The ρ Meson in a Nuclear Medium

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Abstract

In this work, propagation properties of the ρ meson in symmetric nuclear matter are studied. We make use of a coupled channel unitary approach to meson-meson scattering, calculated from the lowest order Chiral Perturbation Theory (χPT) lagrangian including explicit resonance fields. Low energy chiral constraints are considered by matching our expressions to those of one loop χPT. To account for the medium corrections, the ρ couples to $\pi\pi$ and $K\bar{K}$ pairs which are properly renormalized in the nuclear medium.

PACS: 14.40.Aq; 14.40.Cs; 13.75.Lb

1 Description of the model

We study the ρ propagation properties by obtaining the $\pi\pi$ and $K\bar{K}$ scattering amplitudes in the $I = 1$ channel. Our states in the isospin basis are

$$\begin{aligned} |\pi\pi> &= \frac{1}{2}|\pi^+\pi^- - \pi^-\pi^+> \\ |K\overline{K}> &= \frac{1}{\sqrt{2}}|K^+K^- - K^0\overline{K}^0> . \end{aligned} \quad (1)$$

Tree level amplitudes are obtained from the lowest order χPT and explicit resonance field lagrangians of refs. [1], [2]. We collect this amplitudes in a 2×2 K matrix whose elements are

$$\begin{aligned} K_{11}(s) &= \frac{1}{3}\frac{p_1^2}{f^2}\left[1 + \frac{2\,G_V^2}{f^2}\frac{s}{M_\rho^2 - s}\right] \\ K_{12}(s) &= \frac{\sqrt{2}}{3}\frac{p_1\,p_2}{f^2}\left[1 + \frac{2\,G_V^2}{f^2}\frac{s}{M_\rho^2 - s}\right] \\ K_{21}(s) &= K_{12}(s) \\ K_{22}(s) &= \frac{2}{3}\frac{p_2^2}{f^2}\left[1 + \frac{2\,G_V^2}{f^2}\frac{s}{M_\rho^2 - s}\right] \end{aligned} \quad (2)$$

with the labels 1 for $\pi\pi$ and 2 for $K\bar{K}$ states. In equation (2) G_V is the strength of the pseudoscalar-vector resonance vertex, f the pion decay constant in the chiral limit, s the squared invariant mass, M_ρ the bare mass of the ρ meson and $p_i = \sqrt{s/4 - m_i^2}$.

The final expression of the T matrix is obtained following the N/D method, which was adapted to the context of chiral theory in ref. [3]. It reads

$$T(s) = [I + K(s) \cdot g(s)]^{-1} \cdot K(s), \qquad (3)$$

where $g(s)$ is a diagonal matrix given by the loop of two mesons. In dimensional regularization it reads

$$g_i(s) = \frac{1}{16\,\pi^2} \left[-2 + d_i + \sigma_i(s)\, \log \frac{\sigma_i(s)+1}{\sigma_i(s)-1} \right], \qquad (4)$$

where the subindex i refers to the corresponding two meson state and $\sigma_i(s) = \sqrt{1 - 4m_i^2/s}$ with m_i the mass of the particles in the state i. At this stage (vacuum case), the model has proved to be successful in describing $\pi\pi$ P-wave phase shifts and π, K electromagnetic vector form factors [4] up to $\sqrt{s} \lesssim 1.2$ GeV. The d_i constants contain the information of low energy chiral constraints. They are obtained by matching the expressions of the form factors calculated in this approach with those of one-loop χPT.

In our calculation, in which $g(s)$ is modified in the nuclear medium, we use cut-off regularization. The $g_i(s)$ function with a cut-off in the three-momentum of the particles in the loop can be found in Appendix A of ref. [5]. By comparing the expressions in both schemes we can get the equivalent q_i^{max} in order to keep the information of the d_i constants.

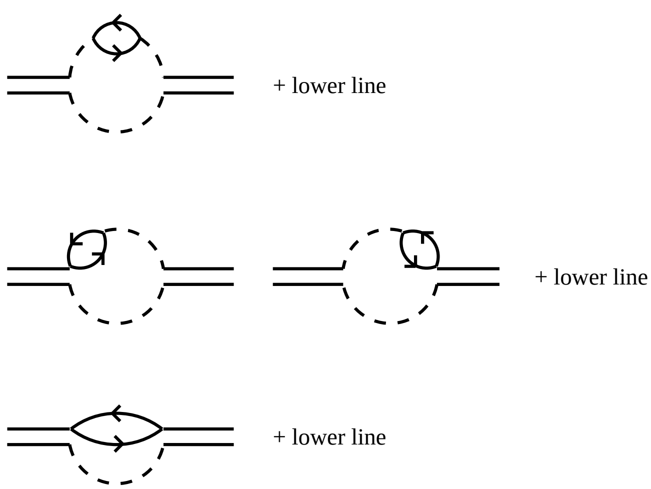

Figure 1: Medium correction graphs: double solid line represents the ρ resonance, dashed lines are π, K mesons in the loop and single solid lines are reserved for particle-hole excitations.

Medium corrections are incorporated in the selfenergies of the mesons in the loops. All the graphs in fig. 1 are considered. In addition to the single $p-h$ bubble we have to account for the medium modifications of the $\rho M M^{'}$ vertex via the $\rho M N$ contact term requested by the gauge invariance of the theory.

The pion selfenergy is written as usual in terms of the Lindhard functions. Both $N-h$ and $\Delta-h$ excitations are included. Short range correlations are also accounted for with the Landau-Migdal parameter g', set to 0.7. The final expression is

$$\Pi_\pi(q,\rho) = \vec{q}^{\,2}\, \frac{(\frac{D+F}{2f})^2\, U(q,\rho)}{1-(\frac{D+F}{2f})^2\, g'\, U(q,\rho)} \tag{5}$$

where $U = U_N + U_\Delta$, the ordinary Lindhard function for $p-h$, $\Delta-h$ excitations [6].

The $\bar{K}$ selfenergy has both S-wave and P-wave contributions. The S-wave piece is obtained from a self-consistent calculation with coupled channels ($\bar{K}N$, $\pi\Sigma$, $\pi\Lambda$, $\eta\Sigma$, $\eta\Lambda$, $K\Xi$) in which both meson and baryon selfenergies in the medium have been considered. The P-wave piece includes $\Lambda-h$, $\Sigma-h$ and $\Sigma^*(1385)-h$ excitations. The whole $\bar{K}$ selfenergy is borrowed from ref. [7].

At low energies the K system interacts with nucleons only by S-wave elastic scattering. We use the expression for the selfenergy from ref. [8, 9],

$$\Pi_K(\rho) \simeq 0.13\, m_K^2 \frac{\rho}{\rho_0}\, (MeV^2) \tag{6}$$

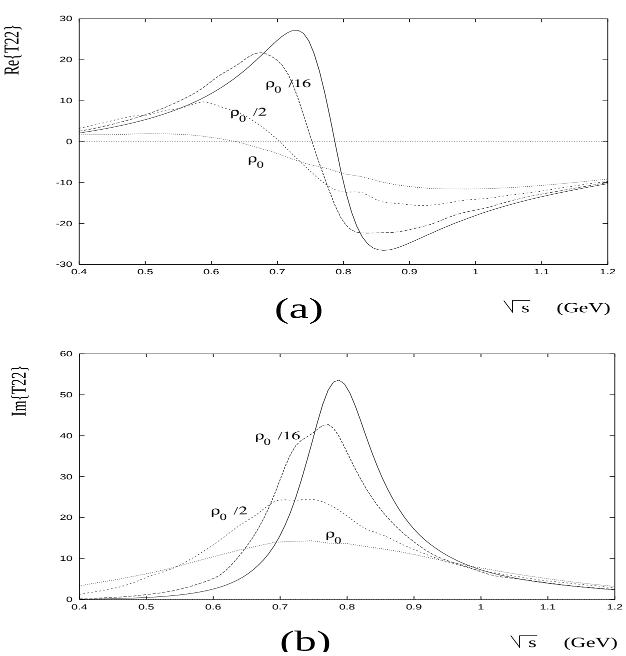

Figure 2: Real (a) and imaginary (b) parts of the amplitude $T_{\pi\pi\to\pi\pi}$. The curves are as follows: Solid line, zero density; long dashed line, $\rho=\rho_0/16$; short dashed line, $\rho=\rho_0/2$; dotted line, normal nuclear density. $\sqrt{s}$ is the invariant mass of the meson pair.

2 Results and discussion

We have plotted in fig. 2 the real and imaginary parts of T_{22} for several densities. As can be seen, the resonance broadens significantly as density is increased, its width being around 350 MeV at $\rho = \rho_0$. The zero of the real part experiences a downward shift which amounts to $100 - 150$ MeV at normal density.

Another interesting result comes from the comparison between coupled and decoupled cases. This is done by setting $K_{12}(s)$ to zero, what automatically makes the T matrix diagonal. We have found very small differences in T_{22} when calculating in these two cases. This tells us that in our model the $K\bar{K}$ system has almost no influence on the $\pi\pi \to \pi\pi$ channel even at normal nuclear density.

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