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Rho meson in dense hadronic matter

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The spectral function of a rho meson that is at rest in dense hadronic matter and couples strongly to the pion is studied in the vector dominance model by including the effect of the delta-hole polarization on the pion. With the free rho-meson mass in the Lagrangian, we find that both the rho-meson peak and width increase with increasing nuclear density, and that a low-mass peak appears at invariant mass around three times the pion mass. Including the decreasing density-dependent hadron masses in the Lagrangian as suggested by the scaling law of Brown and Rho, we find instead that the rho peak moves to smaller invariant masses with diminishing strength when the nuclear density increases. The low-mass peak also shifts down with increasing density and becomes more pronounced. The relevance of the rho-meson property in dense matter to dilepton production in heavy-ion collisions is discussed.

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In heavy-ion collisions the nuclear matter can be compressed to many times the normal nuclear matter density [1]. The study of the property of hadrons in dense matter has recently attracted a lot of attention [2]. We have previously studied dilepton production from the pion-pion annihilation in heavy-ion collisions to see whether one can learn about the pion dispersion relation in a dense medium [3–5]. In particular, we have considered dileptons of invariant mass around twice the pion mass. Gale and Kapusta [6] were the first to show that the dilepton yield around this invariant mass would be enhanced if the softening of the pion spectrum in the nuclear matter is included. This is due to the large momentum range available for the two pions when the pion dispersion relation develops at high densities a minimum at energy less than the pion mass. We have obtained a similar result when the pion self-energy in the nuclear matter is calculated in the delta-hole model [3, 4]. But for dileptons with zero three-momentum the enhancement is canceled by the delta-hole polarization correction to the $\pi\pi\gamma$ vertex as shown by Korpa and Pratt [7], and one obtains instead a suppression of the dilepton yield for invariant mass around twice the pion mass. This cancellation is, however, reduced for dileptons with finite momenta, so there is still some enhancement of the dilepton yield around this invariant mass [5]. The experimental data [8, 9] from the Bevalac on the dilepton invariant mass spectra from heavy-ion collisions have already shown clearly the contribution from the pion-pion annihilation [10, 11]. But for dileptons with invariant masses below about 500 MeV, it is dominated by the eta Dalitz decay and also has an appreciable bremsstrahlung contribution [12]. This makes the enhancement of dileptons with invariant masses around 280 MeV difficult if not impossible to be observed.

Since the electromagnetic form factor of a pion is dominated by the rho meson, the dilepton invariant mass spectrum should also reveal information about the property of the rho meson in dense matter. Since the background from the eta Dalitz decay and bremsstrahlungs is negligible for large dilepton invariant masses, it should be easier to identify the rho meson (770 MeV). In all previous studies [3–6, 10, 11], the free rho-meson mass and width are used in the pion electromagnetic form factor. But studies based on the QCD sum rules show that the rho-meson mass decreases with increasing density as a result of the partial restoration of chiral symmetry in dense matter [2, 13]. This result is similar to the scaling law of Brown and Rho [14] who have shown that the in-medium hadron masses decrease with density and their density dependence is roughly identical when the scaling property of QCD is suitably incorporated in effective chiral Lagrangians. They have also suggested that the residual interactions between in-medium hadrons can then be introduced using effective Lagrangians.

In this paper, we shall report our study of the medium effect on the rho-meson property. This is carried out in the vector dominance model (VDM) [15] together with the in-medium scaling masses of Brown and Rho [14]. The vector dominance model has been previously used by Gale and Kapusta [16] to study the property of a rho meson in a hot pion gas. The details of our study will be published in a lengthier paper.

We shall consider the case of a rho meson at rest in the nuclear matter. Then the strong tensor coupling of the rho meson to the nucleon can be ignored because it is proportional to the rho-meson momentum. Also, the vector coupling of the rho meson to the nucleon can be neglected as the nonrelativistic nucleon particle-hole polarization vanishes at zero momentum. The self-energy

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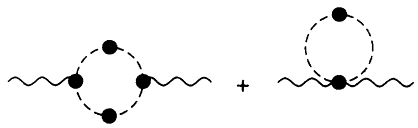

FIG. 1. The rho-meson self-energy diagrams. The wavy and dashed lines with a solid circle denote the rho meson and the pion, respectively.

of a rho meson in the nuclear medium is thus determined by its coupling to the pions, which are modified by the delta-hole polarization in the nuclear matter. This is shown in Fig. 1, where the rho meson is denoted by the wavy line while the dressed pion is given by the dashed line with a solid circle. The second diagram in the figure results from treating the rho meson as a gauge boson in the VDM.

For a rho meson with four-momentum k in the nuclear matter, its self-energy can be expressed as

$$\Sigma^{\mu\nu}(k) = ig_\rho^2 \int \frac{d^4q}{(2\pi)^4} \left\{ \frac{\Gamma^\mu_{\rho\pi\pi}(k,q)\Gamma^\nu_{\rho\pi\pi}(k,q)}{[q^2 - m_\pi^2 - \Pi(q)][(q-k)^2 - m_\pi^2 - \Pi(q-k)]} - \frac{2\Gamma^{\mu\nu}_{\rho\rho\pi\pi}(k,q)}{q^2 - m_\pi^2 - \Pi(q)} \right\}. \tag{1}$$

In the above, g_ρ is the $\rho\pi\pi$ coupling constant and has a value $g_\rho^2/(4\pi) \approx 2.94$ determined from the rho meson width in free space; the pion mass is denoted by m_π.

The $\rho\pi\pi$ vertex $\Gamma^\mu_{\rho\pi\pi}(k,q)$ in Eq. (1) is shown in Fig. 2 and is given by

$$\Gamma^\mu_{\rho\pi\pi}(k,q) \approx (2q-k)^\mu + (q-k)_\nu \Pi^{\nu\mu}(q-k) + q_\nu \Pi^{\nu\mu}(q). \tag{2}$$

The first term is the bare $\rho\pi\pi$ vertex given by the first diagram in Fig. 2 while the next two terms take into account vertex corrections from the delta-hole polarization as shown in diagrams two and three in Fig. 2. There are two other vertex correction diagrams in Fig. 2 which are neglected in the present study as they are expected to be less important than the first three diagrams because of the extra delta or nucleon propagator in the diagrams. When multiplied by k_μ and k_ν, the quantity $\Pi^{\mu\nu}(q)$ gives the pion self-energy $\Pi(q)$ due to the delta-hole polarization, i.e., $\Pi(q) = k_\mu \Pi^{\mu\nu}(q) k_\nu$.

The $\rho\rho\pi\pi$ vertex $\Gamma^{\mu\nu}_{\rho\rho\pi\pi}(k,q)$ in Eq. (1) is given by

$$\Gamma^{\mu\nu}_{\rho\rho\pi\pi}(k,q) \approx g^{\mu\nu} + \Pi^{\mu\nu}(k-q). \tag{3}$$

In the above, the first term is the bare $\rho\rho\pi\pi$ vertex shown by the first diagram of Fig. 3 while the second term is the vertex correction from the second diagram of Fig. 3. The last three vertex correction diagrams in Fig. 3 contain an extra delta or nucleon propagator and are again neglected.

The pion self-energy in the nuclear matter has been extensively studied in the past using the delta-hole model [17]. In the nonrelativistic approximation, it is given by $\Pi(q) \approx \mathbf{q}^2 \chi(q)$, with

$$\chi(q) = \frac{\chi_0(q)}{1 - g'\chi_0(q)}, \tag{4}$$

where $g' \approx 0.6$ is the Migdal parameter representing the short-range delta-hole interaction. For pions with energy q_0 larger than the nucleons' kinetic energy, the delta-hole polarization $\chi_0(q)$ has the approximate form

$$\chi_0(q) \approx \frac{8}{9}\left(\frac{f_\Delta}{m_\pi}\right)^2 \rho_N \frac{\omega_R}{q_0^2 - \omega_R^2} \exp(-2\mathbf{q}^2/b^2), \tag{5}$$

with $\omega_R = \sqrt{\mathbf{q}^2 + m_\Delta{}^2} - m_N - i\Gamma_\Delta/2$. In the above, $f_\Delta \approx 2$ is the $\pi N\Delta$ coupling constant; the width of the form factor is $b \approx 7m_\pi$; and ρ_N is the nuclear matter density. The masses of nucleon and delta are m_N and m_Δ, respectively. The width Γ_Δ of the delta in matter can be calculated self-consistently by extending the usual delta-hole model to include the effect of the softening of the pion spectrum in the nuclear matter [4]. For simplicity, we use here the value in free space, i.e., $\Gamma_\Delta \approx 115$ MeV. We note that according to Ref. [5] $\Pi_{0\mu} = \Pi_{\mu 0} \approx 0$ and $\Pi_{ij}(q) \approx \delta_{ij}\chi(q)$ in the nonrelativistic limit.

We have introduced the factor i in Eq. (1) so that the rho-meson propagator in the medium D is related to the free propagator D_0 by $(D^{-1})^{\mu\nu} = (D_0^{-1})^{\mu\nu} - \Sigma^{\mu\nu}$. The imaginary part of the rho-meson self-energy is obviously finite. But the real part of the self-energy is divergent and needs to be renormalized. This is done by writing it as $\mathrm{Re}\Sigma^{\mu\nu} = (\mathrm{Re}\Sigma^{\mu\nu} - \mathrm{Re}\Sigma_0^{\mu\nu}) + \mathrm{Re}\Sigma_0^{\mu\nu}$. The difference $\Sigma_R^{\mu\nu} = \mathrm{Re}\Sigma^{\mu\nu} - \mathrm{Re}\Sigma_0^{\mu\nu}$, shown in the parentheses, between the real part of the rho-meson self-energies in the medium and in free space is finite as the pion self-energy in the nuclear matter vanishes at large momenta. The di-

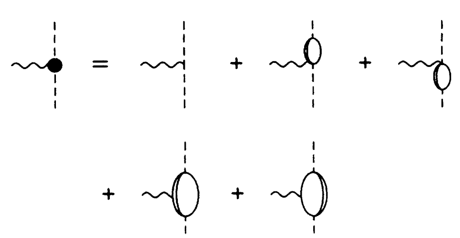

FIG. 2. The $\rho\pi\pi$ vertex. The double and single solid lines denote, respectively, the delta particle and the nucleon hole.

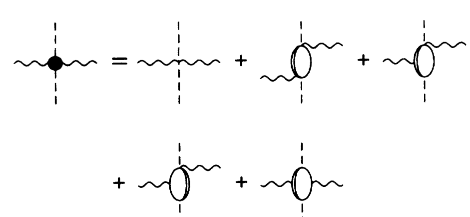

FIG. 3. Same as Fig. 2 for the $\rho\rho\pi\pi$ vertex.

vergent rho-meson self-energy in free space $\mathrm{Re}\Sigma_0^{\mu\nu}$ in the last term is then replaced by the square of the measured rho-meson mass $m_\rho = 770$ MeV.

For a rho meson at rest in the nuclear matter, both $\Sigma_R^{\mu\nu}$ and the imaginary part of the rho meson self-energy $\Sigma_I^{\mu\nu} \equiv \mathrm{Im}\Sigma^{\mu\nu}$ involve only two-dimensional integrations over the energy and momentum of the pion. We have carried out the energy integration analytically using the Cauchy residue theorem, and the remaining momentum integration is evaluated numerically.

If the gauge invariance is kept in the calculation, then the renormalized rho meson self-energy tensor given by $\tilde{\Sigma}^{\mu\nu} \equiv \Sigma_R^{\mu\nu} + i\Sigma_I^{\mu\nu}$ has only three nonvanishing components of the same magnitude: $\tilde{\Sigma}^{11} = \tilde{\Sigma}^{22} = \tilde{\Sigma}^{33} \equiv \Sigma$. The rest are all zero [16]. Neglecting the last two diagrams in Fig. 2 and the last three diagrams in Fig. 3 violates the gauge invariance, and $\tilde{\Sigma}^{00}$ turns out to be nonzero but is much smaller than Σ.

The property of a rho meson in the medium can be expressed by its spectral function which is given by 2π times the imaginary part of its propagator, i.e.,

$$S(M) = -\frac{2\Sigma_I(M)}{[M^2 - m_\rho^2 - \Sigma_R(M)]^2 + [\Sigma_I(M)]^2}, \qquad (6)$$

where Σ_R and Σ_I are the real and imaginary parts of Σ, respectively. We have calculated the rho-meson spectral functions at different nuclear densities. They are shown in Fig. 4. We find that as the nuclear density increases the rho peak shifts to larger invariant masses and its width also becomes larger. These results are similar to those of Chanfray *et al.* [18] who have studied the property of a rho meson in the nuclear matter using a potential model for the interaction between two pions. Our results also show differences from theirs. At high nuclear densities they have found a low-mass peak around twice the pion mass while we have found a peak at masses around three times the pion mass, i.e., the sum of the pion mass and the delta-hole energy. Our low-mass peak comes from the delta-hole polarization correction to the $\rho\rho\pi\pi$ vertex shown by the second diagram in Fig. 3. Their low-mass peak is due to the neglect of the vertex correction in their calculations. Indeed, if we neglect the vertex correction diagrams in both Figs. 2 and 3, and use only the bare vertices in Eq. (1), we also obtain a low-mass peak around twice the pion mass in the rho-meson spectral function at high densities. We note that this low-mass peak in the rho-meson spectral function is related to the predicted enhancement of low mass dilepton pairs from the pion-pion annihilation in heavy-ion collisions [3–6]. The disappearance of the low-mass peak as a result of including the vertex correction is similar to the cancellation found by Korpa and Pratt [7] for the delta-hole polarization correction to the $\pi\pi\gamma$ vertex in the pion-pion annihilation to dileptons with zero three-momentum. This cancellation is, however, reduced for dileptons with finite momenta [5]. It would be interesting to study the smaller invariant mass region of the rho-meson spectral function for nonvanishing three momentum. In this case, the strong vector and tensor couplings of the rho meson to the nucleon need to be included.

As pointed out in the introduction, the rho-meson mass in the effective Lagrangian should be density-dependent as well [14]. This can be included by adopting the scaling law of Ref. [14] and using the empirical density-dependent nucleon effective mass, i.e.,

$$\frac{m_\rho}{m_\rho^{(0)}} \approx \frac{m_N}{m_N^{(0)}} \approx \frac{m_\Delta}{m_\Delta^{(0)}} \approx \frac{\Gamma_\Delta}{\Gamma_\Delta^{(0)}} \approx \frac{1}{1+0.25\rho/\rho_0}, \qquad (7)$$

where ρ_0 is the normal nuclear density. As the pion is a Goldstone boson, its mass in the medium behaves differently and has been assumed to remain unchanged [14]. Because of the small pion mass, we have assumed in the above that the delta width in the medium scales in a similar way. Using this value of rho-meson mass in Eq. (6), we have repeated the above calculations. The results are shown in Fig. 5. It is seen that the rho peak in the spectral function moves to a smaller invariant mass with diminishing strength when the density becomes higher. The low-mass peak also shifts down with increasing density but becomes more pronounced than in the case with bare hadron masses.

In summary, we have studied the rho-meson property in dense matter using the Vector Dominance Model by including the medium effect on the pion in the delta-hole model. With the free rho-meson mass in the VDM Lagrangian, we find that both the mass and width of

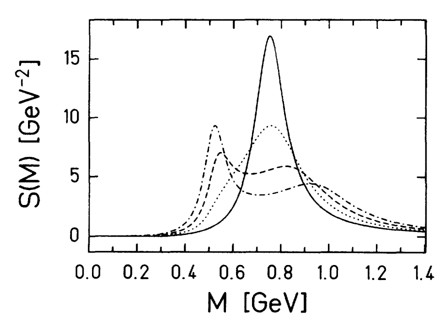

FIG. 4. The spectral function of a rho meson. The solid curve is for a rho meson in free space. For a rho meson in the medium, the dotted, dashed, and dash-dotted curves correspond, respectively, to nuclear densities of ρ_0, $2\rho_0$, and $3\rho_0$, where ρ_0 is the normal nuclear matter density.

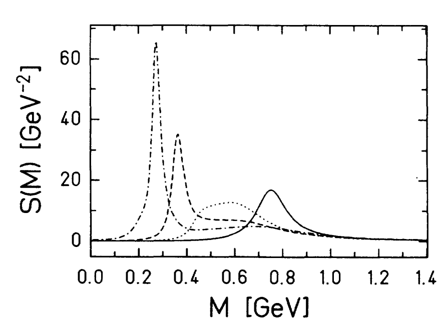

FIG. 5. Same as Fig. 4 with the density-dependent hadron masses in the effective Lagrangian.

a rho meson in dense matter are increased but with fragmented strength leading to a low-mass peak around $3m_\pi$. With a decreasing density-dependent rho-meson mass in the VDM Lagrangian as suggested by the scaling law of Brown and Rho [14], we find instead that the rho-meson mass becomes smaller in dense matter but its strength is reduced significantly. The low-mass peak in the rho-meson spectral function moves to a smaller invariant mass and its strength becomes more pronounced. This result is consistent with what one expects from the restoration of chiral symmetry in dense matter. We thus believe that for the two cases we have studied the one with a decreasing density-dependent rho-meson mass is more realistic. The relation between our result and that from the QCD sum rules [13] is, however, not well understood and deserves further study. Although it will be more difficult to identify the rho meson from the dilepton invariant mass spectrum as its mass becomes smaller because of the background from eta decay and bremsstrahlungs, future experiments to measure the dilepton invariant mass spectrum from heavy-ion collisions still provides a good and probably the only opportunity to verify experimentally the predicted property of rho meson in dense nuclear matter.

Note added in proof. Similar studies have also been carried out by Herrmann, Friman, and Nörenberg [Z. Phys. A **343**, 119 (1992)]. They have not, however, included the delta width and the scaling in-medium hadron masses of Brown and Rho.

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