The Sigma Meson and Chiral Transition in Hot and Dense Matter

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Abstract

It is pointed out that the hadron spectroscopy should be a study of the structure of the QCD vacuum, low-energy elementary excitations on top of which are hadrons. Concentrating on the dynamical breaking of the chiral symmetry in the QCD vacuum, we emphasize the importance to clarify what is going on with mesons in the $I = J = 0$-channel, i.e., the sigma meson channel, because it is connected to the quantum fluctuations of the chiral order parameter. After summarizing the significance of the sigma meson in QCD and low-energy hadron phenomenology, we give a review on some theoretical and experimental effort to try to reveal the possible restoration of chiral symmetry in hot and dense nuclear matter including heavy nuclei.

1 Introduction

A tricky point in the hadron spectroscopy is that QCD, the fundamental theory of the hadron world, is not written in terms of hadron fields but in terms of quark- and gluon-fields from which hadrons are composed: The quarks and gluons are colored objects which can not exist in the asymptotic state, and low-lying elementary excitations on top of the non-perturbative QCD vacuum are composite and colorless, which we call hadrons. Furthermore, symmetries possessed by the QCD Lagrangian, such as the chiral $SU(3)_L \times SU(3)_R$ symmetry in the massless limit of quarks and the color gauge symmetry are not manifest in our every-day world. This complication of the problem is due to the fact that the true QCD vacuum is completely different from the perturbative one and is actually realized through the phase transitions, i.e., the confinement-deconfinement and the chiral transitions. The notion of such a complicated vacuum structure, i.e., the collective nature of the vacuum and the elementary particles was first introduced by Nambu\cite{1}, in analogy with the physics of superconductivity\cite{2}. The nonperturbative nature and the realization of the true QCD vacuum through the phase transitions are being confirmed by the lattice simulations\cite{3}. One may notice that the so called $U_A(1)$ anomaly\cite{4} also characterizes the non-perturbative QCD vacuum. Several rules extracted from the hadron phenomenology such as the vector-meson dominance (VMD)\cite{5,6} and the Okubo-Zweig-Iizuka (OZI) rule\cite{7} might be also related with some fundamental properties of the QCD vacuum. Thus the hadron spectroscopy can not
be failed to be a study of the nature of QCD vacuum including its symmetry properties. In other words, the physics of the hadron spectroscopy is a combination of the condensed matter physics of the QCD vacuum[8, 9] and the atomic physics as played with the constituent quark-gluon model where the vacuum structure is taken for granted[10].

An interesting observation is then that hadrons as elementary excitations on top of the QCD vacuum may change their properties in association with a change or phase transition of the QCD vacuum. What hadrons do change their properties sharply, and how do they in hot and/or dense medium? One should also ask how they are detected in experiment[11, 12, 13, 14, 15]; see also the reviews [8, 16]. For instance, in Table 6.1 in [8], list up are interesting observables and their expected behavior in relation with the chiral transition, possible restoration of the $U_A(1)$-symmetry and precritical deconfinement at finite temperature and/or density. In association with (partial) restoration of chiral symmetry, the mass of the $\sigma$ meson[13, 19] is expected to decrease. Some people[11, 15, 20] expect that the vector mesons $\rho, \omega$ and $\phi$ also show a decrease of their masses in association with the chiral restoration. The $U_A(1)$ anomaly, which is responsible for lifting the $\eta'$ meson mass as high as about 1 GeV and make the $\eta' (\eta)$ almost flavor singlet (octet), may be cured at high temperature, which may manifest itself as the decrease of the mass $m_{\eta'}$[17, 18] for example. The deconfinement may affect the properties of heavy-quark systems such as $J/\psi$[14, 21] than in light hadrons.

In the present talk, I will focus on the chiral transition in hot and dense hadronic matter and discuss the significance of the scalar and isoscalar meson, the sigma meson and the strength function in its channel in the hadronic medium including heavy nuclei.

2 The sigma meson

The order parameter of the chiral transition is the quark condensate $\langle \bar{q}q \rangle \sim \sigma$. There arise two kinds of quantum fluctuations of the order parameter, the modulus and phase fluctuations. The pion corresponds to the latter fluctuations. The particle corresponding to the former fluctuation is a scalar-isoscalar meson, which is traditionally called the $\sigma$ meson. One may notice that the way of the appearance of the $\sigma$ meson is analogous to that of the Higgs particle, which comes to exist through the dynamical breaking of the gauge symmetry in the standard model while the corresponding NG boson is absorbed into the longitudinal component of the gauge fields. As one can now see, the existence of the $\sigma$ meson is logically related to the fundamental property of the QCD vacuum in which the chiral symmetry is spontaneously broken. Therefore searching for such a particle in experiment is not eccentric but as naturally motivated as searching for glue balls in QCD and the Higgs particle in the standard model. If such a particle or the like could not be identified, one must consider possible dynamical origins to hinder them from appearing.

Here are a short summary of the significance of the sigma meson in hadron physics:

1. The existence of the $\sigma$ meson as the quantum fluctuation of the order parameter of the chiral transition accounts for various phenomena in hadron physics which otherwise remain mysterious[22, 8, 23].

2. There have been accumulation of experimental evidence of a low-mass pole in the $\sigma$ channel in the pi-pi scattering matrix[23, 24]. It should be emphasized that for ob-
taining this result, it is essential to respect chiral symmetry, analyticity and crossing symmetry even in an approximate way as in the $N/D$ method\cite{27}: The great achievement of the chiral perturbation theory\cite{28} is indispensable for set the precise boundary condition for the scattering matrix in the low-energy region.

3. It is well known that such a scalar meson with the mass range 500 to 700 MeV is responsible for the intermediate range attraction in the nuclear force.\cite{30}

4. The correlation in the scalar channel as summarized by such the sigma meson may account for the enhancement of the $\Delta I = 1/2$ processes in $K^0 \to \pi^+\pi^-$ or $\pi^0\pi^0$.\cite{29} In fact, the final state interaction for the emitted two pions may include the $\sigma$ pole, then the matrix element for of the scalar operator $Q_6 \sim \bar{q}_R q_L \bar{q}_L q_R$ is sown to be enhanced dramatically.

5. The collective excitation in the scalar channel as described as the $\sigma$ meson is essential\cite{32} in reproducing the empirical value of the $\pi$-$N$ sigma term $\Sigma_{\pi N} = \hat{m}(\bar{u}u + \bar{d}d)$: Empirically, it is known that $\Sigma_{\pi N} \sim 40-50$ MeV, while the naive quark model only gives as small as $\sim 15$ MeV. The basic quantities here are the quark contents of baryons $\langle B|\bar{q}_i q_i|B \rangle \equiv \langle \bar{q}_i q_i \rangle_B (i = u, d, s, \ldots)$. Actually, it is more adequate to call them the scalar charge of the hadron. The point is such a scalar charge of the nucleon is enhanced with the existence of the sigma meson pole; such an enhancement of charges by collective modes are well known in nuclear physics.

4 Partial chiral restoration and the $\sigma$ meson in hadronic matter

Although the recent phase shift analyses\cite{26} of the $\pi$-$\pi$ scattering and the identification of the pole in the $I = J = 0$ channel as mentioned in 2 above is a great development in this field, one must say that it is still obscure whether the pole really corresponds to the quantum fluctuation of the chiral order parameter, i.e., our $\sigma$. If one were to be able to change the environment freely and trace the possible change of the pole position, the nature of the particle corresponding to the pole can be revealed: A change of the vacuum or the equilibrium state leading to the phase transition will make the mode coupled to the order parameter change. Actually this is the usual strategy in the many-body physics\cite{33} to reveal the nature of elementary excitations. Conversely, an observation of the change of the elementary modes as well as that of other thermodynamic quantities tells us the change of the state of the matter.

Effective theories of QCD\cite{13,19} show that the sigma meson mass $m_\sigma$ decreases in association with the chiral restoration in hot and/or dense medium, while the pion mass keeps its value in free space as long as the system is in the Nambu-Goldstone phase. The simulations on the lattice QCD also show a decrease of the screening mass in the sigma meson channel; see for instance, \cite{3,34}. The screening mass which describes the damping of the correlation function in the space direction is not the dynamical mass which is given through the time correlation of the relevant operators. Nevertheless, it is remarkable that the lattice result is not in contradiction with those in the effective theories.
Then the width of the $\sigma$ is also expected to decrease due to the depletion of the phase space for the decay $\sigma \rightarrow 2\pi$. Thus one can expect a chance to see the $\sigma$ meson as a sharp resonance at high temperature and/or density.

Some years ago, the present author proposed several nuclear experiments including one using electro-magnetic probes to produce the $\sigma$ meson in nuclei, thereby have a clearer evidence of the existence of the $\sigma$ meson and also explore the possible restoration of chiral symmetry in the nuclear medium\[23, 36]: As is well known, there arises a scalar-vector mixing in nuclear matter at finite density\[37]. To make a veto for the two pions from the rho meson, the produced pions should be neutral ones which may be detected through four $\gamma$’s.

When a hadron is put in a hadronic medium, the hadron might dissociate into complicated excitations to lose its identity. Then the most informative quantity is the response function or spectral function in the hadron channel of the system. If the coupling of the hadron with the environment is relatively small, then there may remain a peak with a small width in the spectral function corresponding to the hadron. Such a peak is to be identified with an elementary excitation or a quasi particle. Then how will the decrease of $m_\sigma$ in the nuclear medium affect the spectral function.

It has been shown by using linear chiral models that an enhancement in the spectral function in the $\sigma$ channel occurs just above the two-pion threshold along with the decrease of $m_\sigma$\[38]. Subsequently, it has been shown \[39\] that the spectral enhancement near the $2m_\pi$ threshold takes place in association with partial restoration of chiral symmetry at finite baryon density.

Hatsuda et al\[39\] started from the following linear sigma model;

$$L = \frac{1}{4} \text{Tr}[\partial M \partial M^\dagger - \mu^2 MM^\dagger - \frac{2\lambda}{4!} (MM^\dagger)^2 - h(M + M^\dagger)] + \bar{\psi}(i\gamma \cdot \partial - gM_5)\psi + \cdots, \quad (1)$$

where $M = \sigma + i\vec{\tau} \cdot \vec{\pi}$, $M_5 = \sigma + i\gamma_5 \vec{\tau} \cdot \vec{\pi}$, $\psi$ is the nucleon field, and Tr is for the flavor index. Consider the propagator of the $\sigma$-meson at rest in the medium: $D^{-1}_\sigma(\omega) = \omega^2 - m_\sigma^2 - \Sigma_\sigma(\omega; \rho)$, where $m_\sigma$ is the mass of $\sigma$ in the tree-level, and $\Sigma_\sigma(\omega; \rho)$ is the loop corrections in the vacuum as well as in the medium. The corresponding spectral function is given by $\rho_\sigma(\omega) = -\pi^{-1}\text{Im}D_\sigma(\omega)$. One can show that

$$\text{Im}\Sigma_\sigma \propto \theta(\omega - 2m_\pi) \sqrt{1 - \frac{4m_\pi^2}{\omega^2}}, \quad (2)$$

near the two-pion threshold in the one-loop order. On the other hand, partial restoration of chiral symmetry implies that $m_\sigma^*$ defined by $\text{Re}D^{-1}_\sigma(\omega = m_\sigma^*) = 0$ approaches to $m_\sigma$. Therefore, there exists a density $\rho_c$ at which $\text{Re}D^{-1}_\sigma(\omega = 2m_\pi)$ vanishes even before the complete restoration of chiral symmetry where $\sigma$-$\pi$ degeneracy is realized, namely $\text{Re}D^{-1}_\sigma(\omega = 2m_\pi) = [\omega^2 - m_\sigma^2 - \text{Re}\Sigma_\sigma]_{\omega=2m_\pi} = 0$. At this point, the spectral function is solely given in terms of the imaginary part of the self-energy;

$$\rho_\sigma(\omega \approx 2m_\pi) = -\frac{1}{\pi \text{Im}\Sigma_\sigma} \propto \frac{\theta(\omega - 2m_\pi)}{\sqrt{1 - \frac{4m_\pi^2}{\omega^2}}}, \quad (3)$$

which clearly shows the near-threshold enhancement of the spectral function. This is a general phenomenon correlated with the partial restoration of chiral symmetry.
Figure 1: The spectral function $\rho_\sigma(\omega)$ (the upper panel) and $\text{Re}D^{-1}_\sigma(\omega)$ (the lower panel) calculated with a linear sigma model. $\Phi(\rho) \equiv \langle \sigma \rangle / \sigma_0$ measures the rate of the partial restoration of the chiral symmetry at the baryonic density $\rho$.

In \cite{39}, the effect of the meson-loop as well as the baryon density was treated as a perturbation to the vacuum quantities. Therefore, our loop-expansion is valid only at relatively low densities. When we parameterize the chiral condensate in nuclear matter $\langle \sigma \rangle$ as

$$\langle \sigma \rangle \equiv \sigma_0 \Phi(\rho),$$

one may take the linear density approximation for small density; $\Phi(\rho) = 1 - C\rho/\rho_0$ with $C = (g_\sigma/\sigma_0 m_\sigma^2)\rho_0$.

The spectral function $\rho_\sigma(\omega)$ together with $\text{Re}D^{-1}_\sigma(\omega)$ calculated with a linear sigma model are shown in Fig.1: The characteristic enhancements of the spectral function is seen just above the $2m_\pi$. It is also to be noted that even before the $\sigma$-meson mass $m_\sigma^*$ and $m_\pi$ in the medium are degenerate, i.e., the chiral-restoring point, a large enhancement of the spectral function near the $2m_\pi$ is seen.

Is the near-threshold enhancement obtained above specific to the linear representation of the chiral symmetry, where the $\sigma$ degree of freedom is explicit as in (1). Jido et al\cite{40} showed that the nonlinear realization of the chiral symmetry can also give rise to the near $2m_\pi$ enhancement of the spectral function in nuclear medium as shown in Fig.2.

They begin the discussion with the polar parameterization of the chiral field, $M = \sigma + i\vec{\tau} \cdot \vec{\pi} = (\langle \sigma \rangle + S)U$ with $U = \exp(i\vec{\tau} \cdot \vec{\phi}/f^*_\pi)$. Here $f^*_\pi$ is a would-be “in-medium pion decay constant”.

$$\mathcal{L} = \frac{1}{2}[(\partial S)^2 - m_\sigma^2 S^2] - \frac{\lambda\langle \sigma \rangle}{6}S^3 - \frac{\lambda}{4} S^4 + \frac{(\langle \sigma \rangle + S)^2}{4} \text{Tr}[\partial U \partial U^\dagger] + \frac{\langle \sigma \rangle + S}{4} h \text{ Tr}[U^\dagger + U]$$

$$+ \mathcal{L}^{(1)}_{\pi N} - g SNN,$$

(5)
Figure 2: In-medium $\pi\pi$ cross section in the $I = J = 0$ channel in the heavy $S$ limit where $m_\sigma^*$ is taken to be infinity. The cross section is shown in the arbitrary unit (A.U.).

\[ F(r) = 0.7 \]

\[ \sqrt{s} \text{ (MeV)} \]

Figure 3: The new $4\pi$-$N$-$N$ vertex generated in the nonlinear realization. The solid line with arrow and the dashed line represent the nucleon and pion, respectively.

with $\mathcal{L}_{\pi N}^{(1)} = \bar{N}(i\gamma \cdot \partial + i\phi + i\phi \gamma_5 - m_N^*)N$ and $(v_\mu, a_\mu) = (\xi \partial_\mu \xi^\dagger \pm \xi^\dagger \partial_\mu \xi)/2$, and $m_N^* = g\langle \sigma \rangle$.

In this representation, the in-medium $\pi\pi$ amplitude in the tree level reads

\[ A(s) = \frac{s - m_\pi^2}{\langle \sigma \rangle^2} - \frac{(s - m_\pi^2)^2}{\langle \sigma \rangle^2} \frac{1}{s - m_\sigma^*} \]

The first term in (6) comes from the contact $4\pi$ coupling generated by the expansion of the second line in (5) with the coefficient proportional to $1/\langle \sigma \rangle^2$. On the other hand, the second term in (6) is from the contribution of the scalar meson $S$ in the $s$-channel. Fig. 2 shows a unitarized in-medium $\pi\pi$ cross section only with the first term in (6), i.e., what is given by the non-linear realization. One sees a clear enhancement of the cross section near the threshold or a softening as chiral symmetry is restored. Although there is no explicit $\sigma$-degrees of freedom in this heavy $\sigma$ approximation, there arises a decrease of the pion decay constant $f_\pi^*$ in nuclear medium. This is due to a new vertex, i.e., $4\pi$-$N$-$N$ vertex absent in the free space; see Fig. 3. The vertex is responsible for the reduction of $f_\pi^*$ and hence for the spectral enhancement.

5 Possible experimental evidence

Interestingly enough, CHAOS collaboration [41] had measured the $\pi^+\pi^\pm$ invariant mass distribution $M_{\pi^+\pi^\pm}^A$ in the reaction $A(\pi^+, \pi^+\pi^\pm)X$ with the mass number $A$ ranging from 2
to 208: They observed that the yield for $M_{\pi^+\pi^-}^A$ near the $2m_\pi$ threshold is close to zero for $A = 2$, but increases dramatically with increasing $A$. They identified that the $\pi^+\pi^-$ pairs in this range of $M_{\pi^+\pi^-}^A$ is in the $I = J = 0$ state. The $A$ dependence of the the invariant mass distribution presented in [11] near $2m_\pi$ threshold has a close resemblance to our model calculation in Fig.1, which suggests that this experiment may already provide a hint about how the partial restoration of chiral symmetry manifest itself at finite density.

In fact, a state of the art calculation based on the conventional many-body theoretical approach without incorporating the effect of the vacuum change was performed [44]; unfortunately, they all failed in reproducing the sufficient enhancement in the near-threshold region consistently with the other energy region. Once the effect of partial chiral restoration in nuclei is incorporated to the conventional approach [43], as suggested in [39], the agreement of the theory and experiment was remarkable. This is encouraging.

To confirm the threshold enhancement, first of all, more experimental work should be done. Measurement of $2\pi^0$ and $2\gamma$ in experiments with hadron/photon beams off the heavy nuclear targets should be done, which is free from the $\rho$ meson meson background inherent in the $\pi^+\pi^-$ measurement. Such an experiment was in fact performed by the Crystal Ball(CB) [45] collaboration at BNL: They claimed that there is no threshold enhancement that was seen in the CHAOS experiment. A reexamination of the data by the CB group has been done by the CHAOS group [46], and emphasized the importance of the combined ratio

$$C_{\pi\pi}^A(M_{\pi\pi}) = \frac{\sigma^A(M_{\pi\pi})}{\sigma^N(M_{\pi\pi})}$$

(7)

where $\sigma^A$ ($\sigma^N$) is the measured total cross section of the $\pi2\pi$ process in nuclei (nucleon). This ratio yields the net effect of nuclear matter on the interacting $(\pi\pi)$$_{I=J=0}$ system. They have shown that the combined ratio grows near the $2m_\pi$ threshold consistently in the two experiments, although the statistics in the CB data is poorer.

Measuring of $2\gamma$'s from the electro-magnetic decay of the $\sigma$ or $(\pi\pi)$$_{I=J=0}$ in nuclear matter may be interesting because of the small final state interactions, although the branching ratio is small. One needs also to fight with large background of photons mainly coming from $\pi^0$s. Nevertheless, if the enhancement is prominent, there is a chance to find the signal. When $\sigma$ has a finite three momentum, one can detect dileptons through the scalar-vector mixing in matter: $\sigma \rightarrow \gamma^* \rightarrow e^+e^-$. The inverse process can be also used to produce the $\sigma$ or $(\pi\pi)$$_{I=J=0}$ system by the electro-magnetic probes owing to the scalar-vector mixing in the finite density system where the charge conjugation symmetry is violated. Such an experiment has been planned and being performed in SPRING8 [47]. We remark that $(d, ^3He)$ or $(d, ^3He)$ reactions is also useful to explore the spectral enhancement because of the large incident flux. as in the production of the deeply bound pionic atoms and the possible production of $\eta$- or $\omega$- mesic nuclei [48]. The incident kinetic energy $E$ of the deuteron in the laboratory system is estimated to be $1.1\text{GeV} < E < 10\text{ GeV}$, to cover the spectral function in the range $2m_\pi < \omega < 750\text{ MeV}$. A theoretical evaluation of the feasibility of such experiments is now in progress [49].
6 Other possible evidence of partial chiral restoration in nuclear matter

It is interesting that there are other possible experimental evidences for partial chiral restoration in nuclear matter than the chiral fluctuations in the sigma meson channel discussed so far. The spectral function deduced from the lepton pairs from the heavy ion collisions shows a softening, which might be an evidence for the partial chiral restoration in nuclear medium [50]: Pisarski [11] was the first who suggested that a decrease of the rho meson mass may be a signature of the chiral restoration in hot hadronic matter. Brown and Rho [15] conjectured also the decrease of the vector meson masses in association with the chiral restoration on the basis of a scaling argument (the so called Brown-Rho scaling). Hatsuda and Lee [20] discussed the vector meson properties using the QCD sum rules. A KEK experiment also shows the softening of the spectral function in the $\rho/\omega$ channel in heavy nuclei such as Gold [51]. The deeply bound pionic atom has proved to be a good probe of the properties of the hadronic interaction deep inside of heavy nuclei. Yamazaki [52] suggested that the anomalous energy shift of the pionic atoms (pionic nuclei) owing to the strong interaction could be attributed to the decrease of the effective pion decay constant $f^*_{\pi}(\rho)$ at finite density $\rho$ which may imply that the chiral symmetry is partially restored deep inside of nuclei.

7 Summary and concluding remarks

1. The hadron spectroscopy must be a condensed matter physics of the QCD vacuum, because hadrons are elementary excitations on top of the nontrivial QCD vacuum.

2. The $\sigma$ meson as the quantum fluctuation of the order parameter of the chiral transition may account for various phenomena in hadron physics which otherwise remain mysterious.

3. There have been accumulation of experimental evidence of the $\sigma$ pole in the pi-pi scattering matrix. Here it has been noticed that the chiral symmetry, analyticity and crossing symmetry are all important.

4. Partial restoration of chiral symmetry in hot and dense medium leads to a peculiar enhancement in the spectral function in the $\sigma$ channel near the $2m_{\pi}$ threshold.

5. The enhancement is obtained both in the linear and nonlinear realization of chiral symmetry provided that the possible reduction of the quark condensate or $f_{\pi}$ is taken into account.

6. Such an enhancement has been observed in the reaction $A(\pi^+, (\pi^+\pi^-)_{I=J=0})A'$ by CHAOS group, which might possibly be an experimental evidence of the partial restoration of chiral symmetry in heavy nuclei.

7. It seems that there is no serious contradiction between the CHAOS data $\pi^+\pi^-$ and the Crystal Ball data on $2\pi^0$.

8. Further theoretical and experimental works are needed to confirm that chiral symmetry is partially restored in heavy nuclei.
9. There are other possible experimental evidences which show a partial restoration in dense nuclear matter.

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