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The impact of chirally odd condensates on the rho meson

T. Hilger [a,b,*], R. Thomas [a,b], B. Kämpfer [a,b], S. Leupold [c]

[a] Forschungszentrum Dresden-Rossendorf, PF 510119, D-01314 Dresden, Germany
[b] TU Dresden, Institut für Theoretische Physik, 01062 Dresden, Germany
[c] Institutionen för fysik och astronomi, Uppsala Universitet, Sweden

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ABSTRACT

Based on QCD sum rules we explore the consequences of a scenario for the ρ meson, where the chiral symmetry breaking condensates are set to zero whereas the chirally symmetric condensates remain at their vacuum values. This clean-cut scenario causes a lowering of the ρ spectral moment by about 120 MeV. The complementarity of mass shift and broadening is discussed. A simple parametrization of the ρ spectral function leads to a width of about 280 MeV if no shift of the peak position is assumed.

1. Introduction

The impact of chiral symmetry restoration on the properties of hadrons is a much debated issue. In particular light vector mesons have been studied extensively both on the theoretical and the experimental side; for recent reviews see e.g. [1–6]. In fact, in-medium modifications of hadrons made out of light quarks and especially their possible "dropping masses" are taken often synonymously for chiral restoration. The Brown–Rho scaling conjecture [7] and Ioffe's formula for the nucleon [8] suggest such a tight connection. However, experimentally the main observation of in-medium changes of light vector mesons via dilepton spectra is a significant broadening of the spectral shape [9,10]. Such a broadening can be obtained in hadronic many-body approaches, e.g., [11–17], which at first sight are not related directly to chiral restoration in the above spirit. Pion dynamics and resonance formation, both fixed to vacuum data, provide the important input for such many-body calculations. Clearly the pion dynamics is closely linked to the vacuum phenomenon of chiral symmetry *breaking*, but the connection to chiral *restoration* is not so clear. For the physics of resonances the connection is even more loose. There are recent approaches which explain some hadronic resonances as dynamically generated from chiral dynamics [18–24], but again this primarily points towards an intimate connection between hadron physics and chiral symmetry breaking whereas effects of the chiral restoration transition on hadron physics remain open. As suggested, e.g., in [25,26] the link to chiral restoration might be indirect: The in-medium broadening could be understood as a step towards deconfinement. In the deconfined quark–gluon plasma also chiral symmetry is presumed to be restored. All these considerations suggest that the link between chiral restoration and in-medium changes of hadrons is more involved as one might have hoped.

Additional input could come from approaches which are closer to QCD than standard hadronic models. One such approach is the QCD sum rule method [27–31]. A somewhat superficial view on QCD sum rules for vector mesons seems to support the original picture of an intimate connection between chiral restoration and in-medium changes. Here the previously popular chain of arguments goes as follows: (1) Four-quark condensates play an important role for the vacuum mass of the light vector mesons [27,28]. (2) The four-quark condensates factorize into squares of the two-quark condensate [32]. (3) The two-quark condensate decreases in the medium due to chiral restoration [33,34]. (4) Thus the four-quark condensates decrease in the medium accordingly. (5) Therefore the masses of light vector mesons change (decrease) in the medium due to chiral restoration.

Before we critically assess this line of reasoning an additional remark concerning four-quark condensates is in order: In [27,28] it is shown that the vector meson mass emerges from a subtle balance between the gluon and four-quark condensates. In that sense four-quark condensates are important. There are, however,

* Corresponding author at: Forschungszentrum Dresden-Rossendorf, PF 510119, D-01314 Dresden, Germany.
E-mail address: t.hilger@fzd.de (T. Hilger).

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approaches (employing, e.g. finite energy sum rules) which deduce ρ meson properties without using the four-quark condensates, see, e.g., [35]. In this case, one needs additional input to deduce the ρ meson properties (cf. the discussion in [36]). In [35] this input is provided by the assumption that the continuum threshold is related to the scale of chiral symmetry breaking. In the following we use the original sum rule approach of [27,28]. Note that the different approaches of [27,28] and [35] are not mutually exclusive.

In the previous line of reasoning (points 1–5) one seems to have a connection between chiral restoration – descent of two- and four-quark condensates – and in-medium changes, no matter whether it is a mass shift or a broadening [37,38] or a more complicated in-medium modification [16,39]. However, at least point 2 and, as its consequence point 4, are questionable: Whether the four-quark condensates factorize is discussed since the invention of QCD sum rules, see, e.g., [27,28,40–46] in vacuum and for in-medium situations [31,47–51]. With such doubts the seemingly clear connection between chiral restoration and in-medium changes gets lost.

Indeed, a closer look on the QCD sum rules for light vector mesons reveals that most of the condensates, whose in-medium change is translated into an in-medium modification for the respective hadron, are actually chirally symmetric (see below). Physically, it is of course possible that the same microscopic mechanism which causes the restoration of chiral symmetry is also responsible for changes of chirally symmetric condensates. For example, in the scenario [52] about half of the (chirally symmetric) gluon condensate vanishes together with the two-quark condensate. These considerations show that the connection between the mass of a light vector meson and chiral symmetry breaking is not as direct as often expected.

We take these considerations as a motivation to study in the present work a clear-cut scenario where we ask and answer the question: How large would the mass and/or the width of the ρ meson be in a world where the chiral symmetry breaking objects/condensates are zero? In the following we will call this scenario VOC (vanishing of chirally odd condensates). Note that we leave all chirally symmetric condensates untouched, i.e. they retain their respective vacuum values. We stress again that such a scenario may not reflect all the physics which is contained in QCD. There might be intricate interrelations between chirally symmetric and symmetry breaking objects. In that sense the VOC scenario shows for the first time the minimal impact that the restoration of chiral symmetry has on the properties of the ρ meson.

2. Chiral transformations and QCD condensates

For vanishing quark masses, QCD with N_f flavors is invariant with respect to the global chiral $SU_R(N_f) \times SU_L(N_f)$ transformations. Focusing for the time being on the $N_f = 2$ light (massless) quark sector, the corresponding left-handed transformations read for the left-handed quark field $\psi_L = \frac{1}{2}(1-\gamma_5)\psi$ and the right-handed quark field $\psi_R = \frac{1}{2}(1+\gamma_5)\psi$

$$\psi_L \to e^{i\vec{\theta}_L\cdot\vec{\tau}}\psi_L, \qquad \psi_R \to \psi_R, \tag{1}$$

while the right-handed transformations are

$$\psi_R \to e^{i\vec{\theta}_R\cdot\vec{\tau}}\psi_R, \qquad \psi_L \to \psi_L, \tag{2}$$

where $\vec{\tau}$ are the isospin Pauli matrices and $\psi = \binom{u}{d}$ denotes the quark isodoublet. Eqs. (1), (2) represent isospin transformations acting separately on the right-handed and left-handed parts of the quark field operator $\psi = \psi_L + \psi_R$, i.e. the three-component vectors $\vec{\theta}_R$ and $\vec{\theta}_L$ contain arbitrary real numbers. Gluons and heavier quarks remain unchanged with respect to the transformations (1), (2).

A quark current which has the quantum numbers of the ρ meson is given by the vector–isovector current

$$\vec{j}^{\mu} = \frac{1}{2}\bar{\psi}\gamma^{\mu}\vec{\tau}\psi. \tag{3}$$

If a chiral transformation according to (1), (2) is applied to $\vec{j}^{\mu}$, it becomes mixed with the axial-vector–isovector current

$$\vec{j}_5^{\mu} = \frac{1}{2}\bar{\psi}\gamma^{\mu}\gamma_5\vec{\tau}\psi \tag{4}$$

which carries the quantum numbers of the a_1 meson. Indeed, experiments show that the vector current (3) couples strongly to the ρ meson, while the axial-vector current (4) couples to the a_1 meson [53]. Therefore, ρ and a_1 are called chiral partners.

The central object of QCD sum rules [27,28,54] is the retarded current–current correlator which reads for the ρ^0 meson

$$\Pi^{\mu\nu}(q) = i\int d^4x\, e^{iqx}\Theta(x_0)\langle\left[j_3^{\mu}(x), j_3^{\nu}(0)\right]\rangle, \tag{5}$$

where for vacuum ($\langle\cdots\rangle$ means accordingly the vacuum expectation value) the retarded and time-ordered propagator coincide for positive energies, whereas for in-medium situations (e.g. nuclear matter, $\langle\cdots\rangle$ refers then to the Gibbs average), the retarded correlator has to be taken (cf. [31]). The imaginary part of the current–current correlator contains the spectral distribution, i.e. the information which hadronic one-body and many-body states couple to the considered current. For large space-like momenta, $Q^2 \equiv -q^2 \gg \Lambda_{QCD}^2$, the correlator can be reliably calculated from the elementary QCD quark and gluon degrees of freedom due to asymptotic freedom. Results from QCD perturbation theory can be systematically improved by the introduction of quark and gluon condensates using the operator-product expansion (OPE) [55]. The QCD sum rule method connects the mentioned two representations of the correlator by a dispersion relation which reads after a Borel transformation

$$\frac{1}{\pi}\int_0^{\infty} ds\, s^{-1}\, \mathrm{Im}\,\Pi(s)e^{-s/M^2} = \tilde{\Pi}(M^2), \tag{6}$$

where the Borel mass M has emerged from the OPE momentum scale Q (for further details we refer the interested reader to [38]). We consider a ρ meson at rest, therefore, the tensor structure of (5) reduces to a scalar $\Pi = \frac{1}{3}\Pi_{\mu}^{\mu}$. The Borel-transformed OPE reads

$$\tilde{\Pi}(M^2) = c_0 M^2 + \sum_{i=1}^{\infty}\frac{c_i}{(i-1)!M^{2(i-1)}} \tag{7}$$

with coefficients up to mass dimension 6

$$c_0 = \frac{1}{8\pi^2}\left(1 + \frac{\alpha_s}{\pi}\right), \tag{8}$$

$$c_1 = -\frac{3}{8\pi^2}\left(m_u^2 + m_d^2\right), \tag{9}$$

$$c_2 = \frac{1}{2}\left(1 + \frac{\alpha_s}{4\pi}C_F\right)\left(m_u\langle\bar{u}u\rangle + m_d\langle\bar{d}d\rangle\right) + \frac{1}{24}\left\langle\frac{\alpha_s}{\pi}G^2\right\rangle + N_2, \tag{10}$$

$$c_3 = -\frac{112}{81}\pi\alpha_s\langle\mathcal{O}_4^V\rangle - 4N_4 \tag{11}$$

with $C_F = (n_c^2 - 1)/(2n_c) = 4/3$ for $n_c = 3$ colors. A mass dimension 2 condensate seems to be excluded in vacuum [56]. In (8)–(11) we have introduced the strong coupling α_s, the light-quark