Theoretical approaches to hadrons in nuclear matter

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We discuss recent developments concerning the in-medium properties of hadrons in dense and hot matter. The theoretical approaches are discussed in connection with the interpretation of experimental data from intermediate energy machines up to relativistic heavy ion collisions. Special emphasis is put on chiral restoration and its interplay with the substructure of the nucleon.

1. INTRODUCTION

The problem of the behavior of hadrons in dense and hot matter is a central question of present day nuclear and hadronic physics. On the theoretical side which is the main purpose of this article, a very important point is to incorporate the relevant features of chiral dynamics into the many-body problem of interacting hadrons to address the crucial issue of chiral symmetry restoration with increasing baryonic density and/or temperature and its interplay with hadron structure modification and confinement effects. The appropriate effective theories have to be constrained by lattice data when it is possible and experimental information from a variety of sources ranging from intermediate energy machines probing ordinary nuclear matter up to relativistic heavy ion collisions probing hadronic matter under extreme conditions.

2. THE ROLE OF CHIRAL SYMMETRY

2.1. Chiral symmetry breaking

The $\text{SU}(2)_L \otimes \text{SU}(2)_R$ chiral symmetry of the QCD Lagrangian is certainly a crucial key for the understanding of many phenomena in low energy hadron physics. This symmetry originates from the fact that the QCD Lagrangian is almost invariant under the separate flavor $\text{SU}(2)$ transformations of left-handed $q_L = (u_L, d_L)$ and right-handed $q_R = (u_R, d_R)$ light quark fields $u$ and $d$. The explicit violation of chiral symmetry is governed by the quark mass $m_q = (m_u + m_d)/2 \leq 10$ MeV which is much smaller than typical hadron masses of order 1 GeV, indicating that the symmetry is excellent. It is however well established that the QCD vacuum does not possess the symmetry of the Lagrangian \textit{i.e.}, chiral symmetry is spontaneously broken (SCSB) as it is evidenced by a set of remarkable properties. The first one is the building-up of a chiral quark condensate : $\langle \bar{q}q \rangle = \langle \bar{u}u + \bar{d}d \rangle/2$ which mixes, in the broken vacuum, left-handed and right-handed quark ($\langle \bar{q}q \rangle = \langle \bar{q}_L q_R + \bar{q}_R q_L \rangle/2$). Another order parameter at the hadronic scale is the pion decay constant $f_\pi = 94$ MeV which is related to the quark condensate by the Gell-Mann-Oakes-Renner relation : $-2m_q \langle \bar{q}q \rangle_{\text{vac}} = m_q^2 f_\pi^2$ valid to leading order in the current quark mass. It leads to a large negative value $\langle q \bar{q} \rangle_{\text{vac}} \approx - (240 \text{ MeV})^3$ indicating a strong dynamical breaking of chiral symmetry. The second feature is the appearance of soft Goldstone bosons to be identified with the almost massless pions. Finally the chiral asymmetry of the
vacuum associated with the condensation of quark-antiquark pairs is directly visible at the level of the hadronic spectrum: there is no degeneracy between possible chiral partners such as \( \rho(770) - a_1(1260) \) or \( \pi(140) - \sigma(400 - 1200) \). This is really true only for the low mass part of the spectrum but higher in the spectrum chiral symmetry is restored since in heavy hadrons the valence quarks having higher momenta simply decouple from the condensate. In other words, the chiral asymmetry of the vacuum does not affect the valence quarks and the underlying plausible picture for heavy hadrons is a rotating QCD string with bare quarks at the end-points [1].

2.2. Chiral symmetry restoration and hadron structure

When hadronic matter is heated and compressed chiral symmetry is also expected to be restored. This picture is supported by lattice simulation showing a sharp decrease of the quark condensate around \( T_c = 170 \text{ MeV} \) accompanying the deconfinement transition. However far before the critical region, partial restoration should occur through the simple presence of hadrons. Quantitatively from the equation of state (i.e., from the knowledge of the thermodynamical potential \( \Omega(\mu_B, T) \)), it follows that each hadron present with the scalar density \( \rho_h(\mu_B, T) \) contributes to the dropping of the quark density through a characteristic quantity \( \Sigma_h \) (the sigma commutator of the hadron) according to [2]:

\[
\frac{\langle \bar{q}q \rangle(\mu_B, T)}{\langle \bar{q}q \rangle_{\text{vac}}} = 1 + \frac{1}{2\langle \bar{q}q \rangle_{\text{vac}}} \frac{\partial \Omega(\mu_B, T)}{\partial m_q} = 1 - \sum_h \frac{\rho_h(\mu_B, T) \Sigma_h}{f_\pi^2 m_\pi^2}
\]

\[
\Sigma_h = m_q \frac{\partial M_h}{\partial m_q} = m_\pi^2 \frac{\partial M_h}{\partial m_\pi^2}, \quad \rho_h(\mu_B, T) = \frac{\partial \Omega(\mu_B, T)}{\partial M_h}
\]

Fortunately only the lightest hadrons actually contribute since the heavy hadrons just decouple and their corresponding sigma terms are very small. There is a very interesting interplay between chiral restoration and hadron structure since the in-medium chiral condensate behavior is driven, beside the influence of the equation of state, by the sigma term, itself related to the hadron mass obtainable in principle from the lattice. Even if lattice calculations are presently not feasible for quark mass smaller than 60 MeV or equivalently pion mass smaller than 400 MeV, a well controlled chiral model (possessing the correct light and heavy quark limits) for the pion loop correction can be utilized. In the case of the nucleon, one obtains an improved fit with lattice data which accurately extrapolates to the correct nucleon mass in the physical light quark sector [3]. This sort of interplay between phenomenological models and QCD itself has just begun and will be certainly crucial in the future of this field.

2.3. Chiral symmetry restoration in hadronic matter

The restructuring of the QCD vacuum associated with chiral restoration should be visible, as is usual in the many-body problem, at the level of the excitation spectrum. Hence the observable consequences should be studied looking at the in-medium hadronic spectral functions defined as \( \rho_h(\omega, \vec{q}) = -(1/\pi) \text{Im}D_h(\omega, \vec{q}) \) where \( D_h(\omega, \vec{q}) \) is a propagator or a correlator between two currents or fields having the quantum numbers of the hadron \( h \) under consideration. Numerous works have been devoted to the centroids of the mass distributions i.e., the in-medium masses, but the link between the evolution of the condensate and the masses cannot be an absolute one. More generally the modification of the hadronic spectral functions is certainly not restricted to the shift of the centroids of the mass distributions and we have to study the evolution of the whole shape of the spectral functions. Most of the time we expect a broadening of the spectral function (antikaons [4, 5], rho meson [6, 7]) and a dissolving of the resonances originating from various many-body mixing effects with the surrounding hadrons. There is however the notable exception of the sigma meson for which we expect a softening and a sharpening [8, 9]. The key
question is the relationship between the observed reshaping and chiral symmetry restoration. One possible strategy to obtain this crucial connection is to make a simultaneous study of the spectral functions associated with chiral partners. A very important example is the rho meson and the axial-vector meson $a_1$ and it has been established that there is a mixing of the associated current correlators through the presence of the pion scalar density $[10, 11]$.

2.4. Chiral effective field theory

The light scalar-isoscalar meson which is usually called the sigma meson is a particle representing the amplitude fluctuation of the chiral order parameter $\langle \bar{q}q \rangle$ around the minimum of the effective potential. The pion corresponds to the other fluctuation of the condensate namely the phase fluctuation. It is (almost) massless since it is a mode moving at the bottom of the “Mexican hat” effective potential, i.e., the so-called chiral circle. Consequently the sigma meson gets a large decay width into two-pion which makes this object so elusive in the vacuum. In other words, the physical sigma state in QCD can be at most a broad resonance which is a superposition of the ur-sigma (genuine amplitude fluctuation of the order parameter) and a two-pion state. To have some insight on the manifestations of chiral symmetry restoration and to make predictions, one has to rely on effective theories which should incorporate the symmetry properties of the underlying QCD Lagrangian. The sigma and pion taken as effective degrees of freedom are introduced through a $2 \times 2$ matrix $W = \sigma + i \vec{\tau} \cdot \vec{\pi}$. An alternative formulation of the resulting linear sigma model is obtained by going from cartesian to polar coordinates according to:

$$W = \sigma + i \vec{\tau} \cdot \vec{\pi} = S U = (f_\pi + s) \exp \left( \frac{i \vec{\tau} \cdot \vec{\phi}}{f_\pi} \right)$$

(2)

The new pion field $\vec{\phi}$ corresponds to an orthoradial soft mode which is automatically massless (in the absence of explicit CSB) since it is associated with rotations on the chiral circle without cost of energy. The new sigma meson field $s$ describes a radial mode associated with the fluctuations of the “chiral radius”. As demonstrated in $[12]$, this chiral invariant $s$ field can be identified with the famous “sigma meson” of the relativistic QHD theories, thus giving a solution to the long-termed problem of their chiral status. To leading order in density and temperature, the dropping of the chiral condensate is given by:

$$R = \frac{\langle \bar{q}q \rangle(\rho, T)}{\langle \bar{q}q \rangle_{vac}} = \frac{\langle \sigma \rangle(\rho, T)}{f_\pi} \approx 1 - \frac{\langle \phi^2 \rangle(\rho, T)}{2 f_\pi^2} - \frac{\langle s \rangle(\rho, T)}{f_\pi}.$$  

(3)

These two contributions to the dropping of the chiral condensate yield very different observable manifestations of chiral symmetry restoration. The pionic fluctuation piece ($\sim 20\%$ dropping at $\rho = \rho_0$) is associated with axial-vector mixing and does not contribute to the dropping of the masses. It is the scalar piece ($\sim 20\%$ dropping at $\rho = \rho_0$) which governs the evolution of the masses as a consequence of the shrinking of the chiral radius.

3. PIONS IN NUCLEAR MATTER

With the above degrees of freedom, one can build an effective Lagrangian and first address the question of the pion properties in nuclear matter. Such a Lagrangian will depend on parameters constrained by phenomenology and data such as the very recent accurate measurement showing that the pion-nucleon isoscalar scattering length is compatible with zero $[13]$. From the Gell-Mann-Oakes Renner relation, it follows that to leading order in density, the pion decay constant squared behaves like the quark condensate. Recently the attention has focused on the charge
exchange scattering length $b_1$ \cite{14, 15, 16, 17, 18, 19}. The fit to these data \cite{14, 15, 16, 18} suggests a large enhancement associated with chiral restoration of the isovector scattering length $b_1$ in nuclei, as anticipated in \cite{17}. Within the approach described above, one obtains:

$$\frac{b_1^*}{b_1} = 1 + \frac{\Sigma_N \rho}{f_\pi^2 m_\pi^2} - \frac{7}{6} \frac{\Sigma_N^{(\pi)} \rho}{f_\pi^2 m_\pi^2} \simeq 1 + 0.18 \frac{\rho}{\rho_0}.$$  \hspace{1cm} (4)

which comes from the combined effect of the energy dependence \cite{19} of the pion self-energy and of the in-medium renormalization of the charge exchange amplitude related to the Weinberg-Tomozawa piece of the chiral Lagrangian \cite{20}. The effect is more moderate than in the original proposal \cite{17} which ignores the pion-loop correction (last term of eq. 4).

4. SCALAR-ISOSCALAR MODES AND FLUCTUATIONS OF THE CHIRAL CONDENSATE

As mentioned before, the genuine sigma meson is defined as the quantum fluctuating mode of the chiral order parameter around the minimum of the effective potential. In nuclear matter the minimum is shifted and it is crucial to address this question of matter stability in chiral effective theories. The energy density taken as a function of the order parameter, which we call generically $\langle S \rangle$, is the appropriate effective potential:

$$\epsilon(\rho, \langle S \rangle) = \sum_{p<p_F} \sqrt{p^2 + M_N^2\langle S \rangle} + V(\langle S \rangle) + C_V \rho^2.$$  \hspace{1cm} (5)

$V(\langle S \rangle)$ is the “Mexican hat” potential generating vacuum symmetry breaking and the last term corresponds to some vector repulsion. In the NJL model the nucleon can be built as a quark-diquark bound state and the constituent quark mass $M_q^* = g_q \langle S \rangle$ plays the role of the order parameter \cite{21}. In the chiral version of relativistic theories of the Walecka type \cite{12}, the sigma field can be identified with the chiral invariant scalar field from which one can dynamically generate the effective nucleon mass $M_N^* = g_{SN} \langle S \rangle$. Independently of the particular chiral model, the decrease of the curvature of the Mexican hat potential, as one moves away from the vacuum state, implies an increase of the attraction between nucleons. The needed extra-repulsion to get matter stability can be obtained if the sigma-nucleon coupling constant $g_{SN}^*$ becomes a decreasing function of the order parameter. This is precisely what happens if an infrared cut-off simulating confinement is incorporated in the NJL model \cite{21} and the same effect appears in the QMC model from the polarization of the confined quark wave functions \cite{22}. Since the coupling constant $g_{SN}^* = \partial M_N^*/\partial \langle S \rangle$ is essentially the scalar response of the nucleon, which is in principle calculable on the lattice, one gets a connection between nuclear saturation and QCD itself! The sigma mass is defined as the curvature of the effective potential $m_\sigma^2 = \partial^2 \epsilon/\partial \sigma^2$. In case of structureless nucleons, it strongly decreases with the condensate as a consequence of chiral restoration. However when nucleon polarization and/or confinement effects are included, the sigma mass remains remarkably stable \cite{21, 23}. This feature has a direct consequence on the scalar susceptibility defined in terms of the correlator of the quark density fluctuations which encodes the properties of the sigma meson:

$$\chi_s = \frac{\partial \langle \bar{q} q \rangle}{\partial m} = -i \int dt d\vec{r} \langle \delta \bar{q} q(0,0), \delta \bar{q} q(\vec{r},t) \rangle.$$  \hspace{1cm} (6)

Such a quantity can be calculated on the lattice at finite temperature. It becomes very large near the phase transition as it should since the fluctuations of the order parameter become large as a second- or a weak first-order phase transition is approached. In addition lattice calculations
also show that the pseudoscalar susceptibility (pionic channel) becomes identical with the scalar one beyond the transition point indicating chiral restoration \[ 24 \]. At finite density since lattice data are scarce, one has to rely on models. According to a calculation within the kind of effective theory described above, the convergence of these two susceptibilities at density larger than \( 3 \rho_0 \) seems to occur. In this approach the scalar fluctuations are transmitted by the sigma meson and are relayed by the nucleons \[ 25 \].

The in-medium scalar-isoscalar modes in nuclei have been studied experimentally through two-pion production in reactions induced either by pions \[ 26, 27 \] or photons \[ 28 \] on various nuclei. All these collaborations have observed a systematic A dependent downwards shift of the strength when the pion pair is produced in the sigma meson channel as it is apparent on the photoproduction data of the TAPS collaboration \[ 28 \] (see right panel of Fig. 1). So far, conventional calculations are not able to reproduce the data and the proposed explanations rely on an in-medium modification of the unitarized \( \pi \pi \) interaction in the final state of the reaction. Historically the first advocated medium effect is related to the softening of the pion dispersion hence modifying the two-pion propagator in the unitarized \( \pi \pi \) interaction \[ 8, 29 \]. The other effect proposed by Hatsuda and Kunihiro is related to chiral restoration through the dropping of the sigma mass and the scalar condensate \[ 9, 30 \]. This is a very general argument since chiral restoration implies a softening of a collective scalar-isoscalar mode, the sigma meson, which becomes degenerate with its chiral partner, the pion, at full restoration. This implies that at some density the sigma mass is twice the pion mass and a sharp cusp-structure near threshold is generated. This spectral enhancement \[ 9 \] is actually intimately related to enhanced in-medium fluctuations of the chiral condensate. This effect is however weakened if the nucleon polarization effect is included \[ 23 \]. Consequently at moderate density (see Fig. 1) corresponding to the actual experimental situation, the medium effect is mainly driven by pions. Indeed a detailed model calculation including only this latter medium effect \[ 31 \] is able to reproduce quite decently the photoproduction data of the TAPS collaboration, as shown on Fig. 1. Hence whatever the vacuum nature of the sigma meson and the medium effect affecting it are, it appears that the sigma pole moves at lower energy with reduced width from in-medium chiral dynamics.

5. TOWARDS HIGH BARYONIC DENSITIES AND PERSPECTIVES

What happens at higher density is largely unknown and it is a major experimental challenge to investigate this high density region which should complement the high temperature domain studied at RHIC or at CERN/SPS. In that respect, there is a GSI project to study compressed baryonic matter with heavy ions in the range \( 10 - 40 \) AGeV. One crucial point is of course the nature of the phase transition. For instance lattice data show that at finite temperature deconfinement and chiral restoration occur simultaneously but we do not really understand the reason and one question is whether this feature survives in the high density transition. Even if this transition is very difficult to reach experimentally one can adopt a pragmatical bottom-to-top attitude looking at, beside the usual macrodynamical variables (flow) probing the eos, the behavior of the hadron spectral functions as precursor effects of the phase transition. This opens many theoretical challenges which can be illustrated with dilepton production. It is well known that a strong excess of dileptons below the rho mass has been observed at CERN/SPS and it has been attributed to strong medium effects in the interacting fireball. The dilepton production is actually related to the imaginary part of the current-current correlation function in the vector channel. According to the well established vector dominance phenomenology, this correlator is accurately saturated by the rho meson at least for the radiation from the interacting fireball before freeze out. Hence dilepton production probes the rho meson spectral function in
Figure 1. Left panel: sigma strength function in the vacuum (lower curves), with in-medium pionic effects (middle curves) and with chiral restoration on top of in-medium pionic effects (higher curves). Right panel: two-pion invariant mass distributions for $\pi^0\pi^0$ and $\pi^+\pi^0$ photoproduction on various nuclei [28] compared with a calculation with in-medium pionic effects (full lines) and without (dashed lines) in the final $\pi\pi$ interaction [31].

The dense and hot medium. Experimentally one sees a broadening and a flattening of the rho meson spectral function. The resulting spectrum is very similar in shape with what would be radiated by a perturbative quark-gluon phase in which chiral symmetry is restored [4]. The DPR has been studied using various methods ranging from density expansions up to transport codes together with model independent in spirit theoretical tools for calculating or constraining the current-current correlator such as chiral reduction formalism, QCD sum rules or Weinberg sum rules. One important very much debated question concerns the mechanism associated with chiral restoration. In the Rho-Brown dropping scenario [32], the rho meson mass plays the role of an order parameter. Another mechanism is the axial-vector mixing. The emission and the absorption of thermal (finite temperature) or virtual (finite density) pions in the medium is able to transform a vector current into an axial current and at full restoration the axial and vector correlators become identical [10, 11]. This mixing effect together with other ones such as the mixing of the rho with some $N^*-h$ configurations has been explicitly incorporated in the very detailed hadronic calculation [8] of the in-medium rho spectral function (see fig. 2). Once the local rate is space-time evolved through a realistic fireball expansion, this approach (full curve on the left panel of fig.2) correctly reproduces the CERES data and in particular the most recent data at lower SPS energy (40 AGeV) for which the low mass enhancement effect is even
more important. This is compatible with the fact that the medium effects are mainly driven by baryons. Such a study has to be pursued in direction of higher density with the forthcoming HADES data in the GeV range and the future project at GSI. However on the theoretical size some questions remain to be clarified such as the chiral status of the $N^*(1520)$ and this again might be related to an interplay between chiral dynamics and nucleon structure. In addition some new theoretical suggestions have been proposed such as the simultaneous softening of the rho and sigma mesons \cite{15} or the fate of vector dominance at finite temperature or density. In a set of recent works mainly driven by Harada and Yamawaki \cite{36} a novel way of matching an effective field theory with the underlying QCD in the sense of a Wilsonian renormalization group equation has been proposed. This has been explicitly worked out in the HLS model where the rho meson is generated as the gauge boson of a hidden local symmetry. By matching the axial and vectors correlators at a well chosen scale $\Lambda \sim 1\text{ GeV}$, the bare parameters of the effective Lagrangian are determined. Using the renormalization group equations with inclusion of quadratic divergences, the physical quantities such as masses and coupling constants are then obtained. It has been found that the usual vector dominance is recovered in the vacuum but is lost with increasing temperature and density. One obtains a vector manifestation of chiral symmetry in which the (longitudinal) rho becomes massless at the chiral phase transition point. This kind of approach which allows to constrain effective theories is certainly very encouraging and has to be pursued with the explicit incorporation of other degrees of freedom, and in first rank the scalar-isoscalar degrees of freedom. It is also clear that the deep understanding of hot and dense hadronic matter is a vast theoretical challenge. It certainly necessitates the interplay between model building, lattice QCD at finite chemical potential and non-perturbative methods such as renormalization group equations or methods issued from the many-body problem.

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