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Spectral function of ρ in dense and hot hadronic matter

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Abstract: The spectral function of rho meson in hot/dense hadronic matter is studied by taking into account the nucleon-loop on quantum hadrondynamics model level. Different from the hot pion gas effect which changes the spectral function slightly, the nucleon-antinucleon polarization (Dirac sea) makes the spectral function very sharp and shifted towards the low invariant mass region significantly due to the decreasing effective nucleon mass.

Keywords: Sigma Models, Thermal Field Theory.

It is widely prospected that in ultra-relativistic heavy-ion collisions a new phase of matter — quark-gluon plasma (QGP) may be generated and the spontaneously broken chiral symmetry may be restored. Among the proposed various signals which can detect the phase transitions in strongly interacting matter, the electromagnetic signals-dileptons and photons are considered to be the clearest ones, since they can penetrate the medium almost undisturbed. Considering the fact that light vector mesons can directly decay to dilepton pairs, the study about ρ meson in medium is especially interesting because the lifetime of ρ is smaller than that of the fireball formed in heavy-ion collisions and the decay of ρ can be completed inside it. The strong enhancement of low mass dileptons in central $A-A$ collisions observed by CERES-NA45 has excited many theoretical works [1, 2]. Among them, the mass dropping of ρ mesons provides a good description of the data [3]–[6].

The mass spectrum of hadrons in extreme hadronic environment has been widely discussed. One of the familiar results is the Brown-Rho scaling law indicating that the masses of nucleons and mesons decrease in hot/dense hadronic environment. For light vector mesons, it is difficult to extract an unique conclusion from different model calculations. The mean field theory (MFT) and effective lagrangians can give similar results as the Brown-Rho scaling [4, 7], but the results from some QCD sum rules may be different from it and even contrast to it [8, 9, 10]. The property of ρ in hot/dense environment is not yet clear and needs further study.

The hot topic in recent years is discussing the low invariant mass dilepton production in heavy ion collisions. The dilepton distribution is related with the spectral function of ρ meson, i.e., the imaginary part of the retarded propagator of ρ in medium [11, 12, 13], which reflects the comprehensive medium effects. From the point of view of the partial chiral symmetry restoration the ρ spectral function has been widely discussed in recent literature such as in refs. [4, 13] (and references therein).

The key point of discussing the ρ spectral function is how to calculate the ρ meson self-energy in nuclear environment. In this paper, the effects of the decreasing effective nucleon mass on the ρ spectral function in medium are discussed. With quantum hadrodynamics model (QHD) of nuclear matter, the effective nucleon mass drops down with density/temperature and should be taken into account in discussing the effective mass as well as the decay width of ρ in medium, i.e., the spectral function. H. Shiomi and T. Hatsuda have found that the effective ρ meson mass decreases in nuclear matter due to the nucleon polarization at finite density with QHD-I type effective lagrangian [14]. By extending their work to finite temperature, the temperature and density dependence of the ρ-meson spectral function due to nucleon loop is discussed.

In Minkowski space, the self-energy of the light vector meson ρ can be expressed as [11, 15]

$$\Pi^{\mu\nu} = \Pi_L P_L^{\mu\nu} + \Pi_T P_T^{\mu\nu} \,, \tag{1}$$

where $k^2 = k_0^2 - \mathbf{k}^2$. The $P_L^{\mu\nu}(k)$ and $P_T^{\mu\nu}(k)$ are the standard longitudinal and transverse projection tensors

$$P_T^{00} = P_T^{0i} = P_T^{i0} = 0 \,, \qquad P_T^{ij} = \delta^{ij} - \frac{k^i k^j}{\mathbf{k}^2} \,,$$

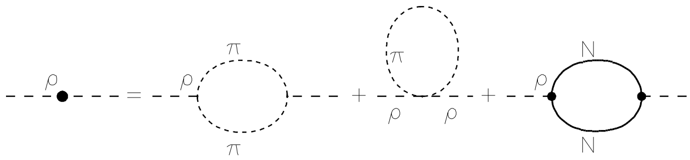

Figure 1: The ρ self-energy Feynman diagrams associated with $\rho\pi\pi$ and $\rho\rho\pi\pi$ as well as ρNN interactions.

$$P_L^{\mu\nu} = \frac{k^\mu k^\nu}{k^2} - g^{\mu\nu} - P_T^{\mu\nu} \,. \tag{2}$$

The longitudinal and transverse elements of the self-energy can be determined by

$$\Pi_L(k) = \frac{k^2}{\mathbf{k}^2}\Pi^{00}(k)\,, \qquad \Pi_T(k) = \frac{1}{2}P_T^{ij}\Pi_{ij}(k)\,. \tag{3}$$

Noting that the self-energy is related to the full ($\mathcal{D}$) and bare ($\mathcal{D}_0$) propagators by

$$\Pi^{\mu\nu} = \left(\mathcal{D}^{-1}\right)^{\mu\nu} - \left(\mathcal{D}_0^{-1}\right)^{\mu\nu} \,, \tag{4}$$

one can obtain

$$\mathcal{D}^{\mu\nu} = -\frac{P_L^{\mu\nu}}{k^2 - m_\rho^2 - \Pi_L} - \frac{P_T^{\mu\nu}}{k^2 - m_\rho^2 - \Pi_T} - \frac{k^\mu k^\nu}{m_\rho^2 k^2}\,, \tag{5}$$

where m_ρ is the free mass of ρ in vacuum.

The property of in-medium ρ is determined by its full propagator. The imaginary part of the retarded propagator is referred to as the spectral function and related to the dilepton production with vector meson dominance model. The study of the ρ spectral function is attributed to calculating the in-medium self-energy. By concentrating on decreasing nucleon mass effects, the in-medium ρ property is analysed in terms of the Feynman diagrams displayed in figure 1. The pion effect has been analyzed in ref. [11], and in Minkowski space the pion-loop contribution to ρ self-energy can be written as

$$\Pi_{\mu\nu}^{\rho\pi\pi}(k) = -g_\rho^2 T\sum_{p_0}\int\frac{d^3p}{(2\pi)^3}\frac{(2p+k)_\mu(2p+k)_\nu}{(p^2-m_\pi^2)[(p+k)^2-m_\pi^2]} + 2g_{\mu\nu}g_\rho^2 T\sum_{p_0}\int\frac{d^3p}{(2\pi)^3}\frac{1}{p^2-m_\pi^2}\,, \tag{6}$$

where the 0-component of π loop momentum is related to temperature via $p_0 = 2n\pi Ti$, with $n = 0, \pm1, \pm2, \ldots$.

The contribution of nucleon excitations through nucleon-loop to ρ self-energy is analyzed in terms of the effective lagrangian [14, 16]

$$\mathcal{L}_{\rho NN} = g_{\rho NN}\left(\bar\Psi\gamma_\mu\tau^a\Psi V_a^\mu - \frac{\kappa_\rho}{2M_N}\bar\Psi\sigma_{\mu\nu}\tau^a\Psi\partial^\nu V_a^\mu\right), \tag{7}$$

where V_a^μ is the ρ meson field and Ψ the nucleon field. It can be written as

$$\Pi_{\mu\nu}^{\rho NN}(k) = 2g_{\rho NN}^2 T\sum_{p_0}\int\frac{d^3p}{(2\pi)^3}\mathrm{Tr}\left[\Gamma_\mu(k)\frac{1}{\not p - M_N^*}\Gamma_\nu(-k)\frac{1}{(\not p - \not k) - M_N^*}\right], \tag{8}$$

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where Γ_μ is defined as $\Gamma_\mu(k) = \gamma_\mu + \frac{i\kappa_\rho}{2M_N}\sigma_{\mu\nu}k^\nu$ with $\sigma_{\mu\nu} = \frac{i[\gamma_\mu,\gamma_\nu]}{2}$, M_N and M_N^* are the nucleon masses in vacuum and medium, respectively. The 0-component of nucleon loop momentum is related to temperature via $p_0 = (2n+1)\pi Ti + \mu^*$ with μ^* being the effective chemical potential of nucleon.

With residue theorem the ρNN contribution can be separated into two parts

$$\Pi^{\rho NN}_{\mu\nu}(k) = \left(\frac{k_\mu k_\nu}{k^2} - g_{\mu\nu}\right)\Pi^{\rho NN}_F(k) + \Pi^{\rho NN}_{D,\mu\nu}(k). \tag{9}$$

The first part $\Pi^{\rho NN}_F(k)$ corresponding to Π^F of ref. [14] contains divergent integrals and needs to be regularized. However, it can not be renormalized by the conventional method. Using the dimensional regularization method and taking a phenomenological procedure [14]–[19]

$$\partial^n \Pi^{\rho NN}_F(k)/\partial\left(k^2\right)^n|_{M_N^*\to M_N, k^2=m_\rho^2} = 0\,, \qquad (n = 0,1,2,\ldots,\infty) \tag{10}$$

one can eliminate the real vacuum ($T = 0$) part and obtain the finite result

$$\begin{aligned}
\Pi^{\rho NN}_{F,L(T)}(k) &= k^2\frac{g^2_{\rho NN}}{\pi^2}\left(P_1 + \frac{\kappa_\rho M_N^*}{2M_N}P_2 + \left(\frac{\kappa_\rho}{2M_N}\right)^2\frac{k^2P_1 + {M_N^*}^2 P_2}{2}\right),\\
P_1 &= \int_0^1 dx x(1-x)\ln c\,, \qquad P_2 = \int_0^1 dx \ln c\,,\\
c &= \frac{{M_N^*}^2 - x(1-x)k^2}{{M_N}^2 - x(1-x)k^2}\,.
\end{aligned} \tag{11}$$

It is easy to see that the medium effect on $\Pi^{\rho NN}_F$ is also introduced by the effective nucleon mass M_N^* in hadronic environment which will be determined by QHD-I below.

The second part $\Pi^{\rho NN}_{D,\mu\nu}(k)$ in (9) is explicitly related to distribution function $n_N(T,\mu^*)$ (corresponding to the Fermi sea contribution at $T = 0$). Its calculation is lengthy. We list here only the longitudinal results

$$\begin{aligned}
\Pi^{\rho NN}_{D,L}(k) &= \Pi^{\rho NN}_{1D,L}(k) + \Pi^{\rho NN}_{2D,L}(k) + \Pi^{\rho NN}_{3D,L}(k)\,,\\
\Pi^{\rho NN}_{1D,L}(k) &= -\frac{g^2_{\rho NN}k^2}{\pi^2\mathbf{k}^2}\int\frac{p^2dp}{\omega}(n_N+\bar{n}_N)\times\left[2+\frac{k^2-4\omega k_0+4\omega^2}{4p|\mathbf{k}|}\ln a+\frac{k^2+4k_0\omega+4\omega^2}{4p|\mathbf{k}|}\ln b\right],\\
\Pi^{\rho NN}_{2D,L}(k) &= \frac{g^2_{\rho NN}k^2}{\pi^2|\mathbf{k}|}\frac{\kappa_\rho}{2M_N}M_N^*\int\frac{pdp}{\omega}(n_N+\bar{n}_N)\left[\ln a + \ln b\right],\\
\Pi^{\rho NN}_{3D,L}(k) &= \frac{g^2_{\rho NN}k^2}{\pi^2\mathbf{k}^2}\left(\frac{\kappa_\rho}{2M_N}\right)^2\int\frac{p^2dp}{\omega}(n_N+\bar{n}_N)\left[2k_0^2 + \frac{\mathbf{k}^2(k^2-4p^2)+(k^2-2\omega k_0)^2}{4p|\mathbf{k}|}\ln a +\right.\\
&\qquad\left. + \frac{\mathbf{k}^2(k^2-4p^2)+(k^2+2\omega k_0)^2}{4p|\mathbf{k}|}\ln b\right],
\end{aligned} \tag{12}$$

where a, b, ω, n_N, $\bar{n}_N$ are defined by

$$\begin{aligned}
a &= \frac{k^2 - 2p|\mathbf{k}| - 2k_0\omega}{k^2 + 2p|\mathbf{k}| - 2k_0\omega}\,, \qquad b = \frac{k^2 - 2p|\mathbf{k}| + 2k_0\omega}{k^2 + 2p|\mathbf{k}| + 2k_0\omega}\,,\\
\omega &= \sqrt{p^2 + {M_N^*}^2}\,, \qquad n_N = \frac{1}{e^{\beta(\omega-\mu^*)}+1}\,, \qquad \bar{n}_N = \frac{1}{e^{\beta(\omega+\mu^*)}+1}\,.
\end{aligned} \tag{13}$$

Before making further discussions, it should be emphasized that the inclusion of the pion tadpole diagram is very crucial for the current conservation condition [11]. It is interesting that the self-energy is divided into two parts such as in (9) with residue theorem and the two parts separately satisfy the current conservation. The current conservation condition ensures the transversality of $\Pi^{\mu\nu}$, which is reflected in the properties of the projection tensors $P_L^{\mu\nu}$ and $P_T^{\mu\nu}$ such as $k_\mu P_{L(T)}^{\mu\nu} = 0$.

After analytical continuation according to $k_0 \to E + i\varepsilon$, $E = \sqrt{M_\rho^2 + \mathbf{k}^2}$ with M_ρ being the ρ invariant mass in medium, one can obtain the real and imaginary parts of the self-energy. Then by using the definition of ρ meson spectral function

$$\mathcal{A}_{L(T)}(k) = -2 \frac{\mathrm{Im}\,\Pi_{L(T)}(k)}{\left[M_\rho^2 - (m_\rho^2 + \mathrm{Re}\,\Pi_{L(T)}^\rho(k))\right]^2 + \left[\mathrm{Im}\,\Pi_{L(T)}^\rho(k)\right]^2}\,, \tag{14}$$

where $\Pi_{L(T)}$ is the total longitudinal or transverse self-energy, one can analyze the medium effects on ρ meson.

The effective mass M_N^* and effective chemical potential μ^* of the nucleon in $\Pi^{\rho NN}$ are determined from the simplest QHD-I at mean field level [20, 21]. The QHD-I is a renormalizable model including nucleon and meson degrees of freedom

$$\begin{aligned}\mathcal{L} = \bar{\psi}\left[\gamma_\mu(i\partial^\mu - g_v V^\mu) - (M_N - g_s\phi)\right]\psi + \frac{1}{2}(\partial_\mu\partial^\mu\phi - m_s^2\phi^2) - \\ -\frac{1}{4}F_{\mu\nu}F^{\mu\nu} + \frac{1}{2}m_v^2 V_\mu V^\mu + \delta\mathcal{L}\,,\end{aligned} \tag{15}$$

where ψ is the nucleon field, ϕ the neutral scalar field with free mass m_s, $F_{\mu\nu} = \partial_\mu V_\nu - \partial_\nu V_\mu$ the field tensor of ω meson with free mass m_v, and $\delta\mathcal{L}$ the renormalization counterterm.

In mean field approximation, the meson field operators are replaced by the ground-state expectation values

$$\phi \to \langle\phi\rangle = \phi_0\,, \qquad V^\mu \to \langle V^\mu\rangle = g^{\mu 0}V^0\,. \tag{16}$$

With MFT by neglecting the vacuum fluctuation contribution, the classical field ϕ_0 is a dynamical quantity which makes the nucleon mass drop and can be determined self-consistently by [20]

$$M_N - M_N^* = g_s\phi_0 = g_s^2\langle\bar{\psi}\psi\rangle = \frac{g_s^2}{m_s^2}\rho_s\,, \tag{17}$$

where the scalar baryon density ρ_s is defined as

$$\rho_s = \frac{\gamma}{(2\pi)^3}\int d^3\mathbf{k}\frac{M_N^*}{\omega}\left[n_N(\mu^*, T) + \bar{n}_N(\mu^*, T)\right], \tag{18}$$

with the nucleon degenerate factor $\gamma = 4$.

The effective chemical potential μ^* is introduced by

$$\mu^* = \mu - \frac{g_v^2\rho_N}{m_v^2}\,, \tag{19}$$

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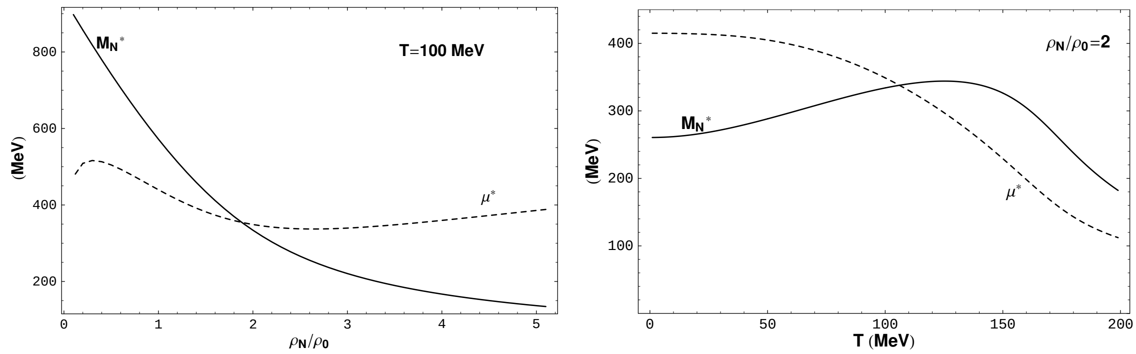

Figure 2: Effective nucleon mass M_N^* and chemical potential μ^* determined by QHD-I as functions of scaled density (left panel) and temperature (right panel) with MFT. The normal nuclear density is chosen to be $\rho_0 = 0.16\ fm^{-3}$.

with the baryon density

$$\rho_N = \frac{\gamma}{(2\pi)^3} \int d^3\mathbf{k} \frac{M_N^*}{\omega} \left[n_N(\mu^*, T) - \bar{n}_N(\mu^*, T) \right]. \tag{20}$$

One can solve the coupled equations (17) and (19) numerically. With the parameters $g_s^2 = 109.626$, $g_v^2 = 190.431$, $m_s = 520\,\mathrm{MeV}$, $M_N = 938\,\mathrm{MeV}$, and $m_v = 783\,\mathrm{MeV}$ according to the bulk binding energy and normal density of nuclear matter at saturation, the effective nucleon mass and chemical potential with MFT are displayed in figure 2.

The longitudinal spectral functions (14) in medium are drawn in figures 3 and 4 for different hadronic environment. The parameters are chosen to be $m_\pi = 139.6\,\mathrm{MeV}$, $m_\rho = 770\,\mathrm{MeV}$, $g_\rho^2 = 4\pi * 2.91$, $g_{\rho NN}^2 = 6.91$, $\kappa_\rho = 6.1$ [16]. It should be noted that, different from ω, the tensor coupling is very important for the interaction of ρ with nucleons. Here we use the coupling constants $g_{\rho NN}$ and κ_ρ determined from the fitting of the nucleon-nucleon interaction data done by the Bonn group. As shown in figure 3, when nucleon-loop is not taken into account, there is only temperature effect and the ρ meson spectral function changes weakly. With the increase of temperature, the spectral function becomes a little bit wider and is shifted towards the high invariant mass region slightly. This behavior agrees with the result of ref. [11].

The spectral function including the nucleon-loop contribution is shown in figure 4. The solid lines are still the calculation in vacuum, but the dashed and dot-dashed lines contain the density and finite temperature effects. The dotted line represents the result of pure density effect ($T = 0$, $\rho_B \neq 0$). The density effect on ρ spectral function is obviously important by comparing figure 3 with figure 4. The nucleon excitation shifts the spectral function towards low invariant mass region. As indicated in the left panel of figure 4, in the case of low density, $\rho_N/\rho_0 = 0.1$, the density effect is already remarkable compared with the pure temperature effect shown in figure 3. The peak position of spectral function is shifted from 0.77 GeV in vacuum to about 0.63 GeV in medium.

The second characteristic of nucleon loop effect is the sharping of ρ spectral function. Even for low density situation, see the left panel of figure 4 with $\rho_N/\rho_0 = 0.1$, the ρ meson width is already reduced to about half of that in vacuum. When density is high enough,

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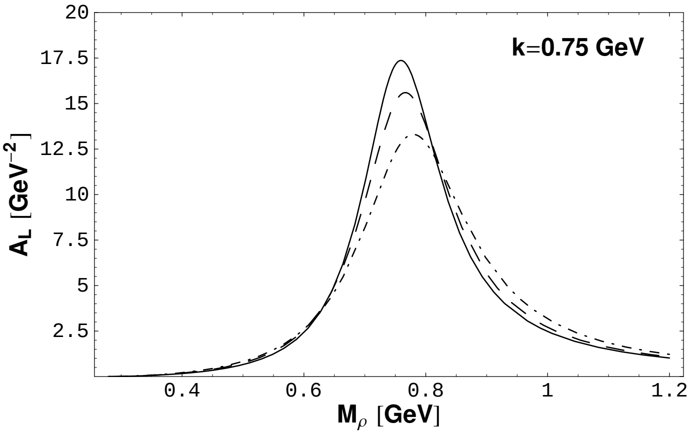

Figure 3: The ρ meson spectral function without considering the nucleon-loop at momentum $k = 0.75\,\mathrm{GeV}$. The solid line represents the vacuum situation, while dashed and dot-dashed lines correspond to temperature $T = 0.1$ and $0.15\,\mathrm{GeV}$, respectively.

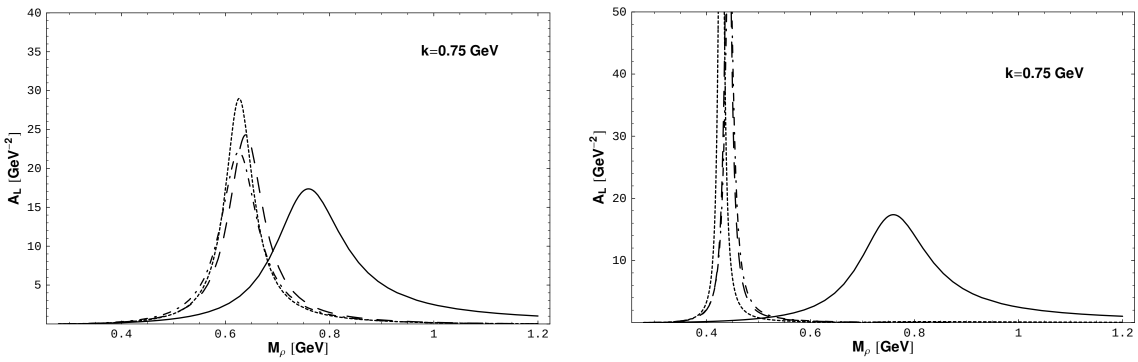

Figure 4: Spectral function including the nucleon-loop contribution at momentum $k = 0.75\,\mathrm{GeV}$. Line style is similar to figure 3 except that the dotted lines represent the $T = 0$ situation. Left panel: $\rho_N/\rho_0 = 0.1$; Right panel: $\rho_N/\rho_0 = 1.5$.

see the right panel of figure 4 with $\rho_N/\rho_0 = 1.5$, the spectral function approaches to a δ-like function. This is mainly a consequence of the reduced two-pion phase space due to the ρ mass decrease in medium.

Another significance of the nucleon loop is its approximate saturation at high density. At $\rho_N/\rho_0 = 1.5$, the two lines with temperature $T = 0.1\,\mathrm{GeV}$ and $0.15\,\mathrm{GeV}$ almost coincide with each other. When density goes up further, for instance taking $\rho_N/\rho_0 = 2$, the spectral function is almost the same as the corresponding line in the right panel of figure 4 for $\rho_N/\rho_0 = 1.5$. This saturation tendency can be seen from the effective mass m_ρ^* determined by the pole position of its propagator in medium [14]

$$k_0^2 - m_\rho^2 - \lim_{|\mathbf{k}|\to 0} \Pi^{L(T)}(k) = 0\,, \tag{21}$$

as indicated by figure 5. For comparison, we also give the effective nucleon mass M_N^*. By taking MFT, m_ρ^* and M_N^* are displayed in the left panel of figure 5. When density is higher than ρ_0, m_ρ^* approaches its minimum value and then increases with the increase of density

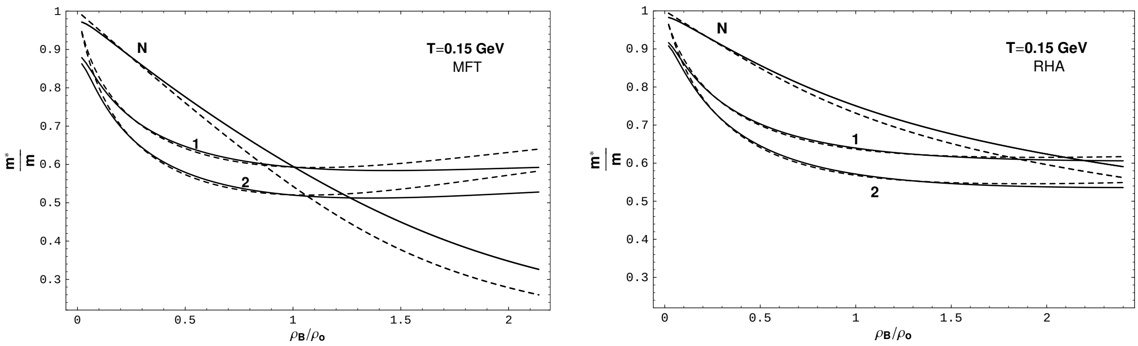

Figure 5: Effective ρ meson mass vs scaled baryon density for $T = 0.15\,\mathrm{GeV}$ with MFT (left panel) and RHA (right panel). For comparison, the effective nucleon mass line is also drawn out. The dashed lines correspond to $T = 0$ situation, while the solid lines to those in the hot medium. The symbol "1" represents the case considering form factor, while "2" without the form factor contribution.

a little bit. The result of m_ρ^* with the nucleon propagator obtained with the relativistic Hartree approximation (RHA) by including vacuum fluctuation contribution instead of MFT is quite similar except the numerical difference, as indicated in the right panel of figure 5. Vector meson masses will decrease with the increase of density for a model including the polarization of nucleon-antinucleon with a decreasing effective nucleon mass [14, 21]. The numerical calculation indicates that the Dirac sea contribution dominates.

It should be noted that the interactions between mesons and nucleons are point-like in QHD. Considering the fact that mesons and nucleon are composite, a phenomenological monopole form factor is multiplied at each meson-N vertex [16]

$$F_\alpha(k^2) = \frac{\Lambda_\alpha^2 - m_\alpha^2}{\Lambda_\alpha^2 - k_\mu^2}\,, \tag{22}$$

where k_μ is the four-momentum transfer, m_α the mass of the exchanged meson and Λ_α the relevant cut-off mass. For ρNN vertex, Λ_ρ is usually taken as $\Lambda_\rho = 1.5\,\mathrm{GeV}$.

The inclusion of form factor attenuates the behavior of effective mass m_ρ^* significantly, which makes the magnitude of mass shift in medium smaller than that without the form factor. For analyzing the influence of form factor on the effective mass m_ρ^*, the two situations with/without form factor contribution have been drawn out in figure 5. The displayed spectral function in figure 4 has included the form factor contribution.

Our result of the spectral function is different from previous results such as in refs. [4, 13]. From figures 4 and 5, one can see that effects of the decreasing effective nucleon mass on ρ spectral function are important but they are not considered in refs. [4, 13]. On the other hand, by focusing on the effects of decreasing nucleon mass on QHD-I level, any other decay channels which can contribute to the imaginary as well as the real parts of the self-energy are not included in our calculation and also cause the difference.

In summary, we discussed the density and temperature effects on ρ meson spectral function with the effective lagrangian. Different from the pure temperature effect of the pion loop which changes ρ meson mass only a little and shifts the spectral function to-

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wards high invariant mass region slightly, the nucleon-loop changes the ρ meson properties differently and significantly: 1) The spectral function is shifted towards low mass region remarkably even in the case of low density; 2) Together with the shift towards low mass region, the spectral function becomes very sharp due to Dirac sea polarization with the decreasing nucleon mass in medium; The density effect on the spectral function approaches to saturation when the density increases. 3) The influence of a phenomenological vertex form factor may prevent the effective ρ mass decreasing to some extent within hadronic level. Although the behavior of m_ρ^* in low density region is expected to be not so stiff, our result indicates that the effects of decreasing nucleon mass may be remarkable and should be taken into account in discussing the in-medium ρ property. The relation between our result and those from QCD sum rules esp. in the low density region is not yet well understood and needs to be clarified further.

Acknowledgments

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References

[1] CERES collaboration, G. Agakishiev et al., *Enhanced production of low mass electron pairs in 200-GeV/u S-AU collisions at the cern SPS*, *Phys. Rev. Lett.* **75** (1995) 1272.

[2] CERES collaboration, P. Wurm, *New results from NA45/CERES*, *Nucl. Phys.* **A 590** (1995) 103c.

[3] G.E. Brown and M. Rho, *Scaling effective lagrangians in a dense medium*, *Phys. Rev. Lett.* **66** (1991) 2720.

[4] R. Rapp and J. Wambach, *Chiral symmetry restoration and dileptons in relativistic heavy-ion collisions*, *Adv. Nucl. Phys.* **25** (2000) 1 [hep-ph/9909229].

[5] G.-Q. Li, C.M. Ko and G.E. Brown, *Enhancement of low mass dileptons in heavy ion collisions*, *Phys. Rev. Lett.* **75** (1995) 4007 [nucl-th/9504025]; *Effects of in-medium vector meson masses on low-mass dileptons from SPS heavy-ion collisions*, *Nucl. Phys.* **A 606** (1996) 568 [nucl-th/9608040].

[6] J. Murray, W. Bauer and K. Haglin, *Low-mass dileptons at the SPS*, *Phys. Rev.* **D 57** (1998) 882 [hep-ph/9611328].

[7] K. Saito and A.W. Thomas, *Variations of hadron masses and matter properties in dense nuclear matter*, *Phys. Rev.* **D 51** (1995) 2757 [nucl-th/9410031].

[8] S. Leupold, W. Peters and U. Mosel, *What QCD sum rules tell about the rho meson*, *Nucl. Phys.* **A 628** (1998) 311 [nucl-th/9708016].

[9] F. Klingl, N. Kaiser and W. Weise, *Current correlation functions, QCD sum rules and vector mesons in baryonic matter*, *Nucl. Phys.* **A 624** (1997) 527 [hep-ph/9704398].

[10] T. Hatsuda and S.H. Lee, *QCD sum rules for vector mesons in nuclear medium*, *Phys. Rev.* **C 46** (1992) 34.

[11] C. Gale and J. Kapusta, *Vector dominance model at finite temperature*, *Nucl. Phys.* **B 357** (1991) 65.

[12] H.A. Weldon, *Reformulation of finite temperature dilepton production*, *Phys. Rev.* **D 42** (1990) 2384.

[13] R. Rapp and J. Wambach, *Low mass dileptons at the cern-sps: evidence for chiral restoration?*, *Eur. Phys. J.* **A6** (1999) 415 [hep-ph/9907502].

[14] H. Shiomi and T. Hatsuda, *Vector mesons in nuclear medium: an effective lagrangian approach*, *Phys. Lett.* **B 334** (1994) 281 [hep-ph/9404337].

[15] J.I. Kapusta, *Finite temperature field theory*, Cambridge University Press 1989.

[16] R. Machleidt, K. Holinde and C. Elster, *The Bonn meson exchange model for the nucleon nucleon interaction*, *Phys. Rept.* **149** (1987) 1.

[17] M.E. Peskin and D.V. Schroeder, *An introduction to quantum field theory*, Weber State University 1995.

[18] H. Kurasawa And T. Suzuki, *Effects of the Dirac sea on the Coulomb sum value for electron scattering. Nucl. Phys.* **A 490** (1988) 571.

[19] A.K. Dutt-Mazumder, B. Dutta-Roy and A. Kundu, *Matter induced ρ-ω mixing*, *Phys. Lett.* **B 399** (1997) 196 [hep-ph/9605247].

[20] B.D. Serot and J.D. Walecka, *The relativistic nuclear many body problem*, *Adv. Nucl. Phys.* **16** (1986) 1.

[21] H.C. Jean, J. Piekarewicz and A.G. Williams, *Medium modification to the ω meson mass in the Walecka model*, *Phys. Rev.* **D 49** (1994) 1981 [nucl-th/9311005].

[22] B.-w. Zhang, D.-f. Hou and J.-r. Li, *The multiple solutions of self-consistency condition in Walecka model and the validity of the brown-ρ scaling law*, *Phys. Rev.* **C 61** (2000) 051302 [hep-ph/0108083].