Light Vector Mesons at Finite Baryon Density *

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Abstract

We summarize the current theoretical and experimental status of the spectral changes of vector mesons ($\rho$, $\omega$, $\phi$) at finite baryon density. Various approaches including QCD sum rules, effective theory of hadrons and bag models show decreasing of the vector meson masses in nuclear matter. Possibility to detect the mass shift through lepton pairs in $\gamma - A$, $p - A$ and $A - A$ reactions are also discussed.

I. INTRODUCTION

At high temperature ($T$) and density ($\rho$), hadronic matter is expected to undergo a phase transition to the quark-gluon plasma. The order parameter characterizing the transition is the chiral quark condensate $\langle \bar{q}q \rangle$, the absolute value of which decreases as ($T, \rho$) increases. Numerical simulations of quantum chromodynamics (QCD) on the lattice are actively pursued to determine the precise nature of the transition at finite $T$ [1], and various model calculations have been done to look for the observable signature of the phase transition.

In this talk, I will concentrate on one of the interesting critical phenomena associated with the QCD phase transition, namely the spectral change of hadrons, in particular the mass shift of light vector-mesons ($\rho$, $\omega$ and $\phi$) in nuclear matter at zero $T$. The vector mesons are unique in the sense that they decay into lepton pairs ($e^+e^-$ and $\mu^+\mu^-$) which can be detected experimentally without much disturbance by complicated hadronic interactions.

In section 2, I will review the current knowledge of the quark condensate in medium. In section 3, various approaches to calculate the vector meson masses in nuclear matter are summarized. Experimental possibilities to detect the spectral change are discussed in section 4. Concluding remarks are given in section 5.

II. QUARK CONDENSATES IN NUCLEAR MATTER

The medium modification of the quark condensate has been calculated since then by various methods (lattice QCD, chiral perturbation theory, Nambu-Jona-Lasinio model etc). See an overview [2]. By these studies, it turned out that there is one noticeable difference

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between the behavior of $\langle \bar{q}q \rangle$ at finite $T$ (with $\rho = 0$) and that at finite $\rho$ (with $T = 0$): In the former case, the significant change of the condensate can be seen only near the critical point $T \sim T_c$ [3]. On the other hand, in the latter case, $O(30\%)$ change of $\langle \bar{q}q \rangle$ could be seen even in normal nuclear-matter density. This observation is based on the following formula in the fermi-gas approximation (independent particle approximation) [4]

$$\langle \bar{u}u \rangle \langle \bar{u}u \rangle_0 \simeq 1 - \frac{4\Sigma_{\pi N}}{f_\pi^2 m_\pi^2} \int_{p_F}^{p_F} d^3 p \frac{M_N}{(2\pi)^3 E(p)}.$$  \hspace{1cm} (1)

Here $m_N(m_\pi)$ is the nucleon (pion) mass, $f_\pi$ is the pion decay constant, $\Sigma_{\pi N} = (45 \pm 10)\text{MeV}$ is the $\pi N$ sigma term, and $E(p) \equiv \sqrt{p^2 + M_N^2}$. $\langle \cdot \rangle$ and $\langle \cdot \rangle_0$ denote the expectation value in nuclear matter and that in the vacuum respectively. The integration for the nucleon momentum $p$ should be taken from 0 to the fermi momentum $p_F$. At normal nuclear matter density ($\rho = \rho_0 = 0.17/\text{fm}^3$), the above formula gives $(34 \pm 8)\%$ reduction of the chiral condensate from the vacuum value. In Fig.1, $\langle \bar{u}u \rangle / \langle \bar{u}u \rangle_0$ as well as the strangeness condensate $\langle \bar{s}s \rangle / \langle \bar{s}s \rangle_0$ are shown in the linear density approximation [5], where the uncertainty of $\Sigma_{\pi N}$ is considered. Estimates taking into account the fermi motion and the nuclear correlations show that these corrections at $\rho = \rho_0$ are less than the above uncertainty [3].

Unfortunately, the condensate itself is not a direct observable and one has to look for physical quantities which are measurable and simultaneously sensitive to the change of the condensate. The masses of light vector-mesons are the leading candidates of such quantities.

### III. VECTOR MESONS IN NUCLEAR MATTER

Let’s consider $\rho$, $\omega$ and $\phi$ mesons propagating inside the nuclear matter. Adopting the same fermi-gas approximation with (1) and taking the vector meson at rest ($\mathbf{q} = 0$), one can generally write the mass-squared shift as

$$\delta m_V^2 \equiv m_V^{*2} - m_V^2 = 4 \int_{p_F}^{p_F} d^3 p \frac{M_N}{(2\pi)^3 E(p)} f_{V N}(\mathbf{p}),$$  \hspace{1cm} (2)

where $f_{V N}(\mathbf{p})$ denotes the vector-meson (V) – nucleon (N) forward scattering amplitude in the relativistic normalization, and $m_V^{*}(m_V)$ denotes the vector meson mass in nuclear matter (vacuum). Here, we took spin-isospin average for the nucleon states in $f_{V N}$. If one can calculate $f_{V N}(\mathbf{p})$ reasonably well in the range $0 < p < p_F = 270 \text{ MeV}$ (or $1709 \text{ MeV} < \sqrt{s} < 1726 \text{ MeV}$ in terms of the $V - N$ invariant mass), one can predict the mass shift. Unfortunately, this is a difficult task: $f_{V N}(\mathbf{p})$ is not a constant in the above range since there are at least two $s$-channel resonances $N(1710), N(1720)$ in the above interval and two nearby resonances $N(1700)$ and $\Delta(1700)$. They all couple to the $\rho - N$ system [3] and give variation of $f_{V N}(\mathbf{p})$ as a function of $p$ in principle. From this reason, one should develop other methods to estimate $\delta m_V^2$ without referring to the detailed form of $f_{V N}(\mathbf{p})$. We will briefly review two of such approaches in the following subsections, namely the QCD sum rules and effective theories of hadron.
A. QCD sum rules

The QCD sum rules (QSR) for vector mesons in nuclear matter were first developed by Hatsuda and Lee [8]. In their approach, one starts with the retarded current correlation function in nuclear matter,

$$\Pi_{\mu\nu}(\omega, q) = i \int d^4x e^{iqx} \langle RJ_\mu(x)J_\nu(0) \rangle,$$  \hspace{1cm} (3)

where $q^\mu \equiv (\omega, q)$ and $RJ_\mu(x)J_\nu(0) \equiv \theta(x^0)[J_\mu(x), J_\nu(0)]$ with the source currents $J_\mu$ defined as $J_\rho,\omega \mu = \frac{1}{2}(\bar{u}\gamma_\mu u \mp \bar{d}\gamma_\mu d)$ ($- (+)$ is for the $\rho^0(\omega)$-meson) and $J_\phi^\mu = \bar{s}\gamma_\mu s$. Although there are two independent invariants in medium (transverse and longitudinal polarization), they coincide in the limit $q \to 0$ and reduce to $\Pi_{\mu\mu}/(-3\omega^2) \equiv \Pi$. $\Pi$ satisfies the following dispersion relation,

$$\text{Re}\Pi(\omega^2) = \frac{1}{\pi} P \int_0^\infty du \frac{\text{Im}\Pi(u)}{u^2 - \omega^2} + \text{(subtraction)}.$$ \hspace{1cm} (4)

In QSR, the spectral density $\text{Im}\Pi$ is modeled with several phenomenological parameters, while $\text{Re}\Pi$ is calculated using the operator product expansion (OPE). The phenomenological parameters are then extracted by matching the left and right hand side of (4) in the asymptotic region $\omega^2 \to -\infty$. The density dependence in the OPE side is solely determined by the density dependent condensates which are evaluated from low energy theorems or from the parton distribution of the nucleon [8].

In the medium, we have three kinds of structure in the spectral density: the resonance poles, the continuum and the Landau damping contribution. For $q \to 0$, the last contribution is calculable exactly and behaves like a pole at $\omega^2 = 0$ [8,9]. In total, the hadronic spectral function looks as

$$8\pi \text{Im}\Pi(u > 0^{-}) = \delta(u^2)\rho_{sc} + F^*\delta(u^2 - m_V^2) + (1 + \frac{\alpha_s}{\pi})\theta(u^2 - S_0^*) \equiv \rho_{had.}(u^2),$$ \hspace{1cm} (5)

with $\rho_{sc} = 2\pi^2\rho/\sqrt{p_F^2 + M_N^2} \simeq 2\pi^2\rho/M_N$. $m_V^*$, $F^*$ and $S_0^*$ are the three phenomenological parameters in nuclear matter to be determined by the sum rules.

Matching the OPE side and the phenomenological side via the dispersion relation in the asymptotic region $\omega^2 \to -\infty$, we can relate the resonance parameters to the density dependent condensates. There are two major procedures for this matching, namely the Borel sum rules (BSR) [11] and the finite energy sum rules (FESR) [11], which can be summarized as

$$\int_0^\infty ds \ W(s) \ [\rho_{had.}(s) - \rho_{OPE}(s)] = 0,$$ \hspace{1cm} (6)

$$W(s) = s^n \theta(S_0 - s) \quad \text{(FESR)}, \hspace{1cm} e^{-s/M^2} \quad \text{(BSR)}.$$ \hspace{1cm} (7)

Here the spectral function $\rho_{had.}(s)$ stands for eq.(5). $\rho_{OPE}(s)$ is a hypothetical imaginary part of $\Pi$ obtained from OPE.

To make quantitative analyses of spectral parameters, the stability analysis based on the Borel transform is more suitable than FESR. Since the Borel mass $M$ is a fictitious parameter introduced in the sum rule, the physical quantities should be insensitive to the
change of $M$ within a Borel interval $M_{\min} < M < M_{\max}$; namely the principle of minimum sensitivity (PMS) is used. One can accomplish this insensitivity by choosing $S_0^*$ suitably at given density. In Fig. 2, the Borel curves for the $\rho(\omega)$ meson for three different values of baryon density are shown with $S_0^*$ chosen to make the Borel curve as flat as possible in the interval $0.41\text{GeV}^2 < M^2 < 1.30\text{GeV}^2$. The upper (lower) bound of the Borel interval is determined so that the power (continuum) correction after the Borel transform does not exceed 30% of the lowest order term in OPE.

By making a linear fit of the result, one obtains [8]

$$m_{\rho,\omega}^* = 1 - (0.15 \pm 0.05) \frac{\rho}{\rho_0},$$

$$\sqrt{\frac{S_0^*}{S_0}} = 1 - (0.15 \pm 0.05) \frac{\rho}{\rho_0},$$

$$F^* = 1 - (0.24 \pm 0.07) \frac{\rho}{\rho_0},$$

and

$$m_{\phi}^* = 1 - (0.15 \pm 0.05) \frac{\rho}{\rho_0},$$

where $y$ is the OZI breaking parameter in QCD defined as $y = 2\langle \bar{s}s \rangle_N/\langle \bar{u}u + \bar{d}d \rangle_N$ with $\langle \cdot \rangle_N$ being the nucleon matrix element. $y$ takes the value $0.1 - 0.2$ [8]. The decrease in eqs. (8,11) is dictated by the density dependent condensates $\langle \bar{q}q \rangle$, $\langle (\bar{q}q)^2 \rangle$ and $\langle \bar{q}\gamma_\mu D_\nu q \rangle$. The errors in the above formulas are originating from the uncertainties of the density dependence of these condensates. The contribution of the quark-gluon mixed operator with twist 4, [8] which may possibly weaken the mass shift, is neglected in the above. Shown in Fig. 3 is the mass shift given in eqs. (8,11) with possible theoretical uncertainties.

Some sophistications of the QSR analyses by Hatsuda and Lee have been done later by several authors.

(i) Asakawa and Ko have introduced a more realistic spectral function than (3) by taking into account the width of the $\rho$-meson and the effect of the collisional broadening due to the $\pi - N - \Delta - \rho$ dynamics [12]. By doing the similar QSR analysis as above, they found that the negative mass shift persists even in this realistic case. The width of the rho meson in their calculation decreases as density increases, which implies that the phase space suppression from the $\rho \to 2\pi$ process overcomes the collisional broadening at finite density. Further examination of this interplay between the mass shift and the collisional broadening is important in relation to the future experiments. Also, finite temperature generalization of the Asakawa-Ko’s calculation should be done.

(ii) Monte Carlo based error analysis was applied to the Borel sum rule by Jin and Leinweber [13] instead of the Borel stability or PMS analysis employed in [8]. They found $m_{\rho,\omega}^*/m_{\rho,\omega} = 1 - (0.22 \pm 0.08)(\rho/\rho_0)$ and $m_{\phi}^*/m_{\phi} = 1 - (0.01 \pm 0.01)(\rho/\rho_0)$, which are consistent with eqs. (8,11) within the error bars.

(iii) Koike analysed an effective scattering amplitude $\tilde{f}_{VN}$ defined as $\delta m_V^2 \equiv \tilde{f}_{VN} \cdot \rho$ using the QSR in the vacuum [14]. Although his original calculation predicting $\tilde{f}_{VN} > 0$ is in error as was pointed out in ref. [8,13], revised calculation gives a consistent result with eqs. (8,11) within the error bars [13]. Note here that $\tilde{f}_{VN}$ does not have direct relation to the scattering length at zero momentum $f_{VN}(0)$. 


B. Effective theories

There have been many attempts so far to calculate the spectral change of the vector mesons using effective theories of QCD. The first attempt by Chin [16] using the quantum hadrodynamics (QHD) shows increasing $\omega$-meson mass in medium due to a process analogous to the Compton scattering:

$$\omega + N \rightarrow \omega + N.$$  \hspace{1cm} (12)

For the $\rho$-meson, similar but more sophisticated calculations taking into account $\Delta$-resonance and in-medium pion show a slight increase of the $\rho$-meson mass [17]. In these calculations, only the polarization of the Fermi sea (the particle-hole excitations) was considered. Also their predictions are different from the general assertion by Brown and Rho claiming that all the hadron masses except for pion should decrease [18].

On the other hand, Saito, Maruyama and Soutome, and Kurasawa and Suzuki [19] have realized that the mass of the $\omega$-meson is affected substantially by the vacuum polarization of the nucleon in medium

$$\omega \rightarrow N^* \bar{N}^* \rightarrow \omega,$$  \hspace{1cm} (13)

where $N^*$ is the nucleon in nuclear matter which has smaller effective mass than that in the vacuum. They show that the vacuum polarization dominates over the Fermi-sea polarization in QHD and leads decreasing vector meson mass. This conclusion was later confirmed by several groups [20] and was generalized for the $\rho$ and $\phi$ mesons [21]. Jaminon and Ripka has also reached a similar conclusion by using a model of vector mesons coupled to constituent quarks [22].

Saito and Thomas have examined a rather different but comprehensive model (bag model combined with QHD) and found decreasing vector-meson masses [23]; $m_{\rho,\omega}^* / m_{\rho,\omega} \sim 1 - 0.09(\rho/\rho_0)$. The spectral shift of the quarks inside the bag induced by the existence of nuclear medium plays a key role in this approach.

Basic idea common in the approaches predicting the decreasing mass may be summarized as follows. In nuclear matter, scalar ($\sigma$) and vector ($\omega$) mean-fields are induced by the nucleon sources. These mean-fields give back-reactions to the nucleon propagation in nuclear matter and modify its self-energy. This is an origin of the effective nucleon mass $M_N^* < M_N$ in the relativistic models for nuclear matter. The same mean-fields should also affect the propagation of vector mesons in nuclear medium. In QSR, the quark condensates act on the quark propagator as density dependent mean-fields. In QHD, the coupling of the mean-field with the vector mesons are taken into account through the short distant nucleon loop with the effective mass $M_N^*$. In the bag-model, the mean fields outside the bag acts on quarks confined in the bag and change their energy spectrum.

Let us show here that one can understand the negative mass shift of the vector mesons in a simple and intuitive way in the context of QHD. More quantitative discussion will be given in the later section. After renormalizing infinities in the vacuum loop, the density-dependent part of the Dirac-sea polarization to the vector-meson propagator is approximately written as

$$D(q) \simeq \frac{1}{Z^{-1}q^2 - m_V^2} = \frac{Z}{q^2 - Zm_V^2},$$  \hspace{1cm} (14)
where $Z$ being the finite wave-function renormalization constant in medium. The pole position is thus obtained as $m_V^* = \sqrt{Z} m_V$. Because of the current conservation, only the wave function part of the propagator is modified in medium. Since the effective mass of the nucleon decreases in medium ($M_N^*/M_N < 1$), physical vector mesons have more probability to be in virtual baryon–anti-baryon pairs compared to that in the vacuum. This means $Z < 1$, which leads to $m_V^*/m_V \equiv Z < 1$ [20,21].

$$M_N^*/M_N < 1 \rightarrow Z < 1 \rightarrow m_V^*/m_V \equiv Z < 1.$$  

IV. EXPERIMENTS

How one can detect the spectral change of vector mesons in experiments? One of the promising ideas is to use heavy nuclei and produce vector mesons in $\gamma - A$ or $p - A$ reactions. Suppose one could create a vector meson at the center of a heavy nucleous. (It does not matter whether it is created at the nuclear surface or at the center as far as the produced vector mesons run through the nucleous before the hadronic decay). It is easy to see that the number of lepton pairs decaying inside the nucleous $N_{in}(l^+l^-)$ and that outside the nucleous $N_{out}(l^+l^-)$ are related as

$$\frac{N_{in}(l^+l^-)}{N_{out}(l^+l^-)} \sim \frac{1 - e^{-\Gamma_{tot}R}}{e^{-\Gamma_{tot}R}},$$  

where $\Gamma_{tot}$ denotes the total width of vector mesons ((1.3fm)$^{-1}$, (23fm)$^{-1}$ and (45fm)$^{-1}$ for $\rho$, $\omega$ and $\phi$, respectively) and $R$ being the nuclear radius. Eq.(16) shows that even the $\phi$ meson has considerable fraction of $N_{in}/N_{out}$ if the target nucleous is big enough.

There exist already some proposals to look for the mass shift of vector mesons in nuclear medium [24]. One is by Shimizu et al. who propose an experiment to create $\rho$ and $\omega$ in heavy nuclei using coherent photon - nucleus reaction and subsequently detect the lepton pairs from $\rho$ and $\omega$. Enyo et al. propose to create $\phi$ meson in heavy nuclei using the proton-nucleus reaction and to measure kaon pairs as well as the lepton pairs. By doing this, one can study not only the mass shift but also the change of the leptonic vs hadronic branching ratio $r = \Gamma(\phi \rightarrow e^+e^-)/\Gamma(\phi \rightarrow K^+K^-)$. Since $m_\phi$ is very close to $2m_K$ in the vacuum, any modification of the $\phi$-mass or the $K$-mass changes the ratio $r$ substantially as a function of mass number of the target nucleous. Similar kinds of experiments are also planned at GSI.

There are also on-going heavy ion experiments at SPS (CERN) and AGS (BNL) where high density matter is likely to be formed. In particular, CERES/NA45 and HELIOS-3 at CERN reported enhancement of the lepton pairs below the $\rho$ resonance [25,26], which may not be explained by the conventional sources of lepton pairs. If this phenomena is real, low mass enhancement of the lepton pair spectrum expected by the mass shift of the vector mesons could be a possible explanation [27]. In nuclear collisions at higher energies (RHIC and LHC), hot hadronic matter or possibly the quark-gluon-plasma with low baryon density are expected to be formed. In such cases, double $\phi$-peak structure proposed by Asakawa and Ko [28] as well as the spectral change of $\rho$, $\omega$ and scalar mesons [29] will be a distinct signal of the chiral restoration in QCD.
V. CONCLUDING REMARKS

The spectral change of the elementary excitations in medium is an exciting new possibility in QCD. By studying such phenomenon, one can learn the structure of the hadrons and the QCD ground state at finite \((T, \rho)\) simultaneously. Theoretical approaches such as the QCD sum rules and the hadronic effective theories predict that the light vector mesons \((\rho, \omega, \phi)\) are sensitive to the partial restoration of chiral symmetry in hot/dense medium. These mesons are good probes experimentally, since they decay into lepton pairs which penetrate the hadronic medium without losing much information. Thus, the lepton pair spectroscopy in QCD will tell us a lot about the detailed structure of the hot/dense matter, which is quite similar to the soft-mode spectroscopy by the photon and neutron scattering experiments in solid state physics.

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Figure Captions

**Fig.1** The light quark condensates in \(N=Z\) nuclear matter in the linear density approximation. Theoretical uncertainty of the \(\pi N\) sigma term is taken into account. We take \(y = 0.12\) for the OZI breaking parameter, where \(y \equiv 2\langle \bar{s}s\rangle_N/\langle \bar{u}u + \bar{d}d\rangle_N\) with \(\langle \cdot \rangle_N\) being the nucleon matrix element.

**Fig.2** Borel curve for the \(\rho(\omega)\) meson mass. Solid, dashed and dash-dotted lines correspond to \(\rho/\rho_0 = 0, 1.0\) and 2.0 respectively. \(S^*_0(\rho)\) determined by the Borel stability method at each density is also shown in GeV\(^2\) unit. The Borel window is chosen to be \(0.41\text{GeV}^2 < M^2 < 1.30\text{GeV}^2\).

**Fig.3** Masses of \(\rho, \omega\) and \(\phi\) mesons in nuclear matter predicted in the QCD sum rules. The hatched region shows theoretical uncertainty.
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Fig. 1

\[ \frac{q}{q_0} \]

\( u, d \) quark

\( s \) quark

\[ \frac{\langle bb \rangle}{\langle bb \rangle_0} \]

\( \rho/\rho_0 \)
Fig. 2

\[ S_0^*(0) = 1.43 \]

\[ S_0^*(\rho_0) = 1.04 \]

\[ S_0^*(2\rho_0) = 0.68 \]
Fig. 3

$m^*/m$ vs. $\rho/\rho_0$ plot with two lines indicating $\rho, \omega$ meson and $\phi$ meson regions.