The rho meson in nuclear matter - a chiral unitary approach

D. Cabrera

Departamento de Física Teórica and IFIC, Centro Mixto Universidad de Valencia-CSIC, Institutos de Investigación de Paterna, Apdo. correos 22085, 46071, Valencia, Spain

Abstract

In this work, the properties of the $\rho$ meson at rest in cold symmetric nuclear matter are studied. We make use of a chiral unitary approach to pion-pion scattering in the vector-isovector channel, calculated from the lowest order Chiral Perturbation Theory ($\chi PT$) lagrangian including explicit resonance fields. Low energy chiral constraints are considered by matching our expressions to those of one loop $\chi PT$. To account for the medium corrections, the $\rho$ couples to $\pi\pi$ pairs which are properly renormalized in the nuclear medium, accounting for both $p-h$ and $\Delta-h$ excitations. The terms where the $\rho$ couples directly to the hadrons in the $p-h$ or $\Delta-h$ excitations are also accounted for. In addition, the $\rho$ is also allowed to couple to $N^*(1520)-h$ components.

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1 Meson-meson scattering in a chiral unitary approach

We study the $\rho$ propagation properties by obtaining the $\pi\pi \rightarrow \pi\pi$ scattering amplitude in the $(I,J) = (1,1)$ channel. The model for meson-meson scattering in vacuum is fully explained in [1, 2]. We start from the $(I = 1)$ $\pi\pi$, $K\bar{K}$ states in the isospin basis:

$|\pi\pi\rangle = \frac{1}{2}|\pi^+\pi^- - \pi^-\pi^+\rangle$

$|K\bar{K}\rangle = \frac{1}{\sqrt{2}}|K^+K^- - K^0\bar{K}^0\rangle.$

(1)

Tree level amplitudes are obtained from the lowest order $\chi PT$ lagrangians [3] including explicit resonance fields [4]. We collect these amplitudes in a $2 \times 2$ symmetric $K$ matrix and work in a coupled channel approach.

The final expression of the $T$ matrix is obtained by unitarizing the tree level scattering amplitudes. To this end we follow the N/D method, which was adapted to the context of chiral theory in ref. [5]. We get

$T(s) = [I + K(s) \cdot G(s)]^{-1} \cdot K(s),

(2)$

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where $G(s)$ is a diagonal matrix given by the loop integral of two meson propagators. In dimensional regularization its diagonal elements are given by

$$G^D_i(s) = \frac{1}{16\pi^2} \left[ -2 + d_i + \sigma_i(s) \log \frac{\sigma_i(s) + 1}{\sigma_i(s) - 1} \right],$$

where the subindex $i$ refers to the corresponding two meson state (1 for $K\bar{K}$, 2 for $\pi\pi$) and $\sigma_i(s) = \sqrt{1 - 4m^2_i/s}$ with $m_i$ the mass of the particles in the state $i$. The $d_i$ constants in eq. (3) are chosen to obey the low energy chiral constraints, and they are obtained by a matching to one loop $\chi PT$.

At this stage, the model successfully describes $\pi\pi$ P-wave phase shifts and $\pi$, $K$ electromagnetic vector form factors up to $\sqrt{s} \lesssim 1.2$ GeV. The results for the $\pi\pi \rightarrow \pi\pi$ scattering amplitude show that the inclusion of the $K\bar{K}$ channel introduces minimum changes compared to the calculation including only pion loops. Keeping this in mind, the calculations in nuclear matter are performed ignoring the contribution of kaon loops.

By using dimensional regularization it is possible to establish connection with other approaches where tadpole terms are explicitly kept in the lagrangian [6]. One can prove that the formalism keeping tadpoles and full off shell dependence of the $\rho\pi\pi$ vertex is equivalent to the one we have followed where only the on shell part of the $\rho\pi\pi$ vertex is kept. In the medium, however, the pion propagator in the tadpole term will change. Hence, in order to stick to the gauge invariance of the vector field formalism the tadpole term is kept.

2. $(I, J) = (1, 1)$ $\pi\pi$ scattering in the nuclear medium

The basic input for the calculation in nuclear matter is the pion selfenergy. It is written as usual in terms of the Lindhard functions accounting for both $p-h$ and $\Delta - h$ excitations. Short range correlations are also accounted for with the Landau-Migdal parameter $g'$, set to 0.7. The final expression is

$$\Pi_\pi(q, \rho) = f(q^2) \frac{(D + F)^2 U(q, \rho)}{1 - (D + F)^2 g' U(q, \rho)},$$

where $q$ is the four-momentum of the pion and $U = U_N + U_\Delta$ the Lindhard function for $p-h$, $\Delta - h$ excitations [7, 8]. We use a monopole form factor $f(q^2) = \frac{\Lambda^2}{\Lambda^2 + q^2}$ for the $\pi NN$ and $\pi N\Delta$ vertices with the cut-off parameter set to $\Lambda = 1$ GeV.

In accordance to the gauge invariance of the theory, a $\rho$-meson-baryon contact term must be considered [9]. Its contribution can be derived from the set of gauge invariant diagrams in Fig. 1 (left), and together with the single insertion of a pion selfenergy, it provides the set of medium correction graphs shown in Fig. 1 (right) [10, 11]. Their contribution is readily incorporated in the $T$ matrix by a proper substitution and redefinition of the $G$ two meson loop function of eq. (2), and using fully dressed pion propagators. A subtraction of the contribution in vacuum is performed to cancel quadratic divergences and convergence is achieved by means of the form factors.

In the same fashion the tadpole diagram in nuclear matter is calculated, and by subtracting the contribution in vacuum quadratic divergences are removed.

In addition to the contact interactions mentioned above there are other medium corrections that arise if one sticks to the gauge vector field formalism and generate interactions...
via minimal coupling scheme [6]. Because of this a set of diagrams involving $\rho NN$ and $\rho \Delta \Delta$ vertices also contribute to the $\rho$ meson selfenergy in nuclear matter. The relevant ones are shown in Fig. 2.

A step forward is done by considering the coupling of the $\rho$ meson to the $N^*(1520)$ resonance. A much detailed work along these lines has been done in [14], where many other resonances are included. This correction manifests as an extra selfenergy term in the $\rho$ propagator. The basic vertex involved in this effect is shown in Fig. 3a, and the lagrangian describing the interaction reads [15]

$$\mathcal{L}_{N^*N\rho} = -g_{N^*N\rho} \bar{\Psi}_N S_I \phi_i \tau_i \Psi_{N^*} + h.c., \quad (5)$$

and the contribution of the selfenergy diagram of Fig. 3b can be written as

$$\Pi_{\rho}^{N^*-h}(P) = \frac{2}{3} g_{N^*N\rho}^2 U_{N^*}(P), \quad (6)$$
in terms of a Lindhard function for the $N^* - h$ excitation, $U_{N^*}(P)$.

3 Results and discussion

We calculated in this approach the real and imaginary parts of $T_{22}$, the $\pi\pi \rightarrow \pi\pi$ scattering amplitude matrix element. The imaginary part shows a clear broadening of the resonance and the peak position is slightly shifted upwards by about 30 MeV, which is also observed in the position of the zero of the real part. The coupling to the $N^* - h$ components manifests as a visible bump at lower energies. As a whole much strength is spread below the resonance mass.

In order to test the model dependence on the phenomenological parameters we performed variations of $\Lambda$ in the range 0.9-1.1 GeV, and of $g'$ in the range 0.6-0.8. The results are rather stable under the first of the variations, showing uncertainties in the position of the $\rho$ meson peak of about 10-15 MeV. Variations of $g'$ are relevant close to the resonance maximum, and lead to uncertainties in the position of the resonance of about 20-25 MeV. This was expected since the pion selfenergy, which is one of the basic ingredients of the medium corrections, is strongly modified by the short range correlations which directly depend on $g'$.

In considering the coupling to baryonic resonances our model does not try to be complete since many other resonances should be included, but this allows us to have an estimate of how these new channels affect the results. The calculation could be improved by following a self-consistent treatment as done in [14].

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