Kaons and antikaons in finite volume hadronic matter

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Introduction

The finite-size effects on the QCD phase diagram have received great attention. This is because when heavy-ion collisions happen between nuclei with different numbers of protons and neutrons, a superhot state of matter called a quark-gluon plasma (QGP) might form. As this QGP cools down, it becomes a more familiar state of matter made up of particles called hadrons. The size of the QGP fireball is finite and influenced by factors such as the centrality of the collision, the size of the colliding nuclei, and the collision energy. Numerous studies have investigated the critical point and the thermodynamics of strongly interacting matter, with a particular emphasis on how the size of the QCD matter influences these properties. It has been demonstrated that considering the finite size of the medium significantly affects both the location of the critical point and the behavior of various thermodynamic quantities. In this study, we will use a chiral SU(3) hadronic mean-field model to explore the behavior of kaons and antikaons within a finite-volume strange hadronic environment.

Methodology

The chiral SU(3) hadronic mean-field model is used in the present work to study finite volume effects. The effective Lagrangian of the model is given as [1]

$$\mathcal{L}_{\text{chiral}} = \mathcal{L}_{\text{kin}} + \sum_{M=S,V,A,Y} \mathcal{L}_{\text{BM}} + \mathcal{L}_{\text{vec}} + \mathcal{L}_0 + \mathcal{L}_{\text{SB}}. \quad (1)$$

The first term of the above equation is the kinetic energy term for baryons and mesons, the second term represents the interactions of baryons with scalar and vector mesons, the third term gives the self-interactions of vector mesons, the fourth and fifth terms define the spontaneous chiral symmetry breaking and the explicit chiral symmetry breaking, respectively. The above Lagrangian is utilized to derive the thermodynamic potential density of the model. By minimizing the thermodynamic potential with respect to the vector and scalar fields, we get the equations of motion. The scalar and vector densities of the i_{th} baryon is thus defined as [1]

$$\rho_i^s = \gamma_i \int \frac{d^3k}{(2\pi)^3} \frac{m_i^*}{E_i^*(\mathbf{k})} \left(n_i(\beta) + \bar{n}_i(\beta)\right), \quad (2)$$

and

$$\rho_i^v = \gamma_i \int \frac{d^3k}{(2\pi)^3} \left(n_i(\beta) - \bar{n}_i(\beta)\right), \quad (3)$$

where $n_i(\beta)$ and $\bar{n}_i(\beta)$ are the finite temperature distribution functions of baryons and antibaryons, respectively. The spin degeneracy factor is represented by γ_i and $\beta = \frac{1}{kT}$. The dispersion relations for kaons and antikaons can be derived by applying a Fourier transform to the equations of motion obtained from the kaons-baryons (KB) interaction Lagrangian and expressed as [2]

$$-\omega^2 + \vec{k}^2 + m_{K(\bar{K})}^2 - \Pi^*(\omega, \vec{k}) = 0. \quad (4)$$

In the above equation, Π^* denotes the in-medium self-energy of kaons and antikaons. We obtain the medium-modified masses of kaons and antikaons by solving the dispersion relation for $|\vec{k}| = 0$. To study the impact of finite volume, a lower momentum cutoff, $k = \frac{\pi}{R}$ is introduced in Eqs. 2 and 3 [3].

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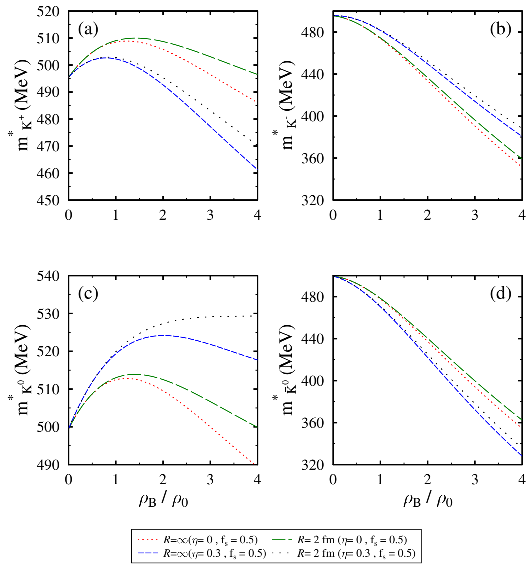

FIG. 1: The in-medium masses of kaons (K) and antikaons ($\bar{K}$) are plotted with respect to the baryon density ρ_B (in units of nuclear saturation density ρ_0), at temperatures, $T = 100$ MeV for varying values of strangeness fraction, f_s, isospin asymmetry parameter, η and system sizes, $R = \infty$ and 2 fm.

Results and Discussion

In this section, we discuss the medium modification of kaons (K^+, K^0) and antikaons $(K^-, \bar{K}^0)$ masses in the strange hadronic matter with finite volume. The in-medium masses of K and $\bar{K}$ mesons are calculated using the medium-modified values of vector and scalar densities of baryons as well as the scalar fields σ, ζ and δ, in the expressions of self energies. Fig. 1 shows the medium modified masses of K^+, K^0, K^- and $\bar{K}^0$ mesons with respect to the baryonic density ρ_B (in units of nuclear saturation density ρ_0), for the temperature $T = 100$ MeV, for the system size $R = \infty$ and 2 fm. In the chiral SU(3) hadronic mean field model, the medium modification of kaons and antikaons arises from several contributions: the Weinberg-Tomozawa term, the explicit symmetry-breaking term, and three range terms. The first range term comes from the kinetic term of pseudoscalar mesons, while the other two range terms come from the d_1 and d_2 terms, respectively. The different terms give either attractive or repulsive contributions to effective masses of kaons and antikaons. In a strange and asymmetric strange medium, for both large and small values of the radius ($R = \infty$ and 2 fm), the masses of kaons, K^+ and K^0, increase with baryon density (ρ_B) up to the baryonic density ρ_0, and then decrease beyond ρ_0. This indicates that both kaons in the K-isospin doublet experience repulsive interactions up to ρ_0 and attractive interactions beyond ρ_0. In contrast, for the antikaon doublet ($\bar{K}$), the masses of K^- and $\bar{K}^0$ decrease as the density of the medium increases. At a constant density of strange matter, increasing the isospin asymmetry parameter (η) from zero to a finite value results in a mass splitting between the members of each isospin doublet of kaons and antikaons as can be seen in Fig.(1). This trend is similar to the ref [4] where the volume effect has been studied using the MRE expansion method and the masses of kaon and antikaon are observed to increase with a decrease in the volume of the system.

In summary, as the medium is compressed into a finite volume, the decrease in the masses of kaons and antikaons is less pronounced than in an infinite volume. This indicates that finite volume plays a significant role in accurately modeling the theoretical aspects of heavy ion collisions and provides a more realistic representation of particle behavior under practical conditions.

References

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