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Reduced σ-meson mass and in-medium S-wave π-π correlations

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The influence of a reduced σ-meson mass on previously calculated in-medium $\pi\pi$ correlations in the $J=I=0$ (σ-meson) channel is investigated. It is found that the invariant-mass distribution around the vacuum threshold experiences a further strong enhancement with respect to standard many-body effects. The relevance of this result for the explanation of recent $A(\pi,2\pi)X$ data is pointed out.

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In-medium s-wave pion-pion correlations have recently attracted much attention both on the theoretical [1–7] and experimental [8] sides. These studies are of relevance for the behavior of the in-medium chiral condensate and its fluctuations with increasing density [7]. In earlier studies we have shown that standard p-wave coupling of the pion to Δ-h and p-h configurations induces a strong enhancement of the $\pi\pi$ invariant-mass distribution around the $2m_\pi$ threshold [2,3], thus signalling increased fluctuations in the σ channel. This fact was independently confirmed in [5]. It has been argued in [2,4] that this effect could possibly explain the $A(\pi,2\pi)$ knockout reaction data from the CHAOS Collaboration [8]. More recently Vicente Vacas and Oset [6] have claimed that the theory underestimates the experimentally found π-π mass enhancement. This claim may be partly questioned, since the reaction theory calls for a calculation with a finite total three momentum of the in-medium pion pairs.[1] On the other hand, Hatsuda *et al.* [7] argued that the partial restoration of chiral symmetry in nuclear matter, which leads to a dropping of the σ-meson mass [10], induces similar effects as the standard many-body correlation mentioned above. It is therefore natural to study the combination of both effects. This is the objective of the present note.

As a model for $\pi\pi$ scattering we consider the linear sigma model treated in leading order of the $1/N$ expansion [9]. The scattering matrix can then be cast in the following form:

$$T_{ab,cd}(s)=\delta_{ab}\delta_{cd}\frac{D_\pi^{-1}(s)-D_\sigma^{-1}(s)}{3\langle\sigma\rangle^2}\frac{D_\sigma(s)}{D_\pi(s)}, \tag{1}$$

where s is the Mandelstam variable. In Eq. (1) $D_\pi(s)$ and $D_\sigma(s)$ are, respectively, the full pion and sigma propagators, while $\langle\sigma\rangle$ is the sigma condensate. The expression in Eq. (1) reduces, in fact, in the soft pion limit, to a Ward identity which links the $\pi\pi$ four-point function to the π- and σ two-point functions, as well as to the σ one-point function. To this order, the pion propagator and the sigma condensate are obtained from the Hartree-Bogoliubov (HB) approximation [9]. In terms of the pion-mass m_π and the decay constant f_π, they are given by

$$D_\pi(s)=\frac{1}{s-m_\pi^2},\qquad f_\pi=\sqrt{3}\langle\sigma\rangle. \tag{2}$$

The sigma meson, on the other hand, is obtained from the random phase approximation (RPA) involving π-π scattering [9] and reads

$$D_\sigma(s)=\left[s-m_\sigma^2-\frac{2\lambda^4\langle\sigma\rangle^2\Sigma_{\pi\pi}(s)}{1-\lambda^2\Sigma_{\pi\pi}(s)}\right]^{-1}, \tag{3}$$

where $\Sigma_{\pi\pi}(s)$ is the $\pi\pi$ self-energy regularized by means of a form factor which is used as a fit function [2] and allows one to reproduce the experimental $\pi\pi$ phase shifts. The coupling constant λ^2 denotes the bare quartic coupling of the linear σ model, related to the mean-field pion mass m_π, sigma mass m_σ, and the condensate $\langle\sigma\rangle$ via the mean-field saturated Ward identity

$$m_\sigma^2=m_\pi^2+2\lambda^2\langle\sigma\rangle^2. \tag{4}$$

It is clear from what was said above that the σ-meson propagator in this approach is correctly defined, since it satisfies a whole hierarchy of Ward identities.

In cold nuclear matter the pion is dominantly coupled to Δ-h, p-h, as well as to the $2p$-$2h$ excitations which, on the other hand, are renormalized by means of repulsive nuclear short-range correlations, (see [3] for details). Since the pion is a (near) Goldstone mode, its in-medium s-wave renormalization does not induce considerable changes. The sigma meson, on the other hand, is not protected against an important s-wave renormalization from chiral symmetry. Therefore, following a very economical procedure, we extract an approximate density dependence of the mean-field sigma meson mass by taking into account the density dependence of the condensate. From Eq. (4) it is clear that the density de-

[1]It was shown in [2] that considering the finite three momenta of the pion pair may further increase the effect of the in-medium pion-pion final-state interaction on the final $\pi^+\pi^-$ invariant mass distribution at threshold. Furthermore, at finite total three momenta of the pair, the sigma-meson couples directly to particle-hole excitations as well, which results in more strength enhancement at threshold, as shown in [7].

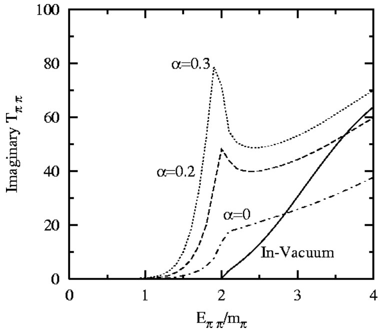

FIG. 1. Results for the imaginary part of the in-medium T matrix for $\pi\pi$ scattering. Except for the vacuum case (full line curve), the remaining in-medium curves are computed at normal nuclear matter density. The dashed-dotted curve is for $\alpha=0$, the dashed for $\alpha=0.2$, and the dotted for $\alpha=0.3$.

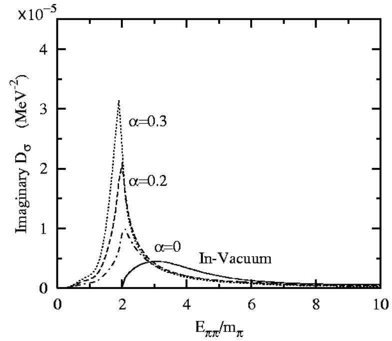

FIG. 2. Results for the imaginary part of the in-medium sigma-meson propagator. Except for the vacuum case (full line curve) the remaining in-medium curves are computed at normal nuclear matter density. The dashed-dotted curve is for $\alpha=0$, the dashed for $\alpha=0.2$, and the dotted for $\alpha=0.3$.

pendence of the sigma-meson is essentially dictated by the density dependence of the condensate.

For densities below and around nuclear saturation density ρ_0 we take for the in-medium $sigma$-meson mass the simple ansatz (see also [7]),

$$m_\sigma(\rho)=m_\sigma\left(1-\alpha\frac{\rho}{\rho_0}\right), \tag{5}$$

where ρ is the nuclear matter density and m_σ is the vacuum σ-meson mass. The parameter α can be estimated from model calculations or QCD sum rules and lies in the range from 0.2 to 0.3. These are the values which we also will use in this work.

The result for the sigma-meson mass distribution $\mathrm{Im}\, D_\sigma(E_{\pi\pi})$, as calculated from Eq. (3) by using the in-medium mass (5), is shown in Fig. 1 for various densities. One sees that, as density increases, a strong downward shift of the sigma-mass distribution occurs. The enhancement at low energies is strongly reinforced as the in-medium σ-meson mass is included. For $\alpha=0.2$ and $\alpha=0.3$ the peak height is increased by factors of 2 and 3 respectively. Similarly for the T matrix, a sizable effect can be noticed in its imaginary part (see Fig. 2). There is therefore a large flexibility to explain the findings of the CHAOS Collaboration.[2] Work in this direction is in progress.

These findings call for some comments. It is clear that vertex corrections, usually a source of repulsion and not taken into account in this work, could weaken the effects. In particular, the incidence of the nuclear density on the coupling constants should be considered. This seems, however, to be of minor importance as was recently shown by Chanfray *et al.* [11]. More care should also be taken in properly incorporating Pauli blocking when renormalizing the pion pairs in matter, although preliminary investigations [12] have shown that this effect is weak.

In conclusion we have shown that a dropping sigma-meson mass, linked to the partial restoration of chiral symmetry in nuclear matter, further enhances the build up of previously found $\pi\pi$ strength in the $I=J=0$ channel. Further studies are necessary to show how precisely this is linked to the recent findings by Bonutti *et al.* [8].

[2]Comparing the curve for $\alpha=0.2$, for instance, and the curves of Fig. 4 (from Ref. [2]), which where used to compute the $\pi^+\pi^-$ mass distribution (Fig. 5 of [2]), one realizes that there is indeed enough strength at threshold to reproduce the experiemtal data.

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