

ϕ -Meson in Nuclear Matter

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ϕ -meson mass in nuclear matter (m_ϕ^*) is investigated using an effective Lagrangian of ϕ interacting with octet baryons. m_ϕ^* decreases in nuclear matter due to the current conservation and effective nucleon/hyperon masses. Its implication to the p - A and A - A collisions are briefly discussed.

In recent years, the effective meson masses in hadronic matter at finite density (ρ) and temperature (T) acquire wide interests both theoretically and experimentally (see the recent reviews.¹⁾) In particular, the ϕ -meson, which is an $\bar{s}s$ resonance in $J^P = 1^-$ channel with a narrow width ($m_\phi = 1019.4$ MeV and $\Gamma_\phi = 4.4$ MeV), is a unique probe for partial restoration of chiral symmetry in hot/dense hadronic matter.²⁾⁻⁴⁾ Detection of ϕ through the decays $\phi \rightarrow K\bar{K}$, e^+e^- , $\mu^+\mu^-$ in nucleus-nucleus (A - A) and proton-nucleus (p - A) collisions could give experimental information on the spectral change of ϕ in matter: preliminary data on $\phi \rightarrow K^+K^-$ in A - A collisions at AGS-BNL has been recently reported,⁵⁾ and an experiment using p - A reactions is planned at KEK.⁶⁾

In this paper, we will report our recent study on the ϕ -meson mass in nuclear matter at zero T . Our starting point is an effective hadronic model composed of ϕ -meson, nucleon and hyperons. This is a generalization of the recent works by Shiomi and Hatsuda⁷⁾ and others⁸⁾⁻¹⁰⁾ who studied the effect of nucleon-loops to the properties of rho and omega mesons in nuclear matter.

Let us start with the vector coupling of ϕ with octet baryons ($B \equiv N, \Lambda^0, \Sigma^\pm, \Sigma^0$),

$$L_{\text{int}} = \sum_B g_{\phi B} \bar{B} \gamma_\mu B \phi^\mu, \quad (1)$$

where $g_{\phi B}$ is the ϕ -baryon coupling constant listed in Table I.

Some remarks are in order here: (i) ϕ - Λ and ϕ - Σ couplings do not break the OZI rule, since the quark lines at the vertices are connected. On the other hand, the ϕ - N coupling is OZI violating. (ii) Ξ is neglected, since its effect to the ϕ self-energy is doubly suppressed by the mass of Ξ and by the OZI violating nature of ϕ - Ξ coupling. (iii) If one relies on the quark counting rule,¹¹⁾ the ϕ -hyperon couplings are related to the ω -hyperon couplings as $g_{\phi\Lambda(\phi\Sigma)} = g_{\omega\Lambda(\omega\Sigma)} / \sqrt{2}$ with $g_{\omega\Lambda(\omega\Sigma)}$ being determined by the fit of the hypernuclear levels.¹²⁾ This is assumed in Table I. (iv) ϕ -nucleon coupling, which is OZI violating, is not known experimentally.

Table I. $g_{\sigma B}$, $g_{\omega B}$ and $g_{\phi B}$ denote σ - B scalar coupling, ω - B vector coupling and ϕ - B vector coupling, respectively. $g_{\sigma B}$ and $g_{\omega B}$ are taken from Ref. 12). The number with * should be considered an upper bound.

Baryons	$g_{\sigma B}$	$g_{\omega B}$	$g_{\phi B}$
N	8.7	10.6	4.2*
Λ	5.2	6.9	4.9
Σ	5.2	6.9	4.9

However, a study of the electromagnetic form-factors of the nucleon yields an upper bound of its strength.¹³⁾ Using the notation of Ref. 13), $g_{\phi N}/g_{\omega N} = (\sin\epsilon + \cos\epsilon \tan\eta_1)/(\cos\epsilon - \sin\epsilon \tan\eta_1) \approx \epsilon + \tan\eta_1 < 0.4$.

We will consider only the $N=Z$ non-strange nuclear matter in this paper. In this case, effects of the hyperons to the ϕ -meson self-energy arise only through hyperon-anti-hyperon loops. Effective masses of hyperons $M_{\Lambda, \Sigma}^*$ in nuclear matter give density dependence of the self-energy. Nucleon contribution to the self-energy has both $N-\bar{N}$ loop (polarization of the Dirac sea) and the scattering with nucleons in nuclear matter (polarization of the Fermi sea).^{8),10),7)} The one-loop self-energy from hyperon and nucleon contributions reads

$$\Pi_B^{\mu\nu}(\omega, \mathbf{q}; \rho) = -ig_{\phi B}^2 \int \frac{d^4 k}{(2\pi)^4} \text{Tr}[\gamma^\mu G(k+q)\gamma^\nu G(k)], \tag{2}$$

where the four momentum of ϕ is $q^\mu = (\omega, \mathbf{q})$, "Tr" is for the Dirac indices, and $G(k)$ denotes baryon propagator in nuclear matter which depends on the effective mass of the nucleon and hyperons M_B^* ($B=N, \Lambda, \Sigma$). (See Ref. 7) for the explicit form of $G(k)$.)

Although one can calculate the density dependence of M_B^* within the framework of quantum hadrodynamics (QHD),¹⁴⁾ we adopt the following forms to study correlations between M_B^* and m_ϕ^* in a qualitative manner:

$$g_{\sigma\Lambda(\sigma\Sigma)}/g_{\sigma N} = (M_{\Lambda(\Sigma)} - M_{\Lambda(\Sigma)}^*) / (M_N - M_N^*), \tag{3}$$

$$M_N^*/M_N \approx 1 - 0.15\rho/\rho_0, \tag{4}$$

where ρ_0 is the normal nuclear-matter density, and $g_{\sigma\Lambda(\sigma\Sigma)}$ and $g_{\sigma N}$ are given in Table I. Equation (3) is a universal relation in the relativistic mean field theory¹²⁾ and Eq. (4) is a standard parametrization for the effective nucleon mass at $\rho < 2\rho_0$.⁹⁾ In Fig. 1, effective masses of N, Λ and Σ parametrized by Eqs. (3) and (4) are shown as a function of baryon density.

The effective ϕ -meson mass m_ϕ^* at rest ($\omega \neq 0, \mathbf{q} = 0$) is obtained as a solution of the dispersion relation

$$\omega^2 - m_\phi^2 + \sum_B \tilde{\Pi}_B(\omega, \mathbf{0}; \rho) = 0, \tag{5}$$

where $\tilde{\Pi}_B(\omega, \mathbf{0}; \rho) \equiv -\tilde{\Pi}_B^{\mu\mu}(\omega, \mathbf{0}; \rho)/3\omega^2$, and m_ϕ is the ϕ -meson mass in the vacuum. $\tilde{\Pi}_B^{\mu\mu}$ denotes the density dependent part of $\Pi_B^{\mu\mu}$: the density independent logarithmic divergence is subtracted out in the dimensional regularization scheme following the procedure given in Refs. 9) and 7), namely, $\tilde{\Pi}_B^{\mu\mu}(\omega, \mathbf{0}; \rho) \equiv \Pi_B^{\mu\mu}(\omega, \mathbf{0}; \rho) - \Pi_B^{\mu\mu}(\omega, \mathbf{0}; 0)$. One should note here that similar "renormalized" self-energy in the relativistic σ - ω

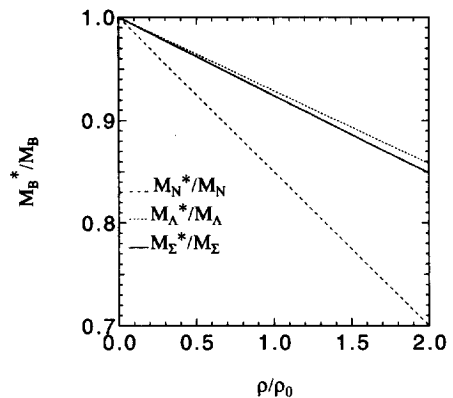


Fig. 1. Ratio of baryon mass in matter M_B^* and that in vacuum $M_B(B=N, \Lambda, \Sigma)$ as a function of ρ/ρ_0 .

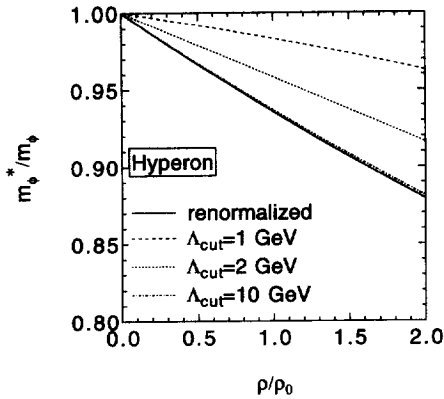


Fig. 2. Ratio of the ϕ -meson mass in matter m_ϕ^* and that in vacuum m_ϕ as a function of ρ/ρ_0 . Only hyperon contributions are included in the ϕ -meson self-energy.

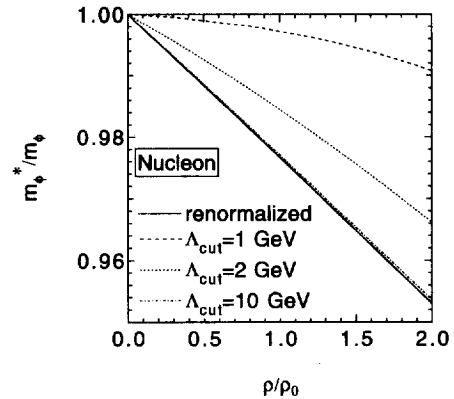


Fig. 3. Same with Fig. 2 except that only the nucleon contribution is included.

model has been used to study the electron-nucleous scattering, and it has been shown that the renormalized Dirac-sea polarization gives rather good agreement with experiments on the quenching of the Coulomb sum values.¹⁵⁾

The solid line in Fig. 2 shows the ratio m_ϕ^*/m_ϕ calculated in the above subtraction procedure with hyperon-loops only. The hyperon contribution is less ambiguous compared to the nucleon contribution, since the absolute value of $g_{\phi N}$ in the latter case is not known. m_ϕ^* decreases by 6–12 % in the range $\rho_0 < \rho < 2\rho_0$. Note that the OZI rule is preserved for ϕ -hyperon vertices, while it is violated in the self-energy $\tilde{\Pi}_B^{\mu\mu}(\omega, \mathbf{0}; \rho)$. This is because the self-energy represents interaction of ϕ ($s\bar{s}$ pair) with *non-strange* nuclear matter. Similar phenomena are known in two-step decay processes such as $\phi \rightarrow K\bar{K} \rightarrow \rho\pi$, $f' \rightarrow K\bar{K} \rightarrow \pi\pi$ and $J/\psi \rightarrow D\bar{D} \rightarrow \rho\pi$, where each vertex preserves the rule while the whole amplitude violates the OZI rule.¹⁶⁾

The solid line in Fig. 3 shows the ratio m_ϕ^*/m_ϕ calculated in the above subtraction procedure with nucleon-loops only. We have used $g_{\phi N}/g_{\omega N}=0.32$ in Fig. 3 which is close to the upper bound given in Table I: thus the resultant decrease of m_ϕ^* in Fig. 3 should be considered to be an upper limit originating from the nucleon-loop. Note here that the nucleon contribution contains the polarization of the Dirac sea and Fermi sea. The former (latter) tends to decrease (increase) the effective mass.

The negative mass shift in Figs. 2 and 3 is a direct consequence of the current conservation ($\partial_\mu(\bar{B}\gamma^\mu B)=0$) and $M_B^*/M_B < 1$, which was first discussed in Refs. 7) and 10) for rho and omega mesons. For the ϕ -meson, the current conservation implies that the propagator of ϕ (without a small Fermi-sea polarization) has a form $D(q) \simeq 1/(Z^{-1}q^2 - m_\phi^2)$ with Z being a *finite* wave-function renormalization in medium. $M_B^*/M_B < 1$ implies that ϕ is more dressed by baryonic clouds in medium, which leads to $Z < 1$. Thus, one arrives at the conclusion $m_\phi^*/m_\phi \equiv Z < 1$. This mechanism is quite general and does not depend on the details of the interaction and on the virtual particles running in the loop, for example, a similar decrease of m_ϕ^* should be seen even when one replaces the baryonic loops by the constituent-quark loop.

To see the effect of the ultraviolet cutoff on the *finite part* of the loop integral in (2), let us define $\tilde{\Pi}_B^{\mu\nu}(\omega, \mathbf{0}; \rho, \Lambda_{\text{cut}}) \equiv \Pi_B^{\mu\nu}(\omega, \mathbf{0}; \rho, \Lambda_{\text{cut}}) - \Pi_B^{\mu\nu}(\omega, \mathbf{0}; 0, \Lambda_{\text{cut}})$ and use this in (5). We take covariant cutoff for Λ_{cut} for simplicity. When $\Lambda_{\text{cut}} \rightarrow \infty$, $\tilde{\Pi}_B^{\mu\nu}(\omega, \mathbf{0}; \rho, \Lambda_{\text{cut}})$ reduces to $\tilde{\Pi}_B^{\mu\nu}(\omega, \mathbf{0}; \rho)$. The dashed lines in Figs. 2 and 3 are the results of such calculations for three cases, $\Lambda_{\text{cut}} = 1, 2, 10$ GeV. Although the cutoff dependence is not negligible, the qualitative picture we draw in the above is not affected.

We have considered only the nucleon and hyperon loops in the ϕ self-energy. Another possible contribution is the kaon-loop in medium, which was studied by Ko et al.⁴⁾ They found that the kaon-loop also has a tendency to decrease m_ϕ^* at low densities provided that the effective kaon mass $\bar{m}_K^* = (m_{K^-}^* + m_{K^+}^*)/2$ decreases in medium. However, it is still controversial whether \bar{m}_K^* really decreases in nuclear matter or not (see, e.g., Ref. 17)). In QCD sum rules (QSR), m_ϕ^* is shown to decrease as a result of the partial restoration of chiral symmetry in nuclear matter, in particular by the medium modification of the strangeness condensate $\langle \bar{s}s \rangle$.³⁾ Unfortunately, it is hard to make a solid connection of this result with that in this paper, since the kinematical region to extract m_ϕ^* in two approaches are quite different (deep Euclidian region in QSR versus on-shell region in the approach here).

Recently, Enyo et al. have proposed an experiment to create ϕ -meson in heavy nuclei using the proton-nucleus reaction and to detect lepton pairs and kaon pairs from ϕ decaying in the nucleus.⁶⁾ A possible signal in this experiment is a double ϕ -meson peak in the e^+e^- spectrum and also a large change of the branching ratio $\Gamma(\phi \rightarrow e^+e^-)/\Gamma(\phi \rightarrow K^+K^-)$. Also, E859 at BNL-AGS has recently reported a possible spectral change of the ϕ -peak in K^+K^- spectrum in heavy ion collisions.⁵⁾ In such experiments, a shoulder structure of the ϕ -peak should be a possible signal of the mass shift of ϕ .

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