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Review

Properties of hadrons in a chiral model with (axial-)vector mesons

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ABSTRACT

Recent advances in the development of a chiral linear σ-model with (axial-)vector mesons are presented. The model is based on the basic requirements of global chiral symmetry and dilatation invariance. The role of (axial-)vector states turns out to be crucial both in the meson and the baryon sectors. First results at non-zero temperature and density are discussed.

1. Introduction

The description of the masses and the interaction of low-lying hadron resonances is a central subject of high-energy physics [1]. To this end, a lot of effort has been put into the development of quantum field theoretical effective hadronic Lagrangians: chiral perturbation theory [2], its extension with vector mesons [3], and linear σ-model(s) [4–8] represent the most outstanding examples.

In this work, we concentrate on the theoretical advances of the latter class of hadronic theories: namely, we focus on a linear σ-model with (axial-)vector mesons, which aims to describe (almost all) hadrons up to 1.7 GeV, both in the vacuum and at non-zero temperature and density. Although the linear σ-model with scalar and pseudoscalar mesons has been extensively studied, its generalization with (axial-)vector mesons has up to now not been systematically investigated. Preliminary studies in this direction have been performed for the case $N_f = 2$ only in [5,6], where N_f is the number of quark flavors. Moreover, in [5], a different theoretical principle based on the so-called local realization of chirally symmetry was employed, and in [6] not all the fields were taken into acocunt (the scalar isotriplet a_0 meson and the pseudoscalar meson η were neglected).

The construction of the Lagrangian of the linear σ model considered here follows two basic requirements stemming from the underlying Quantum Chromodynamics (QCD) theory [7–9]. (i) Global chiral symmetry $U(N_f)_L \times U(N_f)_R$. (ii) Dilatation invariance, with the exception of terms stemming from the gauge sector (scale-anomaly and $U(1)_A$ anomaly, in accord with QCD) and of terms which describe the non-zero values of the quark masses (explicit breaking of the dilatation symmetry). All other terms are thus described by dimensionless coupling constants.

The assignment of the fields of the model with the resonances listed in the Particel Data Group (PDG) [10] is straightforward for the multiplets $J^{PC} = 0^{-+}$, $J^{PC} = 1^{--}$, and $J^{PC} = 1^{++}$. As usual, the scalar meson multiplet $J^{PC} = 0^{++}$ is problematic: the present σ-model indeed shows results which are at odds with previous σ-model studies. Namely, the preferred scenario is realized for scalar mesons between 1 and 2 GeV. This result is a consequence of the inclusion of (axial-)vector degrees of freedom, which generate peculiar interference effects in the decay amplitudes. More in general, the role of the (axial-)vector states is relevant in both the meson and baryon sectors for a proper description of the phenomenology.

Some of the resonances of the multiplet $J^{PC} = 1^{++}$ were interpreted in [11] as dynamically generated states. However, as discussed in [9], unitarization procedures can regenerate preformed quark–antiquark states which were formally integrated

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out in order to obtain the low-energy effective Lagrangians of [2,3]. Thus, the interpretation of the states $J^{PC} = 1^{++}$ as a quark–antiquark multiplet is, in agreement with [10], upheld.[1]

This paper is organized as follows. In Sections 2 and 3 we review the mesonic and baryonic sectors, respectively, and in Section 4 we present our conclusions and outlook.

2. Meson sector

The basic ingredients of the linear σ-model in the meson sector are the glueball/dilaton field G, the (pseudo)scalar multiplet $\Phi = (S^a + iP^a)\,t^a$ and the left-handed and right-handed vectorial multiplets $L^\mu = (V^{a,\mu} + A^{a,\mu})\,t^a$, $R^\mu = (V^{a,\mu} - A^{a,\mu})\,t^a$ (the matrices t^a are the generators of the group $U(N_f)$). The mesonic Lagrangian $\mathscr{L}_{\text{mes}}$ which fulfills the criteria of (i) global chiral symmetry and (ii) dilatation invariance takes the following form for a generic number of flavors N_f [7,8]:

$$\begin{aligned}\mathscr{L}_{\text{mes}} = {} & \frac{1}{2}(\partial_\mu G)^2 - V_{\text{dil}}(G) + \text{Tr}\left[(D^\mu\Phi)^\dagger(D_\mu\Phi) - aG^2\Phi^\dagger\Phi - \lambda_2\left(\Phi^\dagger\Phi\right)^2\right] \\ & - \lambda_1(\text{Tr}[\Phi^\dagger\Phi])^2 + c(\det\Phi^\dagger - \det\Phi)^2 + \text{Tr}[\hat{\varepsilon}(\Phi^\dagger + \Phi)] - \frac{1}{4}\text{Tr}[(L^{\mu\nu})^2 + (R^{\mu\nu})^2] \\ & + \frac{b}{2}G^2\text{Tr}[(L^\mu)^2 + (R^\mu)^2] + \frac{1}{2}\text{Tr}[\hat{\delta}(L^\mu)^2 + (R^\mu)^2] - 2ig_2\left(\text{Tr}[L_{\mu\nu}[L^\mu, L^\nu]]\right. \\ & \left. + \text{Tr}[R_{\mu\nu}[R^\mu, R^\nu]]\right) + h_2\text{Tr}\left[\Phi^\dagger L_\mu L^\mu\Phi + \Phi R_\mu R^\mu\Phi\right] \\ & + 2h_3\text{Tr}\left[\Phi R_\mu\Phi^\dagger L^\mu\right] + \cdots,\end{aligned} \tag{1}$$

where $D^\mu\Phi = \partial^\mu\Phi - ig_1(L^\mu\Phi - \Phi R^\mu)$ and dots represent further terms which are either large-N_c suppressed or unimportant in the evaluation of decays and (on-shell) scattering lengths. The following comments are in order.

(i) Besides the dilaton field G, the mesonic fields of the model are quark–antiquark fields. This can be easily seen by studying the so-called large-N_c limit [13]: the masses are N_c-independent and the widths scale as N_c^{-1} [7].

(ii) The dilaton potential reads $V_{\text{dil}}(G) == \frac{1}{4}\frac{m_G^2}{\Lambda_G^2}\left[G^4\ln\left(\frac{G}{\Lambda_G}\right) - \frac{G^4}{4}\right]$ [14]. The parameter $\Lambda_G \sim N_c\Lambda_{\text{QCD}}$ has dimension energy and sets the energy scale of the theory.

(iii) The $U(1)_A$ anomaly term is parameterized by the parameter c, which has dimension $[\text{Energy}]^{4-2N_f}$.

(iv) In the (pseudo)scalar sector the explicit symmetry breaking of both chiral and dilatation symmetries is encoded in the matrix $\hat{\varepsilon} \propto \text{diag}\{m_u, m_d, m_s, \ldots\}$, where the entries are the bare quark masses. Similarly, in the (axial-)vector sector the analogous diagonal matrix $\hat{\delta}$ has been introduced.

(v) Chiral symmetry breaking takes place when the parameter a is negative. In fact, upon the condensation of the field $G = G_0$, the 'wrong' mesonic mass sign is realized for $aG_0^2 < 0$.

(vi) The calculations are performed at tree level. The inclusion of loops is a task for the future, but only slight changes are expected [15]. Here, we mostly concentrate on decay widths; it is in this respect interesting to notice that the latter do not correspond to a exponential law as function of time because large variations take place for hadrons [16].

Once the shifts of the scalar fields $G \to G_0 + G$ and $\Phi \to \text{diag}\{\sqrt{2}\sigma_N, \sqrt{2}\sigma_N, \ldots\} + \Phi$, where the first term is a diagonal matrix with the quark–antiquark condensates, and necessary redefinitions of the pseudoscalar and axial-vector fields have been performed, the explicit calculations of physical processes are lengthy but straightforward.

The case $N_f = 2$ with frozen glueball ($m_G \to \infty$) has been studied in [7]. It has been shown that the inclusion of (axial-)vector mesons has a strong influence on the overall phenomenology. For instance, the width of the scalar meson σ (the chiral partner of the pion) decreases substantially with respect to the case without (axial-)vector mesons: for this reason, the identification of this field with the resonance $f_0(600)$ is not favored, because the theoretically evaluated width is smaller than 200 MeV, while the experimental one is larger than 400 MeV. In contrast, the identification of the σ field with the resonance $f_0(1370)$ turns out to be in agreement with the experimental results. The description of the (axial-)vector resonances is also in agreement with the experiments reported in [10].

In [8], the glueball with a bare mass of about $m_G \sim 1.5$ GeV, in agreement with the lattice calculation of [17], was studied for the first time in a chiral model with (axial-)vector mesons. (For a compilation of other approaches, see [18] and the references therein). The state $f_0(1500)$ results as the predominantly (75%) glueball state, and the rest of the phenomenology is only slightly affected with respect to the previous case, in which $m_G \to \infty$. Moreover, the gluon condensate can also be evaluated, and it turns out to be in agreement with lattice results.

Future work in the meson sector consists in the study of the cases $N_f = 3$ and $N_f = 4$, respectively. Preliminary results of the former case were already presented in conference proceedings [19] and a systematic study will be concluded soon.

[1] The example of tensor mesons help to clarify this: these states can also be obtained via 'dynamical generation', but fulfill to a very good accuracy all the required properties to be interpreted as a quark–antiquark meson nonet [12].