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Hadrons in dense and hot matter

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Abstract. Theoretical issues and perspectives of hadronic matter at high baryon density are discussed with focus on the restoration of chiral symmetry and observable consequences.

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1 Introduction

The properties of strongly interacting matter under extreme conditions in temperature and density are the central focus of the relativistic heavy-ion program. One of the aims is to explore the phase diagram in the (T,μ)-plane which becomes experimentally accessible provided thermal equilibrium is reached during the early stages of the collision. The hadrochemical analysis of freeze-out abundances indicates that this may indeed be the case over a wide range of collision energies [1]. Our understanding of the phase structure and possible phase transitions remains sketchy. Stringent results from *ab initio* lattice simulations are only available along the T-axis [2] due to numerical difficulties at finite μ. The $\mu = 0$ lattice results indicate that, for physical values of the bare strange quark mass m_s° there is a smooth crossover at a transition temperature of $\sim 170\,\mathrm{MeV}$ at which chiral symmetry is restored, accompanied by a rapid change in the bulk thermodynamic variables. The latter signals the opening up of new degrees of freedom and is interpreted as a signature of deconfinement. It remains to be understood why chiral symmetry restoration and deconfinement seem to occur at the same value of the temperature. Several model studies [3] indicate that at values of $\mu \sim 1\,\mathrm{GeV}$ and small temperatures a chiral phase transition of first order should occur. This implies the existence of a critical point at which the critical line ends. The exact location of this point sensitively depends on the value of m_s° and its experimental determination would be an important milestone in the study of the phase diagram. Possible signatures have been suggested [4] and relate to the long-wavelength fluctuations of the in-medium chiral condensate.

In this paper I will focus on aspects of the restoration of spontaneously broken chiral symmetry which, in my opinion, are better understood than the issues related to deconfinement. Spontaneous chiral-symmetry breaking in the QCD vacuum and its restoration at finite μ and T is intimately related to the question of mass generation for light hadrons and the medium modification of their spectral properties.

2 The restoration of chiral symmetry

The starting point for the equilibrium description of strongly interacting matter is the QCD partition function in the grand canonical ensemble

$$\mathcal{Z}_{\mathrm{QCD}}(V,T,\mu_q) = \mathrm{Tr}\, e^{-(H_{\mathrm{QCD}}-\mu_q N_q)/T}, \tag{1}$$

where N_q is the quark number operator and $\mu_q = \mu/3$ the quark chemical potential. From the free energy $\Omega(T,\mu) = -T \lim_{V\to\infty} 1/V \ln \mathcal{Z}_{\mathrm{QCD}}(V,T,\mu_q)$ all thermodynamic quantities such as pressure, internal energy, entropy, etc. can be derived in a standard way. In addition, an expression for the chiral condensate is obtained as

$$\langle\langle \bar{q}q\rangle\rangle = \frac{\partial \Omega(T,\mu)}{\partial m_q^\circ}, \tag{2}$$

where m_q° denotes the current quark mass. Finally, through the corresponding susceptibilities, the free energy also determines the fluctuation properties of matter and hence the criticality near a phase transition. Besides the specific heat, the compressibility etc., the scalar (chiral) susceptibility

$$\chi_S = \frac{T}{V}\frac{\partial^2 \Omega(T,\mu)}{\partial {m_q^\circ}^2} = \langle\langle (\bar{q}q)^2\rangle\rangle - \langle\langle \bar{q}q\rangle\rangle^2 \tag{3}$$

which relates to the fluctuations of the chiral condensate, plays an important role.

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2.1 Evolution of the chiral condensate

The chiral condensate is one of the order parameters for chiral-symmetry breaking and its evolution with temperature and number density, $n(\mu)$, reflects the restoration of the symmetry. Starting from low T or μ close to the chemical potential of nuclear matter at saturation, μ_0, it is more economical to work with confined hadrons rather than quark-gluon degrees of freedom. The connection can be made rigorous. Using eq. (2) in conjunction with the Gell-Mann Oakes Renner relation (GOR) which is well obeyed in vacuum [5] one can express the ratio of the in-medium condensate to that in the vacuum as a sum over all hadronic states present in matter as

$$\frac{\langle\langle \bar{q}q \rangle\rangle}{\langle \bar{q}q \rangle} \equiv R_\chi = 1 - \sum_h \frac{\Sigma_h \varrho_h^s(T,\mu)}{f_\pi^2 m_\pi^2} \qquad (4)$$

with

$$\Sigma_h = m_q^\circ \frac{\partial m_h}{\partial m_q^\circ} = \frac{1}{m_q^\circ} \langle h|\bar{q}q|h\rangle; \quad \varrho_h^s(T,\mu_q) = \frac{\partial \tilde{\Omega}(T,\mu)}{\partial m_h} \qquad (5)$$

($\tilde{\Omega}(T,\mu) = \Omega(T,\mu) - \Omega(0)$). There are two ingredients that enter eq. (4). One relates to the chiral properties of the hadron in question and is determined by the corresponding "sigma commutator", Σ_h. Physically, Σ_h represents the amount of energy required to displace the vacuum condensate in the vicinity of the hadron. The second involves the scalar density $\varrho_h^s(T,\mu)$ of hadrons in the interacting matter which is determined by $\partial\Omega(T,\mu)/\partial m_h$, where m_h denotes the vacuum mass of the hadron. Here the full complications of the many-body problem enter.

There are only two regions in the phase diagram where we have complete knowledge for the condensate evolution. One is for small T and μ, *i.e.* close to vacuum, and the other near cold nuclear matter at saturation characterized by $T = 0$, $\mu = \mu_0$. For small T and μ, hadronic matter can be viewed as a weakly interacting gas of thermally excited pions. Similarly, nuclear matter in the vicinity of μ_0 and small temperatures approximately behaves as a dilute gas of nucleons interacting with pions. In both cases chiral perturbation theory as a rigorous effective field theory can be applied, to obtain a model-independent leading-order expansion for eq. (4):

$$\frac{\langle\langle \bar{q}q \rangle\rangle}{\langle \bar{q}q \rangle} = 1 - \frac{T^2}{8f_\pi^2} - 0.3\frac{n(\mu)}{n(\mu_0)} + \cdots, \qquad (6)$$

which corresponds to the free gas approximation. Thus, the mere presence of an ideal gas of hadrons diminishes the chiral condensate without changing the vacuum properties of the hadrons! Obviously, medium modifications and the corresponding non-trivial changes of the chiral condensate have to involve hadronic interactions. They become increasingly important as the matter grows hotter and denser, *i.e.* one moves deeper into the (T,μ)-plane and approaches the phase boundary. According to eq. (4), more and more hadronic states will enter, which severely limits the description near the phase transition. Chiral perturbation theory ceases to be applicable and one has to resort to chiral effective Lagrangians that treat higher-mass hadrons as explicit degrees of freedom. In the vicinity of the phase boundary, non-perturbative many-body methods are called for, in addition.

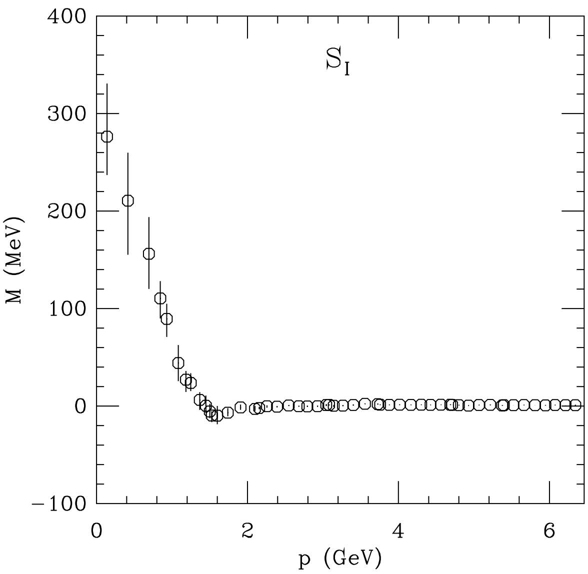

Fig. 1. The lattice quark mass function in Landau gauge [8].

2.2 Hadrons and chiral symmetry

Spontaneous chiral-symmetry breaking plays a decisive role in the mass generation of light hadrons [6,7]. On the other hand, chiral-symmetry breaking is an infrared phenomenon. This is clearly seen in lattice calculations of the Euclidean quark mass function in the Landau gauge [8] (fig. 1) and also follows from Dyson-Schwinger approaches [9]. As a consequence, high-mass mesons and baryons should decouple from the chiral condensate leading to parity doublets. This implies that their respective sigma commutators vanish (or at least become very small). Hence, according to eq. (4), they do not contribute to the condensate evolution. There is some evidence for parity doubling in the meson and baryon spectrum. The recent τ-decay measurements [10] of the vector- and axial-vector spectral distribution suggest that both spectral functions become identical between 1.5 GeV and 2 GeV and coincide with the PQCD limit [11]. This energy scale would be consistent with the lattice results in fig. 1. For the nucleon there are also tantalizing hints for parity doubling in the same range of excitation energy as suggested in ref. [12]. To put this conjecture on firmer grounds, detailed baryon spectroscopy of overlapping resonances is required. This difficult task is being discussed at electron accelerators such as ELSA in Bonn [13].

The fact that high-mass mesons and baryons do not contribute to the evolution of the chiral condensate opens the possibility to construct chiral Lagrangians with a limited number of degrees of freedom, including only hadrons with masses less than $\sim$ 2 GeV. To what extent such hadrons are elementary quark states or dynamically generated resonances remains an open question and is of great importance to evaluate their sigma commutators. For the nucleon, significant progress in this direction is being made by calculating the bare quark mass dependence of the mass, supplemented by chiral extrapolations to realistic values of $m^{\circ}_{u,d}$. Such studies allow for an *ab initio* evaluation of Σ_N. A similar lattice analysis for excited states would be highly desirable.

3 Medium modification of hadrons

What are the signatures of chiral-symmetry restoration in hadronic matter? Being renormalization scale dependent, the chiral condensate is not an observable. Changes in $\Omega(T,\mu)$ and possible phase transitions are, however, reflected in the measurable excitation spectrum. The strategy is therefore to study the in-medium hadronic spectral functions as the elementary excitations the matter in equilibrium. In condensed matter this approach is known as "soft-mode spectroscopy". Quite generally, the restoration of broken chiral symmetry will lead to identical spectral functions for channels of opposite parity.

In QCD, the spectral properties of hadrons are encoded in the two-point correlation functions involving currents with the appropriate quantum numbers,

$$D_i(q_0,\boldsymbol{q}) = i\int \frac{\mathrm{d}^4x}{(VT)} e^{iqx}\theta(x_0)\langle\!\langle[J_i(x),J_i(0)]\rangle\!\rangle, \qquad (7)$$

where J_i are local operators composed of elementary quark fields. Notice the separate dependence on energy q_0 and three-momentum $\boldsymbol{q}$ due to loss of covariance in the medium. The spectral function

$$\rho_i(q_0,\boldsymbol{q}) = -\frac{1}{\pi}\,\mathrm{Im}\,D_i(q_0,\boldsymbol{q}) \qquad (8)$$

represents the excitation spectrum in a given channel of spin and parity. By means of the dispersion relation

$$D_i(q_0,\boldsymbol{q}) = \int_0^\infty \mathrm{d}q_0'^2 \frac{\rho_i(q_0',\boldsymbol{q})}{q_0'^2 - q_0^2 + i\eta}\,, \qquad (9)$$

ρ_i determines the entire correlation function. Rather than as derivatives of the free energy (eq. (3)), the susceptibilities can also be obtained directly from the spectral functions $\rho_i(q_0,\boldsymbol{q})$ as

$$\chi_i = \langle\!\langle J_i^2\rangle\!\rangle - \langle\!\langle J_i\rangle\!\rangle^2 = \lim_{(q_0,\boldsymbol{q})\to 0} D_i(q_0,\boldsymbol{q}) = \int_0^\infty \mathrm{d}q_0'^2 \frac{\rho_i(q_0',0)}{q_0'^2 + i\eta} \qquad (10)$$

which shows that enhanced fluctuations are related to the low-energy and low-momentum behavior of the spectral function.

First-principles lattice calculations of in-medium hadronic spectral functions in Minkowski space have been carried out for finite T and vanishing μ. Using maximum-entropy methods results are reported in refs. [14,15]. Due to the limited number of temporal data points they are still quite crude. At present, more detailed insight into the temperature dependence and the behavior at finite μ is obtained from hadronic models. Formally, the pertinent currents $J_i(x)$ are identified with elementary fields $\phi(x)$ such as the nucleon, Δ-isobar, pion, ρ-meson etc., that constitute the relevant hadronic degrees of freedom. For these, effective field theories, consistent with chiral symmetry, are utilized to calculated the in-medium spectral properties as reliably as possible.

In connection with chiral-symmetry restoration, there are several suggestions for exploring hadrons in the medium. In the following, I will discuss two examples in more detail. One deals with the behavior of the scalar-isoscalar f_0-meson and relates directly to the fluctuations of the chiral condensate. The second concerns the ρ-meson which plays a prominent role for low-mass dilepton production in heavy-ion collisions and has been discussed extensively [16] in connection with the CERES data from the CERN-SpS.

3.1 Scalar modes

As mentioned in sect. 2, the fluctuations of the chiral condensate are indicators for the restoration of chiral symmetry. In a rapid crossover or a weak first-order transition the scalar susceptibility χ_s is strongly enhanced (it diverges in a second-order transition with critical exponents determined by universal behavior). Since χ_s can be obtained directly from the free energy $\Omega(T,\mu)$ (eq. (3)) it can be reliably evaluated on the lattice for vanishing μ. A strong enhancement in the vicinity of the crossover is found [2]. According to eq. (10), this implies that the scalar spectral function must be shifted to lower energy. Within various models there have been several studies of this behavior [17–20] which all come to similar conclusions. As a representative example, I discuss recent results within the linear sigma model in the $1/N$-expansion [21]. Here the scalar quark current $J_s(x) = \bar{q}q(x)$ is identified with the sigma field $\sigma(x)$ [22] and the scalar correlator becomes the in-medium σ-propagator:

$$D_s(q_0,\boldsymbol{q}) \equiv D_\sigma(q_0,\boldsymbol{q}) = i\int \frac{\mathrm{d}^4x}{(VT)} e^{iqx}\theta(x_0)\langle\!\langle[\sigma(x),\sigma(0)]\rangle\!\rangle. \qquad (11)$$

The results displayed in fig. 2 show a strong softening as a function of number density $n(\mu)$. A similar reshaping is also found as a function of temperature. It has been shown explicitly that this effect is also found in non-linear realizations of chiral symmetry [23] and is therefore generic.

What are the experimental signatures? Since the σ- or f_0-meson strongly couples to two-pion states, a softening of the in-medium scalar spectral function leads to the emission of soft pions which should be observable in the p_T spectra or HBT correlations in heavy-ion collisions. There is a precursor to this phenomenon which may have

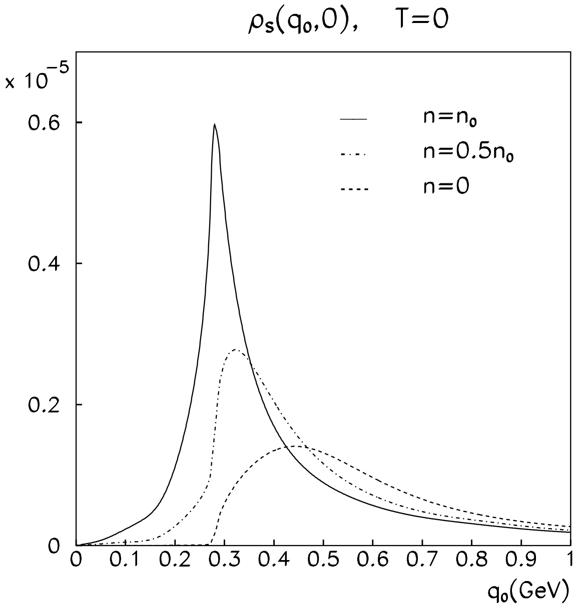

Fig. 2. The in-medium spectral function of the σ-meson for various values of density.

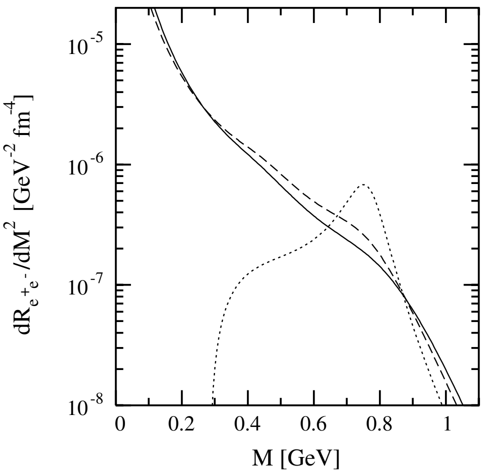

Fig. 3. The theoretical dilepton rate at $T = 150\,\mathrm{MeV}$ and $\mu_{\mathrm{B}} = 3\mu_q = 452\,\mathrm{MeV}$ [28].

been observed already. According to eq. (6), the chiral condensate in the interior of cold nuclei is reduced by about 30%. Therefore, its fluctuations are enhanced — in fact quite substantially— as can be seen from fig. 2. This prediction can be tested in experiments where two pions with small cms momentum and the quantum numbers $J = I = 0$ of the f_0 are produced near threshold in nuclei. Such experiments have been conducted by the CHAOS Collaboration at TRIUMF using an incident π^+ beam on various nuclear targets [24] identifying charged pions in the final state. A second experiment was performed by the Crystal Ball (CB) Collaboration at BNL with an incident π^- beam [25] detecting a π^0 pair in the final state through coincident 4γ decay. Quite recently, the π_0-pair spectrum has also been measured in photon-induced reactions at MAMI-B using the TAPS spectrometer [26]. The photon has the advantage of weak initial-state interaction. In all cases, a shift to lower invariant masses for heavier nuclei has been reported. A quantitative understanding of the details of the distributions still awaits final clarification. Uniquely establishing the results of the measurements as a consequence of the in-medium s-wave $\pi\pi$ interaction would be an important milestone in the study of the chiral-symmetry restoration.

3.2 Vector- and axial-vector spectral functions

The ρ-meson appears as a prominent resonance in the e^+e^--annihilation cross-section as well as in $\tau \to 2n\pi\nu_\tau$ decay. It therefore plays a central role for dilepton production in heavy-ion collisions at invariant masses below 1 GeV. Medium-modifications of the ρ-meson have been suggested as another signal of chiral-symmetry restoration. The conjecture that the (pole) mass is proportional to some power of the condensate ratio R_χ [27] ("Brown-Rho" (BR) scaling) implies a dropping of the ρ mass as R_χ decreases.

In general, the dilepton-production rate is given by the in-medium electromagnetic spectral function as

$$\frac{\mathrm{d}N_{l^+l^-}}{\mathrm{d}^4x\,\mathrm{d}^4q} = L^{\mu\nu}\left(-\frac{i}{\pi}\right)\int \mathrm{d}^4x e^{iqx}\theta(x_0) \times\langle\langle [J^{\mathrm{elm}}_\mu(x), J^{\mathrm{elm}}_\nu(0)]\rangle\rangle, \quad (12)$$

where $L^{\mu\nu}$ denotes the lepton tensor. In the vector dominance model (VDM) [29] which describes the vacuum properties of the ρ very well, the electromagnetic current correlator directly relates to its in-medium properties. In the calculations [16], two important medium effects can be identified. The first is the modification of the intermediate two-pion states to which the ρ-meson strongly couples. Here proper care has to be taken to ensure gauge invariance. The second is a direct coupling to baryonic resonances, most prominently the $N^*(1520)$-resonance. The inclusion of both effects leads to a large broadening of the spectral function at high density and temperature and results in a dramatic reshaping of the dilepton rate, as indicated in fig. 3. Since theses rates are very close to those obtained in hard-thermal-loop resumed perturbation theory for the quark-gluon plasma [30], one would conclude that the signal for chiral-symmetry restoration in the vector sector is a smooth evolution for the hadronic spectral function into that of the plasma. Once the local rate is space-time evolved through a realistic fireball expansion until thermal freeze-out and detector acceptances and background rates from Dalitz decays are properly accounted for, the resulting rates compare favorably with the measurements of the CERES Collaboration. Also the transverse spectra are well reproduced.

The relevance of such results for the restoration of chiral symmetry is not apparent, though. To make a stringent connection requires a simultaneous evaluation of both the vector- and the axial-vector correlator. In the vacuum and in the chiral limit both are related by two "Weinberg sum rules" [31]:

$$\int_0^\infty \frac{\mathrm{d}s}{s}\big(\rho_V^\circ(s) - \rho_A^\circ(s)\big) = f_\pi^2;$$
$$\int_0^\infty \mathrm{d}s\big(\rho_V^\circ(s) - \rho_A^\circ(s)\big) = 0, \tag{13}$$

where the first directly links the vacuum spectral functions to the pion decay constant, f_π. Similar sum rules also hold in the hadronic medium [32] and they serve as an important constraint of effective field theories that intend to properly implement chiral symmetry in the correlators. This is quite difficult especially when dealing with high baryon density. Here baryonic resonances of both parities enter as chiral partners and an understanding of their chiral structure is a necessity. As mentioned earlier, possible parity doubling for high masses is an important issue in this connection.

In the purely mesonic sector, relevant for RHIC energies, there have been several recent attempts to calculate the vector- and axial-vector correlator simultaneously, maintaining gauge invariance and chiral symmetry. One such approach [33,34] starts from the linear sigma model which is globally gauged with elementary ρ and a_1 fields as chiral partners. At high temperatures, a significant reshaping of distributions is observed, especially in the low-energy region. Nevertheless, the ρ and a_1 peaks remain present, even in the vicinity of the phase boundary. The parameters of the model Lagrangian can be adjusted such that, at the tree level, the ρ-meson mass is proportional to the in-medium chiral condensate $\langle\langle\sigma\rangle\rangle$. This is the BR-scaling scenario. To one-loop order, however, it can be proven analytically that the pole mass of the ρ-meson remains unchanged to order T^2 and only receives contributions of order T^4 and higher, hence putting BR-scaling into question. In a series of recent papers [35–37] the original BR scaling conjecture has been revisited in the context of the "vector manifestation" of broken chiral symmetry [38]. At the chiral phase transition this alternative way of breaking chiral symmetry requires the presence of a massless vector meson which is identified with the (longitudinal) ρ-meson. From the dilepton measurements a the BR scenario cannot be rule out, *a priori*, and it will presumably have to be decided in lattice simulations of the pertinent in-medium spectral functions whether the VM is a viable alternative to describe chiral-symmetry restoration.

4 Outlook

Progress has been made in our understanding of the in-medium properties of hadrons and their relation to the restoration of broken chiral symmetry. Several questions and issues remain open, though. They include: 1) the chiral structure of low-mass hadrons, 2) the role of high-mass mesons and baryons and the possible occurrence of parity doubling, 3) further developments of chirally consistent non-perturbative many-body methods that uniquely link the equilibrium properties of matter to those of the spectral functions, 4) comparison of hadronic models for in-medium properties with lattice data, 5) the confinement mechanism for light hadrons, and 6) the role and signatures of deconfinement in the (T, μ) phase diagram.

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