons, we explore the rapidity distributions of kaons and antikaons.

1. Introduction
Heavy ion collisions lead to the formation of large regions of deconfined quarks and gluons, which serves as an important probe to study the underlying fundamental theory of strong interactions, the Quantum Chromodynamics (QCD). Various transport models are used to study the experimental observables in heavy-ion collisions. To study experimental properties of kaons and antikaons in presence of mean field potential, we have used AMPT (A Multi-Phase Transport Model) for heavy-ion collisions [1]. AMPT consists of four important elements, the initial phase (includes excited strings, minijet partons and spectator nucleons), partonic interactions (stops at parton freezing), the transformation of partons to the hadrons, and interaction of hadrons. Initially, the particle production in HIJING model is described in terms of a hard and soft component. The hard processes include the formation of energetic minijets which are treated via PYTHIA program while soft component are sculpted by formation of strings. The partonic interactions are defined by Boltzmann equations, which are formulated using Zhangs parton cascade (ZPC) [2]. The formation of hadrons in AMPT is described by two mechanisms: Lund string fragmentation and quark coalescence. String melting version of AMPT converts excited strings (which are not projectile) and target nucleons without any interactions to partons whereas, the default version uses only minijets from HIJING model, which are combined with their parent strings to form excited strings, that are further converted into hadrons by Lund String fragmentation. Hadronization in string melting version is modeled by quark coalescence, where two nearest partons combine to form a meson and three nearest quarks (antiquarks).
form baryons (antibaryons). Hadronic interactions are defined by ART model, which includes baryon-meson, baryon-baryon, and meson-meson inelastic and elastic scatterings [3]. The $K^*$ resonances are implicitly included by elastic $\pi K$ scattering with the standard Breit-Wigner form for the cross section, which enhances the elastic scattering between pions and kaons. In present study, we have used the string melting version to analyze Au-Au collisions with value $2.28 \text{ fm}^{-1}$ of parton screening mass, strong coupling constant $\alpha_s=0.47$ at center of mass energies $\sqrt{s_{\text{NN}}}=7.7$ and 19.6 GeV. We have compared the rapidity distributions of $K^+$ and $K^-$ with and without the optical mean field effect, incorporated using chiral SU(3) model. Using the dispersion relation from the model, we calculate the energy of kaons and antikaons after the introduction of effective mean field.

2. The Chiral SU(3) Model

The Lagrangian of the Chiral model is given as [4]

$$\mathcal{L}_{\text{chiral}} = \mathcal{L}_{\text{kin}} + \sum_{M=SV} \mathcal{L}_M + \mathcal{L}_{\text{vec}} + \mathcal{L}_0 + \mathcal{L}_{SB}. \quad (1)$$

As elucidation of model, $\mathcal{L}_{\text{kin}}$ corresponds to the kinetic energy terms of the baryons and the mesons, $\mathcal{L}_B$ describes the baryon-meson interaction and $S$ and $V$ are scalar and vector densities, $\mathcal{L}_{\text{vec}}$ explains the self-interactions of the vector fields and also the mass generation of the vector mesons by coupling to the scalar fields, $\mathcal{L}_0$ contains the meson-meson interaction, $\mathcal{L}_{SB}$ describes the explicit chiral symmetry breaking [5] and is based on broken scale invariance [6] and trace anomaly. The broken scale invariance is being conserved by introduction of scalar dialton field $\chi$. The mean field approximations are used in the model to neglect the effect of fluctuations near phase transitions. The self-energy of kaons and antikaons is modified by scalar and vector densities of baryons which are modified due to scalar and vector fields. We have obtained the dispersion relation by doing the Fourier transformation of interaction Lagrangian of $K^+$ and $K^-$ as

$$-\omega^2 + \vec{k}^2 + m_{K(\bar{K})}^2 - \Pi^*(\omega, |\vec{k}|) = 0, \quad (2)$$

where $\Pi^*$ symbolize the in-medium self-energy of kaons [7] and is given by

$$\Pi_{K}^*(\omega, |\vec{k}|) = -\frac{1}{4f_{K}^2} [3(\rho^v_p + \rho^v_n \pm (\rho^v_p - \rho^v_n))\omega + \left( \frac{d_1}{2f_{K}^2}((\rho^v_p + \rho^v_s) \pm (\rho^v_p - \rho^v_s)) \right) + \frac{d_2}{4f_{K}^2}((\rho^v_p + \rho^v_n) \pm (\rho^v_p - \rho^v_n))](\omega^2 - \vec{k}^2). \quad (3)$$

In above equation, the $\pm$ sign gives the self energy for $K^+$ and $K^0$ respectively, and for antikaons it is given by

$$\Pi_{K}^*(\omega, |\vec{k}|) = \frac{1}{4f_{K}^2} [3(\rho^v_p + \rho^v_n \pm (\rho^v_p - \rho^v_n))\omega + \left( \frac{d_1}{2f_{K}^2}((\rho^v_p + \rho^v_s) \pm (\rho^v_p - \rho^v_s)) \right) + \frac{d_2}{4f_{K}^2}((\rho^v_p + \rho^v_n) \pm (\rho^v_p - \rho^v_n))](\omega^2 - \vec{k}^2), \quad (4)$$

where the $\pm$ sign gives the self energy for $K^-$ and $K^0$ respectively. The first term in the expression of self-energy is the Weinberg-Tomozawa term (vectorial interaction term), which arises from kinetic part of interaction Lagrangian. The second and third term are termed as range terms and are obtained from baryon meson interaction Lagrangian of chiral model [8]. The model successfully explains the nuclear matter, hyper nuclei, finite nuclei, and neutron stars.
3. Results and Discussion

In this section, we discuss the numerical observation of medium modification of kaons and antikaons rapidity distributions and production ratio. In figure 1, we have shown the rapidity spectra of $K^+$ and $K^-$ mesons for center of mass energies $\sqrt{s_{nn}} = 7.7$ and 19.6 GeV. Figure 2 depicts the production ratio of $K^+/K^-$ as a function of rapidity for these center of mass energies. For medium modification of $K^+$ and $K^-$, we consider symmetric nuclear matter at zero temperature with approximation $\rho_p^v = \rho_p^s$ and $\rho_n^v = \rho_n^s$. The values of $m_K = 494$ MeV, $f_K = 122.14$ MeV, $d_1 = 2.56/m_K$ and $d_2 = 0.73/m_K$ are considered. The values of $d_1$ and $d_2$ are fitted to the low energy kaon-nucleon ($KN$) scattering length. The different terms of dispersion relation explains the baryonic interaction of kaons and antikaons. The Weinberg-Tomozawa term has an attractive contribution for antikaons and repulsive for the kaons [9]. Both range terms have an attractive contribution for kaons and antikaons. The insertion of $d_1$ and $d_2$ term modifies the self energy of kaons and antikaons in a way that leads to more notable decrease in production ratio. Thus due to this contribution of range terms, the kaons potential becomes less repulsive and more attractive for antikaons. Due to this modifications of mass in presence of mean field, the rapidity distributions show different trends. As a consequence of stronger attractive antikaon potential as compared to kaons, the effect of mean field is more considerable on transverse flow of antikaons [10]. The stronger mean field potential of antikaons makes $K^-$ less energetic and leads to a narrower rapidity distribution as compared to case without potential at central rapidity regions. It is quite evident from figure 1 that production of $K^+$ and $K^-$ decreases at projectile and target rapidities, but increases at mid-rapidity region due to insertion of potential of kaons and antikaons. In the absence of effective mean field potential, antikaons flow in the direction opposite to nucleons and get absorbed due to strong strange-exchange interactions, whereas the inclusion of mean field potential causes the flow of antikaons in direction of nucleons [10]. As shown in figure 2, we observe a decrease in production ratio of $K^+/K^-$ at mid rapidity regions. It has been observed that there is comparatively a lesser drop in the production ratio as we increase center of mass energy. This can be clearly seen from that difference in production ratio of $K^+/K^-$ with mean field becomes less significant as center of mass energy increases from 7.7 to 19.6 GeV.

4. Conclusion

To summarize, we observe that production ratio of kaons and antikaons shows a substantial drop in the mid-rapidity region due to the introduction of mean field potential. As the center of
Figure 2. The production ratio of $K^+/K^-$ is plotted as a function of rapidity at center of mass energy $\sqrt{s_{\text{nn}}} = 7.7$ (a) and 19.6 GeV (b) for semi-central ($b \leq 4$ fm).

mass energy increases, the effect of mean field is less visible in the rapidity distributions. In the future work, we plan to incorporate the full chiral model including hyperons and scalar and vector fields to study the elliptical flow splitting of kaons, pions and nucleons in presence of mean field potential.

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