Chiral Transition in QCD and Scalar Correlations

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We review recent developments in exploring possible precursory phenomena of partial restoration of chiral symmetry in nuclear medium by examining the spectral function in the scalar channel. We emphasize that the wave function renormalization of the pion in the medium plays an essential role to induce the decrease of the pion decay constant as the order parameter of chiral transition. We also show that the $\sigma$ meson pole in the complex energy plane moves toward the origin as chiral symmetry is restored in hot and/or dense nuclear matter.

§1. Introduction

Hadrons are low-lying elementary excitations on top of the non-perturbative QCD vacuum, although QCD Lagrangian itself is written in terms of quark- and gluon-fields of which hadrons are composed. Furthermore, symmetries possessed by the QCD Lagrangian are not manifest in the low-energy regime. These complication are owing to the fact that the true QCD vacuum is realized through the phase transitions, i.e., the confinement-deconfinement and the chiral transitions. Thus one recognizes that hadron spectroscopy based on QCD must be a study of the nature of QCD vacuum.

In the present report, focusing on the chiral transition in hot and/or dense hadronic matter, I will discuss some characteristic changes in the scalar correlations associated with the (partial) restoration of chiral symmetry in the hadronic medium. The present report is more or less based on 1) - 6).

§2. Chiral symmetry restoration as a phase transition of QCD vacuum

The true QCD vacuum is realized through the chiral transition, which is clearly demonstrated by lattice simulations.

A heuristic argument based on a Hellman-Feynman theorem also tells us that the chiral condensate $\langle \bar{q}q \rangle$ decreases at finite density $\rho_B$ as well as at finite $T$.

For the degenerate nucleon system $|\mathcal{N} \rangle$, for instance, the quark condensate of the system can be given by,

$$\langle \mathcal{N} | \bar{q}q | \mathcal{N} \rangle = \frac{\partial \langle \mathcal{N} | \mathcal{H}_{QCD} | \mathcal{N} \rangle}{\partial m_q},$$

where the expectation value of QCD Hamiltonian may be evaluated to

$$\langle \mathcal{N} | \mathcal{H}_{QCD} | \mathcal{N} \rangle = \varepsilon_{\text{vac}} + \rho_B [M_N + B(\rho_B)].$$

Here, $\varepsilon_{\text{vac}}$, $M_N$ and $B(\rho_B)$ denote the vacuum energy, the nucleon mass and the
nuclear binding energy per particle, respectively. Thus one has
\[
\langle \bar{q}q \rangle_{\rho_B} = \langle \bar{q}q \rangle_0 \cdot \left[ 1 - \frac{\rho_B}{f_{\pi}^2 m_{\pi}^2} \left( \Sigma_{\pi N} + \hat{m} \frac{d}{d\hat{m}} B(\rho_B) \right) \right],
\]
where \( \Sigma_{\pi N} = (m_u + m_d)/2 \cdot \langle N | \bar{u}u + \bar{d}d | N \rangle \) denotes the \( \pi - N \) sigma term with \( \hat{m} = (m_u + m_d)/2 \); the semi-empirical value of \( \Sigma_{\pi N} \) is known to be \((40 - 50) \text{ MeV}^{10,11}\). Notice that the correction term with finite \( \rho_B \) is positive and gives a reduction of almost 35\% of \( \langle \bar{q}q \rangle_0 \) already at the normal nuclear matter density \( \rho_0 = 0.17 \text{fm}^{-3} \).

If one believes in the above estimate\(^\ast\), one can conclude that the central region of heavy nuclei could be dense enough to cause a partial restoration of chiral symmetry\(^2\), which may induce some characteristic phenomena of the chiral restoration in nuclear medium\(^1,12\).

One may recall that if a phase transition is of second order or weak first order, there may exist specific collective excitations called soft modes\(^13\). They are the quantum fluctuations of the order parameter. In the case of chiral transition, there are two kinds of fluctuations, those of the phase and the modulus of the chiral condensate. The former is the Nambu-Goldstone boson, i.e., the pion, while the latter the \( \sigma \) with the quantum numbers \( I = 0 \) and \( J^{PC} = 0^{++} \).\(^{14}\)

§3. The significance of the \( \sigma \) meson in low-energy hadron QCD

The recent cautious phase shift analyses of the \( \pi - \pi \) scattering have come to claim a pole identified with the \( \sigma \) in the \( s \) channel together with the \( \rho \) meson pole in the \( t \) channel\(^7,15,16\). The \( \sigma \) pole has a real part \( \text{Re} \ m_\sigma = 500-600 \text{ MeV} \) and the imaginary part \( \text{Im} \ m_\sigma \simeq \text{Re} m_\sigma \). More recently, it has been also found that the \( \sigma \) pole gives a significant contribution to the decay processes of heavy particles involving a charm and \( \tau \) leptons\(^{17-19}\). A summary of the locations of the \( \sigma \) pole in the complex energy plane may be found in\(^{20}\).

The elusiveness of the \( \sigma \) meson comes from the fact that it strongly couples to two pions to acquire a large width \( \Gamma \sim m_\sigma \). Although the chiral perturbation theory\(^{21}\) have made a great achievement for establishing the essential role of chiral symmetry in describing (very) low-energy hadron phenomena, it is beyond the scope of the theory to describe resonances\(^{22}\).

The important points in establishing the \( \sigma \) pole consistently with chiral symmetry is to incorporate analyticity, unitarity and especially (approximate) crossing symmetry\(^\ast\ast\); Igi and Hikasa\(^{25}\) constructed an invariant amplitude for the \( \pi - \pi \) scattering using the \( N/D \) method\(^{26}\) so that it satisfies the chiral symmetry low energy theorem, analyticity, unitarity and especially (approximate) crossing symmetry. They calculated two cases with and without the scalar pole degenerated with the \( \rho \) meson, the existence of which was taken for granted. What they found is that the \( \rho \) only scenario can ac-

\(^\ast\) It is said that one of mistakes which theoretical physicists often do is not believing in their results with enough strength and not pursuing the consequences of them.

\(^\ast\ast\) For instance, the phase shift in the \( I = J = 0 \) channel could be well reproduced with a unitarized scattering amplitude lacking the \( \sigma \) pole but including the \( \rho \) meson pole in the \( t \)-channel\(^{23,24}\).
count only about a half of the observed phase shift, while the degenerate \(\rho-\sigma\) scenario gives an excellent agreement with the data.

In fact, the \(\sigma\) meson has been an enigma in hadron physics\(^{16}\): It may be noticed, however, that the \(\sigma\) meson as the quantum fluctuation of the chiral order parameter must be a collective state composed of many \(q\bar{q}\) states as the pion is\(^{27},^{14}\); notice that the pion can not be understood within the conventional constituent quark model.

The possible existence of the \(\sigma\) meson implies an accumulation of the strength in the \(I = J = 0\) channel, so is relevant to some observables\(^1,^2\); (1) \(\Delta I = 1/2\) rule in the kaon decay\(^{28}\), (2) the intermediate-range attraction in nuclear force\(^{29},^{30}\), (3) \(\pi\)-\(N\) sigma term\(^{31}\) and so on.

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§4. Partial chiral restoration and the \(\sigma\) meson in hadronic matter

As was first shown in\(^{14}\), if the \(\sigma\) is really associated with the fluctuation of the chiral order parameter, one can expect that the \(\sigma\) pole moves toward the origin in the complex energy plane in the chiral limit and the \(\sigma\) may become a sharp resonance as chiral symmetry is restored at high temperature and/or density; the \(\sigma\) can be a soft mode\(^{13}\) of the chiral restoration; see also\(^{32}\).

Some years ago\(^{33},^2\), several nuclear experiments including one using electromagnetic probes were proposed to create the scalar mode in nuclei, thereby obtain a clearer evidence of the existence of the \(\sigma\) meson and also examine the possible restoration of chiral symmetry in nuclear medium. It was also mentioned that to avoid the huge amount of two pions from the \(\rho\) meson, detecting neutral pions through four \(\gamma\)'s may be convenient.

One must, however, notice that a hadron put in a heavy nucleus may dissociate into complicated excitations to lose its identity. Moreover, as remarked above, it is still uncertain whether the \(\sigma\) pole really corresponds to the pre-existing quantum fluctuation of the chiral order parameter or only a \(\pi\)-\(\pi\) molecule generated dynamically. Then the most proper quantity to observe is the response function or spectral function in the channel with the same quantum number as the hadron has.

Hatsuda, Shimizu and the present author (HKS)\(^{34}\) showed that the spectral enhancement near the \(2m_\pi\) threshold takes place in association with partial restoration of chiral symmetry at finite baryon density. The calculation is a simple extension of the finite \(T\) case\(^{35}\). The following should be, however, noticed; since HKS is based on a perturbation theory for treating the effects of the meson-loops as well as the baryon density, their loop-expansion should be valid only at relatively low densities. There are some attempts for developing the chiral perturbation theory i.e., the non-linear realization of chiral symmetry, for a finite density system\(^{36} - ^{38}\).

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§5. Role of the wave function renormalization; chiral restoration in nonlinear realization

In the linear representation of chiral symmetry as given by the linear sigma model, it is rather apparent that the possible chiral restoration affects the dynamics
in the medium because the \( \sigma \) degree of freedom is explicit from the outset. How can the possible chiral restoration be implemented in the non-linear realization where the \( \sigma \) degree of freedom is absent? Jido et al\(^40\) showed that the nonlinear realization of the chiral symmetry can also give rise to a near \( 2m_\pi \) enhancement of the spectral function in nuclear medium. The enhancement of the cross section is found due to the wave function renormalization of the pion in nuclear medium which causes the decrease of the pion decay constant \( f_\pi^*(\rho) \) in the medium. They identified that the wave function renormalization and hence the decrease of \( f_\pi^*(\rho) \) are owing to the following new vertex:

\[
\mathcal{L}_{\text{new}} = -\frac{3g}{2\lambda f_\pi} \hat{N} N \text{Tr}[\partial U \partial U^\dagger].
\] (5.1)

Here a couple of remarks are in order: (i) The vertex eq.(5.1) has been known to be one of the next-to-leading order terms in the non-linear chiral Lagrangian in the heavy-baryon formalism\(^41\). (ii) The essential role of the wave-function renormalization of the pion field on the partial restoration of chiral symmetry is also shown in the chiral perturbation theory in a more systematic way\(^36\),\(^37\) and has been also revealed in accounting for the anomalous repulsion seen in the deeply bound pionic nuclei\(^39\).

\(\S 6.\) The behavior of the \( \sigma \) pole in the complex energy plane

We emphasize here the relation of the near-threshold enhancement and the softening of the fluctuating mode in the \( \sigma \) channel in nuclear matter. We shall show that such a fluctuating mode can be characterized by a complex pole of the unitarized scattering amplitude \( T(s) \).

The \( T \) matrix resummed in the inverse amplitude method\(^42\) in the non-linear realization reads (\( s = p^2 \))

\[
T(s) = T_2/(1 + T_2g(s)),
\] (6.1)

where \( T_2 = s/f_\pi^2 \) and \( g(s) \) is the pion loop integral;

\[
g(s) = i \int \frac{d^4q}{(2\pi)^4} \frac{1}{q_+^2 - m_\pi^2 + i\epsilon} \frac{1}{q_-^2 - m_\pi^2 + i\epsilon}, \quad q_\pm = q \pm p/2.
\] (6.2)

Notice that \( g(s) \) satisfies the dispersion relation

\[
g(s) = \frac{1}{\pi} \int \frac{\text{Im}g(s')}{s' - s - i\epsilon} ds'.
\] (6.3)

Here one can easily find that \( \text{Im}g(s) = -(1/16\pi)\sqrt{1 - 4m_\pi^2/s} \cdot \theta(s - 4m_\pi^2) \).

The dispersion integral which is logarithmically divergent is evaluated with a simple cutoff. The analytic continuation of the function \( g(z) \) to the 2nd Riemann sheet (\( \text{Im} z < 0 \)) is given by

\[
g(z) = \frac{1}{\pi} \int_{C'} \frac{\text{Im}g(s')}{s' - z} ds'.
\] (6.4)
where $C' = C + (z)$ with $C$ being a straight line on $0 \leq z \leq \Lambda^2$. The integral along the circle gives an extra term, $2\pi i$. We remark that with this definition, $g(z)$ is continuous when $z$ crosses the real axis from the upper to the lower plane.

In the chiral limit, one obtains $g(z) = -\frac{1}{16\pi^2}\{\log(1 - \Lambda^2/z) + 2\pi i\}$, $(\text{Im} z < 0)$. Here $\log z$ denotes the principal value of the logarithm, which has a cut along the real negative axis and $-\pi < \text{Arg} \log z < \pi$. The pole is given as the solution to the following dispersion equation $T^{-1}_2(z) = -g(z)$. When $z$ is located in the 2nd sheet, the equation has the form of

$$16\pi^2 f^*_\pi = z\{\log(-\Lambda^2/z) + 2\pi i\}. \quad (6.5)$$

Let $z/\Lambda^2 = a - ib \ (a, b > 0)$, and write $b/a = \tan \theta$, then $\text{Im} [\log(-\Lambda^2/z)] = -(\pi - \theta)$. Thus eq.(6.5) is finally reduced to $16\pi^2 f^*_\pi = z\{-\log(|z|/\Lambda^2) + i\theta + i\pi\}$. When $a, b \ll 1$, or $|z|/\Lambda^2 \ll 1$ and $\theta \ll 1$, we have $16\pi^2 f^*_\pi \simeq i\pi z$. This will give a check of the numerical calculation.

The numerical solution to eq.(6.5) is shown in Fig.1:

1) A pole exists in the lower half plane in the complex $s$ plane. 2) The pole moves toward the origin along the solid line as $f^*_\pi = \langle \sigma \rangle$ is decreased. Thus one sees that the mass and the width of the soft mode decreases as the chiral symmetry is restored.

The sift of the Sigma Pole of the T matrix

![Graph](image)

Fig. 1. The movement of the $\sigma$ meson pole (in the chiral limit) as $f^*_\pi$ decreases toward 0. 5)

§7. Discussions

7.1. Experimental results on the spectral function in the $\sigma$ channel

There are a few relevant experiments which might show the softening of the spectral function in the $I = J = 0$ channel.
1. CHAOS collaboration\textsuperscript{44} observed that the yield for $M^A_{\pi^+\pi^-}$ near the $2m_\pi$ threshold increases dramatically with increasing $A$. They identified that the $\pi^+\pi^-$ pairs in this range of $M^A_{\pi^+\pi^-}$ is in the $I = J = 0$ state. Although this experiment was motivated to explore the $\pi-\pi$ correlations in nuclear medium\textsuperscript{45}, the near $2m_\pi$-threshold enhancement might be attributed to a partial restoration of chiral symmetry in heavy nuclei. Here it should be remarked, however, that there are some attempts to explain the CHAOS data solely by the many-body effects without recourse to a possible vacuum change\textsuperscript{43}.

2. The experiment to explore the spectral function in the same channel in heavy nuclei were also performed by Crystal Ball group\textsuperscript{46}. The CHAOS group claims\textsuperscript{44} that there is no essential difference between the two experiments, although otherwise had been spelled out in\textsuperscript{46}.

3. A similar but more clear experimental result which shows a softening of the spectral function in the $\sigma$ channel in the nuclear medium has been also obtained by TAPS group\textsuperscript{47}.

7.2. Deeply bound nuclei and chiral restoration

The deeply bound pionic atom has proved to be a good probe of the properties of the hadronic interaction deep inside of heavy nuclei. There is a suggestion\textsuperscript{48,49,39} that the anomalously repulsive energy shift of the pionic atoms (pionic nuclei) owing to the strong interaction could be attributed to the decrease of $f^*_\pi(\rho)$ in heavy nuclei. It may also imply that the chiral symmetry is partially restored deep inside of nuclei. A remarkable point is that the decrease of $f^*_\pi(\rho)$ is owing to the wave-function renormalization of the pion field in nuclei\textsuperscript{39}, as is for the in-medium $\pi\pi$ interaction in the $I = J = 0$ channel.

§8. Summary and concluding remarks

The present report may be summarized as follows.

1. Partial restoration of chiral symmetry in hot and dense medium as represented by the decreasing $f^*_\pi$ leads to a shift of the $\sigma$ meson pole in the 2nd Riemann sheet even in the non-linear realization of chiral symmetry. (2) The decrease of $f^*_\pi$ in the nuclear medium is a direct consequence of the wave function renormalization of the pion field in the medium, which also accounts for the anomalous repulsion seen in the deeply bound pionic nuclei. (3) Even a slight restoration of chiral symmetry in the hadronic matter leads to a peculiar softening of the spectral function in the $\sigma$ channel. (4) Such an enhancement might have been observed in the reactions creating two pions in nuclei.

In passing, some remarks are in order: (a) Possible evidences of the partial restoration of chiral symmetry in hot and/or dense matter are also obtained in the vector channel\textsuperscript{50,51}. (b) The $N/D$ method applied to hot and/or dense medium suggests that the $\sigma$ and the $\rho$ mesons can become a soft mode simultaneously for the chiral restoration\textsuperscript{53}. (c) It is found\textsuperscript{54,55} that a singular behavior inherent to the chiral transition also shows up in the baryon number susceptibility at finite chemical potential $\mu_B \neq 0$ owing to the scalar-vector mixing at $\mu_B \neq 0$. 
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