Effects of $\bar{N}N$ polarization on vector meson masses at finite temperature

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(Received 10 November 1994)

Effects of $\bar{N}N$ polarization on vector meson (ρ and ω) masses at finite temperature are studied. Including a reduced nucleon mass in a hot matter, we find that the reduction of vector meson masses due to the vacuum effect is larger than the increase of their masses from interactions with nucleons and pions in the hot matter. The vector meson masses at finite temperature thus decrease with temperature.

PACS number(s): 12.38.Mh, 11.30.Rd, 12.40.Vv, 21.65.+f

High-energy nucleus-nucleus collisions offer the possibility to create in the laboratory a hadronic matter at finite temperature [1]. To understand the properties of the hot matter is not only of interest in itself but is also essential for the identification of the signatures for the quark-gluon plasma expected to be formed in the initial stage of the collisions. Recently, the temperature dependence of vector meson masses in a hot matter has been extensively studied using various models. In QCD sum rules, it has been shown that both vector and axial-vector meson masses decrease with increasing temperature [2, 3]. These results are consistent with that based on considerations of the broken scale invariance of QCD [4]. On the other hand, calculations using effective Lagrangians show that vector meson masses increase with temperature [5, 6]. In QCD sum rules at finite temperature, hadron masses are modified as a result of the change of the vacuum in hot matter. In particular, the decrease of quark condensates with temperature leads to the reduction of vector meson masses. In the effective Lagrangian approach, the modification of meson masses is related to scattering processes in the hot matter which turns out to increase their masses. The vacuum effect in the effective Lagrangian approach is only included in the renormalized physical quantities at zero temperature. Thus the modification of the vacuum at finite temperature has not been taken into account in these calculations. It has been shown in the Walecka model that medium modifications of the vacuum affect significantly the ω meson [7, 8] and ρ meson [9] masses in dense matter. Including the reduction of the nucleon mass in a medium, the $\bar{N}N$ vacuum polarization is found to reduce the ω and ρ meson masses. In this paper, we shall study a similar effect on vector meson masses in a hot matter.

The hadron effective mass in a medium is defined as the pole of its propagator [6]. It is the quantity to be compared with that calculated in the QCD sum rules and is also related to the peak position in dilepton spectra. In a medium, the vector meson propagator $\mathcal{D}_{\mu\nu}$ is related to its propagator in free space $\mathcal{D}_{0\mu\nu}$ by

$$\mathcal{D}_{\mu\nu}^{-1} = \mathcal{D}_{0\mu\nu}^{-1} + \Pi_{\mu\nu}, \quad (1)$$

where $\Pi_{\mu\nu}$ is its self-energy due to interactions. For a vector meson interacting with a conserved current, the self-energy can be written as

$$\Pi^{\mu\nu} = F P_L^{\mu\nu} + G P_T^{\mu\nu}, \quad (2)$$

in terms of the transversal $P_T^{\mu\nu}$ ($P_T^{00} = P_T^{0i} = P_T^{i0} = 0$, $P_T^{ij} = \delta^{ij} - k^i k^j / \mathbf{k}^2$) and the longitudinal $P_L^{\mu\nu} = k^\mu k^\nu / k^2 - g^{\mu\nu} - P_T^{\mu\nu}$ projection tensor. In the above, F and G are functions of the energy (ω) and momentum ($\mathbf{k}$) of the vector meson. From Eqs. (1) and (2), the vector meson propagator in a medium is given by

$$\mathcal{D}^{\mu\nu} = \frac{P_L^{\mu\nu}}{F + m^2 - k^2} + \frac{P_T^{\mu\nu}}{G + m^2 - k^2} - \frac{k^\mu k^\nu}{k^2 m_\rho^2}. \quad (3)$$

While the imaginary part of the self-energy is related to the absorption of the vector meson in matter, the real part determines its effective mass. From the pole position of the vector meson propagator in the limit $\mathbf{k} \rightarrow 0$, the effective mass can be obtained. Since the transversal and longitudinal modes are not distinguishable in this limit, we have $F = G$. The effective mass of a vector meson in a medium is then determined from the equation

$$\omega^2 - m^2 - \text{Re}[F(\omega, \mathbf{k} \rightarrow 0)] = 0, \quad (4)$$

where $\text{Re}[F(k)]$ is related to the self-energy by

$$\text{Re}[F(k)] = \frac{k^2}{\mathbf{k}^2} \text{Re}[\Pi^{00}(k)]. \quad (5)$$

For a ρ meson in a hot matter, its self-energy due to interactions with pions has been evaluated in Refs. [5, 6]. To calculate the contribution from its interaction with nucleons, we consider the following phenomenological ρNN interaction Lagrangian:

$$\mathcal{L}_{\rho NN} = g_{\rho NN} \left[\bar{\psi} \gamma_\mu \tau \cdot \psi \rho^\mu(x) + \frac{\kappa_\rho}{2M} \bar{\psi} \sigma_{\mu\nu} \tau \cdot \psi \partial^\mu \rho^\nu(x) \right], \quad (6)$$

where ρ_μ and ψ are the ρ meson and nucleon fields, respectively. The nucleon mass in free space is denoted by M . We take the values of the coupling constants from the Bonn boson exchange potential [10], i.e.,

$$\frac{g_{\rho NN}^2}{4\pi} = 0.92, \quad \kappa_\rho = 6.1. \quad (7)$$

We note that the tensor interaction given by the second term in Eq. (6) is much stronger than the vector inter-

action given by the first term in Eq. (6).

In the imaginary time formalism [11], the ρ meson self-energy from its interactions with nucleons at temperature T as shown by the diagram in Fig. 1 can be written as

$$\Pi_{\rho}^{\mu\nu}(k) = 2g_{\rho NN}^2 T \sum_{n=-\infty}^{\infty} \int \frac{d^3p}{(2\pi)^3} \times \text{Tr} \left\{ \Gamma_{\mu}(k) \frac{1}{\not{p} - M^*} \Gamma_{\nu}(-k) \frac{1}{(\not{p} - \not{k}) - M^*} \right\}, \quad (8)$$

with the time component of p given by $p_0 = (2n+1)\pi T i$. In the above, M^* is the nucleon mass in hot matter and

$$\Gamma_{\mu}(k) = \gamma_{\mu} + \frac{i\kappa_{\rho}}{2M} \sigma_{\mu\nu} k^{\nu}. \quad (9)$$

The self-energy can be further written as a sum of the vacuum part $\Pi_{\rho, \text{vac}}^{\mu\nu}$ and the matter part $\Pi_{\rho, \text{mat}}^{\mu\nu}$, i.e.,

$$\Pi_{\rho}^{\mu\nu} = \Pi_{\rho, \text{vac}}^{\mu\nu} + \Pi_{\rho, \text{mat}}^{\mu\nu}. \quad (10)$$

The vacuum contribution $\Pi_{\rho, \text{vac}}^{\mu\nu}$ is divergent but can be evaluated using dimensional regularization. Requiring that the renormalization constant is such that the vacuum contribution vanishes at zero temperature, the vacuum contribution to the self-energy of a ρ meson at rest in a hot matter is then given by

FIG. 1. One-loop diagram for the vector meson self-energy due to interactions with nucleons.

$$\text{Re}[F_{\rho, \text{vac}}^N(\omega, \mathbf{k} \rightarrow 0)] = \frac{g_{\rho NN}^2}{\pi^2} \omega^2 \left[P_1 + M^* \left(\frac{\kappa_{\rho}}{2M} \right) P_2 + \frac{1}{2} \left(\frac{\kappa_{\rho}}{2M} \right)^2 (\omega^2 P_1 + M^{*2} P_2) \right], \quad (11)$$

where

$$P_1(\omega) = \int_0^1 dz z(1-z) \ln \left[\frac{M^{*2} - \omega^2 z(1-z)}{M^2 - m_{\rho}^2 z(1-z)} \right], \quad (12)$$

$$P_2(\omega) = \int_0^1 dz \ln \left[\frac{M^{*2} - \omega^2 z(1-z)}{M^2 - m_{\rho}^2 z(1-z)} \right]. \quad (13)$$

In the above, M^* is the nucleon effective mass in a hot matter.

The matter part is due to particle-hole polarization in hot matter. It is finite and in the limit $\mathbf{k} \rightarrow 0$ has the following form:

$$\text{Re}[F_{\rho, \text{mat}}^N(\omega, \mathbf{k} \rightarrow 0)] = -\frac{8g_{\rho NN}^2}{\pi^2} \int p^2 dp \frac{1}{\omega_N^* (e^{\beta\omega_N^*} + 1)} \frac{1}{\omega^2 - 4\omega_N^{*2}} \times \left\{ \frac{2}{3} (2p^2 + 3M^{*2}) + 2M^* \left(\frac{\kappa_{\rho}}{2M} \right) \omega^2 + 2 \left(\frac{\kappa_{\rho}}{2M} \right)^2 \left(\frac{p^2}{3} + M^{*2} \right) \omega^2 \right\}, \quad (14)$$

where $\omega_N^* = \sqrt{p^2 + M^{*2}}$ and $\beta = 1/T$.

The change of the nucleon mass at finite temperature can be obtained from the Walecka model [12]. In the mean-field approximation, the nucleon effective mass satisfies the equation

$$M^* = M - \frac{g_s^2}{m_s^2} \frac{4}{(2\pi)^3} \int d^3p \frac{M^*}{(\mathbf{p}^2 + M^{*2})^{1/2}} \times [n_p(T) + \bar{n}_p(T)], \quad (15)$$

with

$$n_p(T) = \frac{1}{e^{\beta(\omega_N^* - \mu)} + 1}, \quad \bar{n}_p(T) = \frac{1}{e^{\beta(-\omega_N^* + \mu)} + 1}. \quad (16)$$

We are interested in the case of zero baryon chemical potential $\mu = 0$. As shown in Fig. 2 by the dotted curve, the nucleon effective mass decreases with temperature, and the reduction becomes appreciable near $T \sim 200$ MeV.

The ρ meson mass at finite temperature is also shown in Fig. 2. Including only the matter contribution, the ρ

meson mass increases at finite temperature as shown by the dashed curve. When we include also the vacuum polarization effect with the in-medium nucleon mass, the ρ meson mass, shown by the solid curve in Fig. 2, decreases

FIG. 2. Effective masses of nucleon and ρ meson at finite temperature.

with temperature. Thus the vacuum contribution affects the ρ meson mass much more than the matter contribution. It is also more important than the effects due to interactions of the ρ meson with pions in the hot matter [5, 6], which lead to an increase of its mass with temperature. Including the latter contribution as given in [5, 6], the ρ meson mass is shown by the dashed-dotted curve and still decreases with temperature. We note that the large effect from the vacuum contribution is mainly due to the strong tensor interaction between ρ meson and nucleon. This conclusion is similar to that obtained in Ref. [9] for a ρ meson in a dense nuclear matter.

The above discussions can be applied to the ω meson mass at finite temperature. Its interactions with other mesons are given by the anomalous Wess-Zumino couplings, which are small and will be neglected [6]. The interaction with a nucleon is given by the Lagrangian,

$$\mathcal{L}_{\omega NN} = g_{\omega NN} \bar{\psi} \gamma_\mu \omega^\mu \psi. \quad (17)$$

The empirical value for the ωNN coupling constant varies in different models. In the Bonn boson-exchange potential, it has a value $\frac{g_{\omega NN}^2}{4\pi} \approx 20.0$. In the Walecka model, the value is $\frac{g_{\omega NN}^2}{4\pi} \approx 10.8$. There is no tensor coupling for the ω meson, so the self-energy of the ω meson is given by a similar expression as that for the ρ meson except that terms which are proportional to κ_ρ are absent. The effective mass of the ω meson is shown in Fig. 3 by the dashed and solid curves for the two values of ωNN coupling constant. We see that in both cases the ω meson mass decreases with temperature. Because of the absence of a strong tensor coupling, the reduction of the ω meson mass due to the change of vacuum polarization at finite temperature is much less than that of the ρ meson mass.

Our results indicate that the modification of the vacuum is very important in understanding the properties of vector mesons in hot matter. Without vacuum effects the vector meson effective masses increase with temperature because of their interactions with pions and nucleons in the hot matter. Their interactions with virtual nucleons in the modified vacuum gives, however, a larger reduction in their masses and leads to a decrease of their masses at high temperature. The ω meson mass at finite temperature has also been studied in Ref. [13]. These authors have only included the matter contribution and have found that it already leads to a decrease of the ω meson mass at finite temperature. This is contrary to our results on the matter contribution, and we believe that their results are incorrect as arguments based on simple second-order perturbation theory show that the matter contribution should give a positive self-energy.

FIG. 3. Effective mass of ω meson at finite temperature.

In this paper, the simple Walecka model has been used to evaluate the nucleon mass at finite temperature. Since the nucleon-antinucleon polarization always reduces the vector meson masses if the nucleon mass is reduced, our results are not expected to be qualitatively changed if different nucleon in-medium masses, resulting from different models, are used. Also, we have used the Walecka model in the mean-field level; then there is no effect due to vector mesons on the nucleon mass as the latter is determined only by the scalar field. Finally, as the vector meson masses decrease at finite temperature, their widths are reduced due to the reduction in the phase space for decays into pions. However, the change of the nucleon mass has no effect on the widths of vector mesons as the nucleon-antinucleon threshold at finite temperature is still larger than the vector meson masses. The matter polarization also contributes to the imaginary part of the vector meson self-energies, but the effect is negligible.

In our study and in Refs. [7–9, 13], the form factors at the ρNN and ωNN vertices have been ignored. Since the renormalized vacuum contribution at finite temperature is mainly due to $\bar{N}N$ pairs with not very large momenta, form factors are not expected to change the results significantly. Nevertheless, it is of interest to study quantitatively the effect of form factors, and work on such an investigation is in progress.

This work was supported in part by the National Science Foundation under Grant No. PHY-9212209 and by the Welch Foundation under Grant No. A-1110.

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