Mass and decay width of ϕ meson in hadronic medium with finite volume effect

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Introduction

The in-medium properties of hadrons at finite temperature and density are crucial for understanding the strong interaction physics of the QCD phase diagram. In particular, light vector mesons, such as the ϕ meson, play a significant role in dilepton production in heavy-ion collisions (HICs) [1], offering a valuable probe of the hadronic medium due to their weak interaction with other particles. Despite being composed primarily of strange quarks, ϕ mesons interact strongly with nuclei and strange baryons, making them an interesting subject of study. Investigations into the finite-size effects on the QCD phase diagram, especially in the context of heavy-ion collisions, have shown that the finite volume of the quark-gluon plasma (QGP) influences the location of the critical point and alters thermodynamic properties. However, the effects of finite size on the physical properties of hot and dense hadronic fireballs have not been extensively explored. The transport coefficients of hadronic matter have been studied within the Hadron Resonance Gas (HRG) model, incorporating a lower momentum cut-off [2]. This work examines the mass and decay width of the ϕ meson in a finite volume to better understand its behavior in such environments.

Methodology

The in-medium mass and decay width of ϕ meson have been derived by using the chiral SU(3) hadronic model. The total thermodynamic potential density of the model is given by [3]

$$\frac{\Omega}{V} = -\frac{T\gamma_i}{(2\pi)^3}\sum_i \int d^3k \left\{ \ln\left(e^{-\beta[E_i^*(\mathbf{k})-\mu_i^*]}+1\right) + \ln\left(e^{-\beta[E_i^*(\mathbf{k})+\mu_i^*]}+1\right)\right\} - \mathcal{L}_{\text{vec}} - \mathcal{L}_0 - \mathcal{L}_{\text{SB}} - \mathcal{V}_{vac}. \tag{1}$$

The first term represents the baryon-meson interactions, the second term accounts for vector meson self-interactions, the third and fourth terms correspond to spontaneous and explicit chiral symmetry breaking, respectively, and the last term is the vacuum potential term. The spin degeneracy factor is represented by γ_i and factor, $\beta = \frac{1}{kT}$. The equations of motion for scalar and vector fields are derived by minimizing the above-defined thermodynamic potential. For incorporating the finite volume contributions, a lower momentum cutoff, $k = \frac{\pi}{R}$ is introduced in the scalar and vector densities. The in-medium masses and decay width of ϕ mesons are calculated using the effective kaon and antikaon masses in a finite-volume hadronic medium, which are obtained from the dispersion relation given as

$$-\omega^2 + \vec{k}^2 + m^2_{K(\bar{K})} - \Pi^*(\omega,\vec{k}) = 0. \tag{2}$$

The ϕ meson self-energy is obtained via the decay process $\phi \to K\bar{K}$ at one-loop, with the interaction Lagrangian given by [4]

$$\mathcal{L}_{\text{int}} = ig_\phi \phi^\mu \left[\bar{K}\left(\partial_\mu K\right) - \left(\partial_\mu \bar{K}\right)K\right],$$

where, g_ϕ is the coupling constant. Thus the scalar component of the self-energy can be expressed as

$$i\Pi^*_\phi(p) = -\frac{8}{3}g_\phi^2 \int \frac{d^4q}{(2\pi)^4}\vec{q}^2 D_K(q) D_{\bar{K}}(q-p), \tag{3}$$

where, $D_K(q)$ and $D_{\bar{K}}(q-p)$ are the propagators for kaons and antikaons, respectively,

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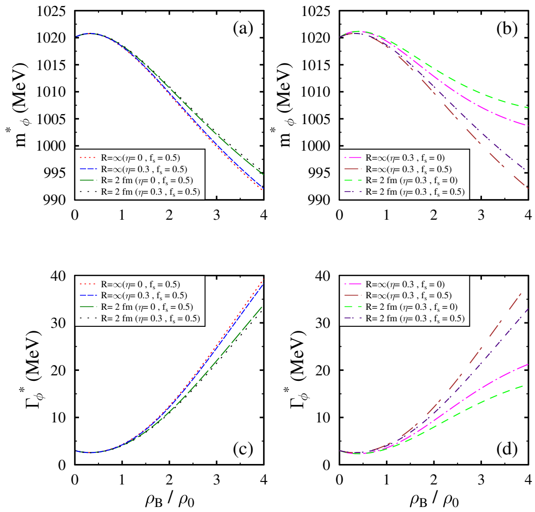

FIG. 1: The in-medium masses and decay width of ϕ mesons are plotted as a function of the baryon density ρ_B (in units of nuclear saturation density ρ_0), at temperatures, $T = 100$ MeV for varying values of strangeness fraction, f_s, isospin asymmetry parameter, η and system sizes, $R = \infty$ and 2 fm.

p denotes the four-momentum vector of the ϕ meson, with m^*_ϕ as the in-medium ϕ meson mass. The decay width of the ϕ meson is obtained by evaluating the imaginary part of its self-energy, $\mathrm{Im}\,\Pi^*_\phi$. This expression depends on the in-medium masses of the ϕ, K, and $\bar{K}$ mesons.

Results and Discussion

In this section, we have investigated the finite volume effects in the strange and asymmetric medium on the mass and decay width of the ϕ meson. The in-medium mass of the ϕ meson is determined by calculating its one-loop self-energy for the process $\phi \to K\bar{K}$. The effective mass of ϕ mesons in the finite volume strange hadronic matter is calculated using Eq. (3), which depends upon the real part of the self-energy of ϕ mesons. Fig. (1) illustrates how the effective mass and decay width of ϕ meson varies in the strange hadronic medium for infinite ($R = \infty$) and finite ($R = 2$ fm) volume. A cut-off parameter of $\Lambda_c = 3$ GeV is used to regularize the loop integral. In-medium mass and decay width of ϕ meson is dependent on the medium-modified masses of kaons and antikaons. The effective mass initially shows a slight increase, followed by a decrease as the baryon density increases, for both $R = \infty$ and 2 fm. In contrast, the decay width of the ϕ meson increases as the baryon density ρ_B increases in both infinite and finite hadronic media. This trend is similar to the ref [5] where the volume effect has been studied using the MRE expansion method and the mass is observed to increase and decay width of ϕ meson are observed to decrease with a decrease in the volume of the system.

When the medium is confined to a finite volume, the reduction in the masses of kaons and antikaons is less pronounced compared to an infinite volume scenario. As a result, the mass of the ϕ meson decreases less in a finite volume than it does in an infinite volume. However, at a given medium density, as the system size R decreases to a finite value, the decay width of the ϕ meson decreases due to the increase in the effective masses of the K and $\bar{K}$ mesons. This reduction in decay width occurs because the available phase space for the decay process $\phi \to K\bar{K}$ becomes smaller as the volume of the hadronic medium is reduced. In conclusion, the finite volume considerations have a significant impact on the decay width as well as the effective mass of the ϕ meson.

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