Vector Mesons in Nuclear Medium
Tetsuo Hatsuda and Hiroyuki Shiomi

Institute of Physics, University of Tsukuba, Tsukuba, Ibaraki 305, Japan

We summarize the current theoretical and experimental status of the spectral change of the vector mesons in dense matter.

1. Introduction

Effective masses of the vector mesons ($\rho$, $\omega$, $\phi$) in hadronic medium have recently attracted wide interests. The decrease of the masses can be interpreted as an evidence of the partial restoration of chiral symmetry and as a precursor of the transition to the quark gluon plasma [1]. Current SPS (CERN) and AGS (BNL) experiments are suitable to look for such finite density phenomena while RHIC and LHC will serve as machines for the “hot” quark-gluon plasma. Several experiments are also planned to detect the partial restoration of chiral symmetry in heavy nuclei through the reactions such as $\gamma + A \rightarrow A^* + e^+e^-$ and $p + A \rightarrow A^* + e^+e^-$ [2].

In this report, we will summarize the current theoretical and experimental status of the spectral change of the vector mesons in dense matter.

2. Partial restoration of chiral symmetry at finite density

The hadronic mass shift as well as the change of the chiral condensate are known to occur only when $T$ is close to $T_c$ [1]. On the other hand, at finite baryon density, one may expect partial restoration of chiral symmetry even in the heavy nuclei [3,4];

\[
\langle \bar{u}u \rangle_\rho = 1 - \frac{4\Sigma_{\pi N}}{f_{\pi}^2 m_{\pi}^2} \int_{p_F} \frac{d^3p}{(2\pi)^3 E_p},
\]

where $E_p \equiv \sqrt{p^2 + m_N^2}$, $\Sigma_{\pi N} = (45 \pm 10)$MeV, and the integration for $p$ should be taken from $0$ to the fermi momentum $p_F$. At normal nuclear matter density ($\rho = \rho_0 = 0.17$/fm$^3$), the above formula gives (34±8)\% reduction of the chiral condensate from the vacuum value. Several estimates show that corrections to this simple fermi-gas approximation are small at $\rho_0$ [5]. If this is the case, the heavy ion collisions and also the reactions in heavy nuclei are good testing ground of the partial chiral restoration.

2.1. Vector mesons in nuclear matter

Let’s consider $\rho$ and $\omega$ mesons propagating inside the nuclear matter. Adopting the same fermi-gas approximation with [1] and taking the vector meson at rest ($q = 0$), one
Figure 1. (a) Masses of $\rho$, $\omega$ and $\phi$ mesons in nuclear matter predicted in the QCD sum rules (left) [7] together with the prediction of the Walecka model (right) [9]. $M^*/M$ in the right figure shows the effective mass of the nucleon.

can generally write the mass-squared shift as

$$\delta m_{V}^2 \equiv m_{V}^* - m_{V}^2 = 4 \int^{p_f} d^3p \frac{m_N}{(2\pi)^3 E_p} f_{VN}(p),$$

(2)

where $f_{VN}(p)$ denotes the vector-meson (V) – nucleon (N) forward scattering amplitude in the relativistic normalization. Here, we took spin-isospin average for the nucleon states in $f_{VN}$. If one can calculate $f_{VN}(p)$ reasonably well in the range $0 < p < p_F = 270$ MeV (or $1709$ MeV < $\sqrt{s}$ < $1726$ MeV in terms of the $V - N$ invariant mass), one can predict the mass shift. Unfortunately, this is a formidable task: $f_{VN}(p)$ is not constant at all 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 [4] and give a rapid variation of $f_{VN}(p)$ as a function of $p$. Thus one should look for totally different approach to estimate $\delta m_{V}$, one of which is the QCD sum rules in medium.

2.2. Constraints from QCD sum rules

Starting from the retarded correlation of the vector currents in nuclear medium, one can write down QCD sum rules for the spectral functions in medium [7]. Parametrizing the spectral function by the peak position of the resonance, the continuum threshold and the integrated strength of the resonance, one can extract the mass shift. In Fig. 2(a), results of such analysis using the Borel sum rule are shown [4]:

$$\frac{m_{V}^*}{m_{V}} \simeq 1 - c_{V} \frac{\rho}{\rho_0};$$

(3)

where $c_{\rho,\omega} = 0.18 \pm 0.05$ and $c_{\phi} = (0.15 \pm 0.05)y$ with $y = 0.1 - 0.2$ being the OZI breaking parameter in the nucleon. $c_{V}$ is obtained by neglecting the contribution of the quark-gluon mixed operator with twist 4; inclusion of them moves the central value of $c_{\rho,\omega}$ to 0.15 [8].
2.3. Use and misuse of the QCD sum rules in nuclear medium

As we have mentioned, $f_{VN}(p)$ must be a rapidly varying function of $p$. In terms of the mass shift, the (invalid) approximation $f_{VN}(p) = f_{VN}(0)$ for $0 < p < p_F$ implies that $\delta m_V^2 \simeq f_{VN}(0) \rho$. Although this formula is valid at extremely low density, it is useless at nuclear matter density. Motivated by the formula, however, it is claimed in ref. [10] that the mass shift is positive. It can be shown that this claim is erroneous [8]: Firstly, the mass shift and the scattering length does not have direct connection in nuclear matter due to the momentum dependence of $f_{VN}(p)$. Secondly, sum rules for the $V-N$ scattering amplitude cannot predict the $V-N$ scattering length without dimension 8 operators in OPE. Thirdly, sum rules for $\omega^2 \Pi^V(\omega)$ which is adopted in ref. [10] does not work at all even in the vacuum without dimension 8 operators and so does in the medium.

2.4. Effective theory approaches

There exist many attempts so far to calculate the spectral change of the vector mesons in effective theories. Chin [11], using the Walecka model, predicted the increasing $\omega$-meson mass in medium due to the scattering process $\omega + N \to N \to \omega + N$. More sophisticated calculations for the $\rho$-meson predict also a slight increase of the $\rho$-mass [12]. In all these calculations, the effect of the polarization of the Fermi sea is only taken into account.

On the other hand, Kurasawa and Suzuki have found that the mass of the $\omega$-meson is affected substantially by the vacuum polarization in medium $\omega \to N_\ast \bar{N}_\ast \to \omega$, where $N_\ast$ is the nucleon in nuclear medium [13]. The vacuum polarization dominates over the Fermi-sea polarization and leads decreasing vector meson mass. This conclusion was confirmed later by other authors [14] and also generalized to the $\rho$-meson [15] (see Fig.2(b)).

What is missing in the Fermi sea approaches [11,12] is the effect of the scalar mean-field on the vector meson mass. On the other hand, Dirac sea approaches [13,14,15] have close similarity with other mean-field models such as those of Brown and Rho [15], Jaminon and Ripka [16], and Saito and Thomas [17], which predict the decrease of the vector-meson masses. It is desirable to develop a unified effective lagrangian which embodies the essential part of these approaches [18].

3. Experimental status

There exist already two proposals to look for the mass shift of the vector mesons in nuclear medium [2]. 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 $R = \Gamma(\phi \to e^+e^-)/\Gamma(\phi \to K^+K^-)$, which is sensitive to the change of the $\phi$-mass as well as $K$-mass in medium.

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 at CERN recently reported an enhancement of the $e^+e^-$ pairs below the $\rho$ resonance, which is hard to be explained by the conventional sources of the lepton pairs [19]. Also, E859 at BNL-AGS reported a possible spectral change of the $\phi$-peak in $K^+K^-$ spectrum [20]. If these effects are real, the shoulder structure of the spectrum expected by the mass shift of the vector
mesons could be a possible explanation.

4. 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. Some theoretical models predict that the light vector mesons \((\rho, \omega\) and \(\phi)\) are sensitive to the partial restoration of chiral symmetry in hot/dense medium. These mesons are also experimentally good probes 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. The theoretical approaches to study the spectral changes are still in the primitive stage and new methods beyond QCD sum rules and naive effective lagrangian approaches are called for.

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