CHIRAL MIXING IN DENSE QCD MATTER*

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We study the vector spectral function in the presence of the chiral mixing induced by finite baryon density. The transverse polarizations receive a direct modification from the mixing, so that the entire spectral function is deformed drastically at high density. This becomes significantly pronounced when the mass difference between parity partners decreases. The resultant enhancement in the production rates of dileptons serves as an excellent signature of the partially-restored chiral symmetry to be verified in heavy-ion collisions.

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1. Introduction

The light vector mesons, which may change their chiral properties in hot/dense matter, directly couple to the electromagnetic current–current correlation function. A virtual photon can propagate in a medium without disturbance and decays into a pair of leptons. Dileptons are thus one of the promising probes of the chiral symmetry restoration driven by finite temperature and/or baryon density. An enhancement of the dilepton spectra below the ρ/ω resonances observed at the CERN SPS is a strong evidence that the vector mesons indeed change their characteristics [1]. Yet, it is inconclusive whether the observed modification is the direct consequence of the chiral restoration.

The ideal way to characterize the restoration is to measure the *degenerate* current–current correlation functions in opposite parity channels. There exist combinatorial complications which make it technically difficult to reconstruct the in-medium axial-vector spectrum. The key facet in this situation is the fact that the axial-vector meson contributes to the vector spectrum

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in a medium via the *chiral mixing*, *i.e.* potential modifications of the axial-vector state can emerge not only in the axial-vector but also in the vector spectral functions.

In this contribution, we briefly present the model-independent consequence of the absence of charge conjugation invariance at finite chemical potential, which leads to a new class of the chiral mixing, and how the vector spectrum and dilepton production rates are modified by the mixing near the chiral symmetry restoration based on [2].

2. Chiral mixing

In a medium, the pion loop yields a mixing of the vector with the axial-vector correlator. At low temperature or density, this phenomenon is known as a model-independent theorem [3–5]. There exist some systematic calculations at finite temperature via the theorem [6, 7] and in a chiral reduction formalism [8]. Within a chiral effective theory at one-loop order, it was shown that the chiral symmetry restoration dictates the two distinct maxima of the vector and axial-vector states in the correlators to be merged, leading to *no* chiral mixing [9]. One finds the same trend in Ref. [10] where the axial-vector spectral function at finite temperature was constructed by utilizing in-medium Weinberg's sum rules [11], and a substantial mass drop of the a_1 meson as well as a strong width broadening of the ρ and a_1 near the chiral symmetry restoration were reported.

There exists another distinct class of the chiral mixing at finite baryon density. The corresponding operator appears at tree level in the chiral Lagrangian and thus directly modifies the dispersion relations of the vector and axial-vector states. This term emerges in the 4-dim low-energy effective theory of QCD-like theories based on the AdS/CFT correspondence [12], producing the following dispersion relations for the transverse polarizations:

$$p_0^2 - \vec{p}^{\,2} = \frac{1}{2}\left[m_{\mathrm{V}}^2 + m_{\mathrm{A}}^2 \pm \sqrt{\left(m_{\mathrm{A}}^2 - m_{\mathrm{V}}^2\right)^2 + 16\,c^2\vec{p}^{\,2}}\right], \tag{1}$$

with the lower sign for the vector and the upper one for the axial-vector mesons, and the mixing parameter c. The longitudinal polarizations follow the ordinary dispersion relations, $p_0^2 - \vec{p}^{\,2} = m_{\mathrm{V,A}}^2$. The mixing strength c carries an explicit dependence on the net baryon density ρ_{B} and its value can be determined in the standard prescription along with the gauged Wess–Zumino–Witten action. With empirical numbers, one obtains the expectation value of the omega meson $\langle\omega_0\rangle = g_{\omega NN}\,\rho_{\mathrm{B}}/m_\omega^2$, hence the strength $c = g_{\omega\rho a_1}\langle\omega_0\rangle \simeq 0.1$ GeV at normal nuclear density ρ_0 [13].

Its phenomenological impact in dense QCD is a structural change of the vector spectrum which may lead to visible modifications in dilepton rates under the assumption that those mesons do not change their masses, although this requires a rather strong mixing $c \simeq 0.3$ GeV [13]. The mixing effect becomes stronger as density is increased, on the other hand, the partial restoration of chiral symmetry is expected to set in gradually as well. In the recent paper [2], we have introduced the chiral order parameter as a function of temperature and chemical potential to the current correlation function in the presence of the density-induced mixing, and carefully examined a possible signal of the partially restored chiral symmetry, with a special emphasis put on the competition between the in-medium mixing and the mass degeneracy of the parity partners, as well as their self-consistent determination.

In the following, we utilize the nucleon parity-doublet model to quantify the explicit dependence of temperature and baryon density of the sigma $\langle\sigma\rangle$ and omega $\langle\omega_0\rangle$ expectation values in the mean field approximation, where the lowest nucleon and its negative-parity counterpart $N(1535)$ play the important role in describing the nuclear ground state and its stability [14, 15]. The model has been extended further by introducing the confinement nature and confronted with the recent observations of neutron stars and their mergers [16]. In Fig. 1, we present the mass-splitting, which is equivalent to the order parameter of chiral symmetry breaking, and the chiral mixing at temperature $T = 50$ MeV *versus* baryon chemical potential μ_{B}.

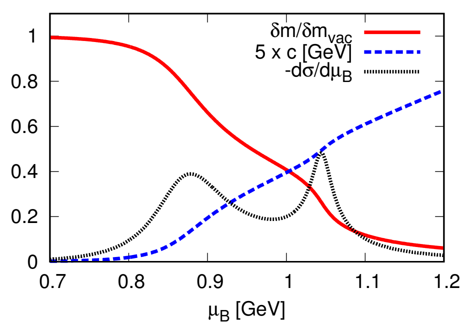

Fig. 1. The mass difference of the opposite parity states, δm, normalized by its vacuum value, the chiral mixing c and the derivative of the sigma mean-field at temperature $T = 50$ MeV as functions of baryon chemical potential μ_{B} [2].

The model yields a chiral crossover at $\mu_{\mathrm{B}} \simeq 1.05$ GeV (equivalently, the pseudo-critical density $\rho_{\mathrm{B}} \simeq 2.5\,\rho_0$), at which all the parity partners involved in this study, *i.e.* the nucleon and $N(1535)$, the scalar and pseudo-scalar as well as the vector and axial-vector states, become nearly degenerate.

We will not naively replace $\langle\omega_0\rangle$ with $\langle\phi_0\rangle$ to find the mixing between the ϕ and $f_1(1420)$ states because of the following reason: The mean-field calculations typically yield the strange-quark condensate $\langle\bar{s}s\rangle$ decreasing in a much milder way than the light-quark condensate, resulting in a significant delay of vanishing δm in the strange-quark sector. This obviously contradicts the vector screening mass of the $\bar{s}s$ state found in lattice QCD simulations [17], where a large set of the screening masses exhibits a substantial modification near the chiral crossover and this arises nearly independent of the quark flavors. Therefore, we shall impose the same critical behavior as in the lattice observation, *i.e.* the modification of the ϕ and $f_1(1420)$ states is dominated by the two-flavor chiral dynamics, which is well-justified for the bulk thermodynamic quantities and a large set of various charge fluctuations and correlations in $N_\mathrm{f} = 2+1$ QCD.

3. Dilepton production

With the given chiral Lagrangian together with the mixing term, one readily constructs the vector-current correlator. Its imaginary part, *i.e.* the spectral function, at $T = 50$ MeV is shown in Fig. 2. In the ρ–ω sector, the distinct peak of the longitudinal ω meson stays at any μ_B but its strength is gradually decreased as the density is increased because of the mixing effect. At $\delta m/\delta m_\mathrm{vac} = 0.7$, the system remains rather far from the chiral restoration and the mixing effect with $c \simeq 34$ MeV is entirely irrelevant. At higher μ_B, the mixing effect starts to be enhanced because of decreasing $\delta m/\delta m_\mathrm{vac}$, and the spectrum shows multiple bumps of the transverse polarizations. The transverse ρ gets lighter to produce a substantial contribution near the chiral crossover, leading to a strong enhancement at small $\sqrt{s}$ in the spectrum.

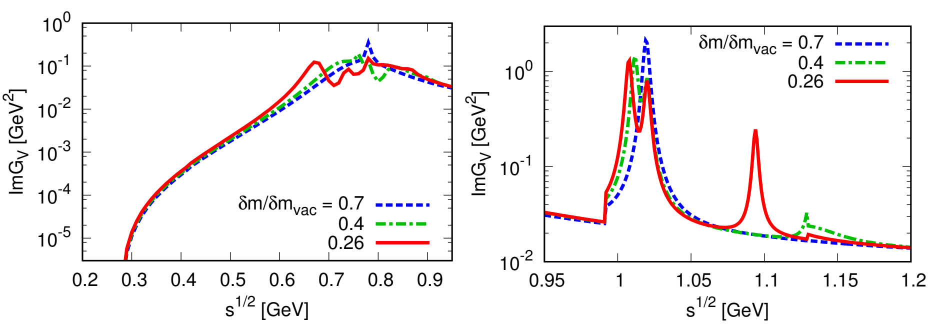

Fig. 2. The vector spectral function with $|\vec{p}| = 0.5$ GeV at $T = 50$ MeV in the ρ–ω (left) and ϕ (right) channels for $\delta m/\delta m_\mathrm{vac} = 0.7, 0.4$ and 0.26 [2].

In the ϕ sector at the chiral crossover ($\delta m/\delta m_{\rm vac} = 0.26$), the typical structure with the three bumps is clearly seen. The most-left peak of the transverse ϕ shifts its position to lower $\sqrt{s}$ as $\mu_{\rm B}$ is increased, and when it meets the $2m_K$ threshold a two-peak structure emerges for some smaller $\delta m/\delta m_{\rm vac}$. It is emphasized that these modifications in the spectral function disappear totally when the mass of the axial-vector meson stays unchanged. Therefore, the drastic change seen in Fig. 2 is the *direct* consequence of the partially restored chiral symmetry.

Given the in-medium vector spectrum, one can straightforwardly calculate the production rate of a lepton pair. The differential rate at finite T and $\mu_{\rm B}$ is represented with the imaginary part of the vector correlation function as

$$\frac{{\rm d}N}{{\rm d}^4p}\left(p_0,\vec{p};T,\mu_{\rm B}\right) = \frac{\alpha^2}{\pi^3 s}\frac{{\rm Im}G_{\rm V}\left(p_0,\vec{p};T,\mu_{\rm B}\right)}{{\rm e}^{p_0/T}-1}\,, \tag{2}$$

where $\alpha = e^2/4\pi$ is the electromagnetic coupling constant. We define the three-momentum integrated rate as

$$\frac{{\rm d}N}{{\rm d}s}\left(s;T,\mu_{\rm B}\right) = \int \frac{{\rm d}^3\vec{p}}{2p_0}\frac{{\rm d}N}{{\rm d}^4p}\left(p_0,\vec{p};T,\mu_{\rm B}\right)\,. \tag{3}$$

In Fig. 3, we show the integrated rate of dileptons in the range of $0 \leq |\vec{p}| \leq 1$ GeV at $T = 50$ MeV for two representative values, $\delta m/\delta m_{\rm vac} = 0.4$ and 0.26. The characteristic modification remains there, although somewhat weakened because of the integral over $\vec{p}$. The modified ρ and ω mesons yield a significant enhancement in low $\sqrt{s}$ region, and the axial-vector partner of the ϕ meson produces one additional and well-separated peak around $\sqrt{s} \sim 1.1$ GeV near the chiral symmetry restoration, whereas the transverse ϕ appears rather close to the longitudinal polarization with the given $\mu_{\rm B}$, and consequently the spectrum around the vacuum ϕ state becomes broadened.

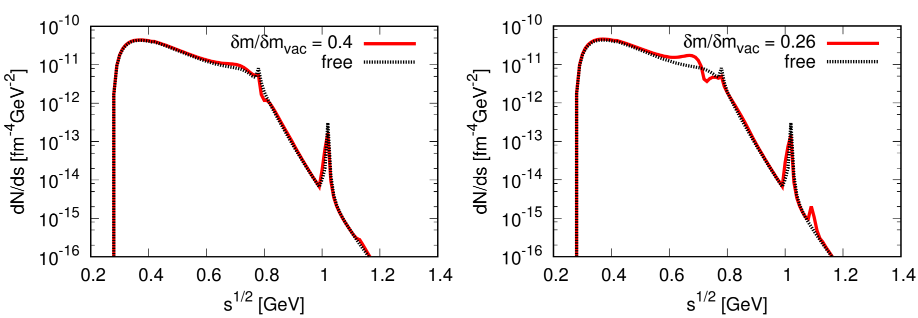

Fig. 3. The dilepton production rate at $T = 50$ MeV for $\delta m/\delta m_{\rm vac} = 0.4$ (left) and 0.26 (right) [2].

In the above calculations, widths broadening due to many-body interactions was excluded just for simplicity. In a more realistic set-up with the baryon-induced interactions, the observed new structure in the spectrum may be screened, especially in the ρ–ω sector. On the other hand, the ϕ meson is expected to stay as a narrow resonance in a medium [18]. Therefore it is anticipated that the modified ϕ spectrum is more adequate of being a convincing signal of the chiral symmetry restoration. An illustrative calculation for potential effects from the width broadening is presented at the chiral restoration point $\delta m/\delta m_{\rm vac} = 0.26$ in Fig. 4. One clearly finds the enhancement below and above the vacuum ϕ meson survives. This encourages us to possibly measure a signature of the chiral symmetry restoration along with the chiral mixing if the created matter in heavy-ion collisions is sufficiently dense and cold.

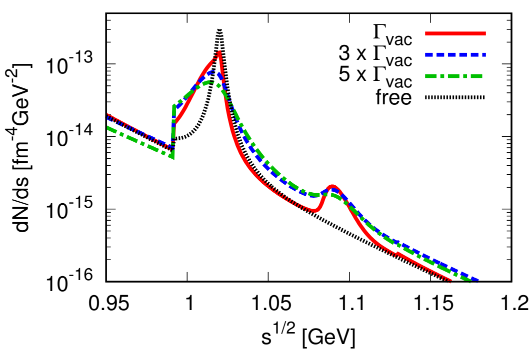

Fig. 4. The dilepton production rate at $T = 50$ MeV for $\delta m/\delta m_{\rm vac} = 0.26$ with various decay widths of the ϕ meson [2].

4. Summary

We have studied the consequences of the absence of charge conjugation invariance at finite density, resulting in the modified dispersion relations for the transverse polarizations of the vector and axial-vector states. This further leads to the characteristic structural change of the vector spectral function and thus the dilepton production rates as well.

The most striking result is that, even with a marginal strength of the chiral mixing, $c \sim 0.1$ GeV, decreasing δm reinforces the structural modification of the spectral function, in a sharp contract to the scenario without the chiral restoration [13]. Therefore, the arising enhancement around the vector resonances, especially the ϕ meson and its parity partner, in the dilepton rates serves as a promising signature of the restored chiral symmetry to be verified in heavy-ion collisions at FAIR, NICA and J-PARC.

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