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The $\pi\rho$ cloud contribution to the ω width in nuclear matter

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ABSTRACT

The width of the ω meson in cold nuclear matter is computed in a hadronic many-body approach, focusing on a detailed treatment of the medium modifications of intermediate $\pi\rho$ states. The π and ρ propagators are dressed by their self-energies in nuclear matter taken from previously constrained many-body calculations. The pion self-energy includes Nh and Δh excitations with short-range correlations, while the ρ self-energy incorporates the same dressing of its 2π cloud with a full 3-momentum dependence and vertex corrections, as well as direct resonance-hole excitations; both contributions were quantitatively fit to total photo-absorption spectra and $\pi N \to \rho N$ scattering. Our calculations account for in-medium decays of type $\omega N \to \pi N^{(*)}, \pi\pi N(\Delta)$, and 2-body absorptions $\omega NN \to NN^{(*)}, \pi NN$. This causes deviations of the in-medium ω width from a linear behavior in density, with important contributions from spacelike ρ propagators. The ω width from the $\rho\pi$ cloud may reach up to 200 MeV at normal nuclear matter density, with a moderate 3-momentum dependence. This largely resolves the discrepancy of linear T–ϱ approximations with the values deduced from nuclear photoproduction measurements.

1. Introduction

The low-mass vector mesons ρ, ω and ϕ play a special role in the study of hot and dense nuclear matter, as their dilepton decay channel (l^+l^-) provides a pristine window on their in-medium properties. This feature has been extensively and successfully exploited in the measurement of dilepton spectra in heavy-ion collisions [1–3]. In these reactions, the thermal emission of low-mass dileptons is dominated by the ρ meson, due to its much larger dilepton width compared to the ω, $\Gamma_{\rho\to ll} \simeq 10\,\Gamma_{\omega\to ll}$. Dilepton data from the SPS and RHIC can now be consistently understood by a strong broadening ("melting") of the ρ meson, as computed from hadronic many-body theory in the hot and dense system [4,5]. This approach also yields a good description [6,7] of the ρ broadening observed in nuclear photoproduction, if the data are corrected with absolute background determination [8,9]. As a further test of the validity and generality of the hadronic in-medium approach, the ω meson, as the isospin zero pendant of the ρ, is a natural candidate.

The small dilepton decay width of the ω led the CB-TAPS Collaboration to pursue the $\pi^0\gamma$ decay channel in photon-induced production off nuclei. Early results for invariant-mass spectra reported significant downward mass shifts [10], seemingly in line with proton-induced dilepton production off nuclei [11]. However, with improved background determination these results were not confirmed [12,13], leaving no evidence for a mass drop. As an alternative method, absorption measurements have been performed for ϕ and ω mesons in e^+e^- [14,15] and $\pi^0\gamma$ [16] channels. These data are not directly sensitive to possible mass shifts, but they can be used to assess the in-medium (absorptive) widths. For both ϕ and ω, large in-medium widths have been deduced, e.g., $\Gamma_\omega^{\rm med} \simeq 130$–$150$ MeV [16], or even above 200 MeV [15], for the ω at normal nuclear matter density. These values exceed the free ω width by a factor of $\sim$20, posing a challenge for theoretical models [17–25].

Most of the calculations thus far are based on the so-called T–ϱ approximation, where the in-medium ω self-energy is computed from the vacuum scattering amplitude and therefore depends linearly on nuclear density, ϱ_N (see, however, Refs. [26,27]). In the present work we go beyond this approximation by simultaneously dressing the π and ρ propagators in the $\pi\rho$ loop of the ω self-energy. In the vacuum, the ω decay into $\pi\rho$ has a nominal threshold of $m_\pi + m_\rho \simeq 910$ MeV and only proceeds through the low-mass tail of the ρ resonance, which is suppressed and possibly responsible for the small width of $\Gamma_{\omega\to 3\pi} \simeq 7.5$ MeV. A broadening of the ρ in the medium enhances this decay channel, further augmented if the pion is dressed as well. This is a key point we aim to convey and elaborate quantitatively in this Letter by utilizing realistic in-medium π and ρ propagators.

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Our Letter is organized as follows. In Section 2 we set up the $\omega \to \pi\rho$ self-energy in vacuum (Section 2.1) and discuss the implementation of the π and ρ propagators in nuclear matter (Section 2.2). In Section 3 we quantitatively evaluate the consequences of the in-medium propagators on the density and 3-momentum dependence of the ω width. We summarize and give an outlook in Section 4.

2. ω self-energy

2.1. ω width in vacuum

In vacuum we describe the coupling of the ω to a pion and a ρ meson with the chiral anomalous interaction Lagrangian introduced, e.g., in the work by Jain et al. [28],

$$\mathcal{L}^{\rm int}_{\omega\rho\pi} = g_{\omega\rho\pi}\epsilon_{\mu\nu\sigma\tau}\partial^\mu\omega^\nu\partial^\sigma\vec{\rho}^{\,\tau}\cdot\vec{\pi}. \tag{1}$$

The value of the coupling constant, $g_{\omega\rho\pi}$, determines the partial decay width $\Gamma_{\omega\to\rho\pi}$ and will be discussed below. A straightforward application of Feynman rules for the $\pi\rho$ loop yields the polarization-averaged self-energy of an ω of 4-momentum $P = (P^0, \vec{P})$ as

$$-i\Pi_\omega(P) = IF\frac{1}{3}\sum_{\lambda,\delta}\epsilon^\nu_\lambda(P)\epsilon^{\nu'}_\delta(P)ig_{\omega\rho\pi}ig_{\omega\rho\pi}\varepsilon_{\mu\nu\alpha\beta}\varepsilon_{\mu'\nu'\alpha'\beta'} \times\int\frac{d^4q}{(2\pi)^4}P^\mu q^\alpha P^{\mu'}q^{\alpha'}iD^{\beta\beta'}_\rho(q)iD_\pi(P-q), \tag{2}$$

where the isospin factor $IF = 3$ accounts for the different $\pi\rho$ charge states. Using standard representations of the polarization sum and of the spin-1 ρ propagator, $D^{\beta\beta'}_\rho$, which we decompose in transverse (T) and longitudinal (L) modes [29], one finds

$$-i\Pi_\omega(P) = -\frac{4}{3}IFg^2_{\omega\rho\pi}\int\frac{d^4q}{(2\pi)^4}D_\pi(P-q)\big\{v_1(q,P)D^T_\rho(q) + v_2(q,P)\big[D^T_\rho(q)-D^L_\rho(q)\big]\big\} \tag{3}$$

where $D_\pi(P-q) = 1/[(P-q)^2 - m^2_\pi - \Pi_\pi]$ and $D^{T,L}_\rho(q) = 1/[q^2 - M^2_\rho - \Pi^{T,L}_\rho]$ are the scalar parts of the meson propagators with complex self-energies. The two vertex functions arise from the Lorentz contractions with the T and L projectors of the ρ propagator, $v_1(q,P) = P^2q^2 - (Pq)^2$ and $v_2(q,P) = q^2(\vec{P}^2 - \vec{P}\cdot\vec{q}/\vec{q}^{\,2})/2$. The above expression is valid both in vacuum and in medium and incorporates the ω 3-momentum dependence. Using the Lehmann representation for the propagators one finds

$$\Pi_\omega(P) = -2\frac{4}{3}IF\,g^2_{\omega\rho\pi}\int_0^\infty d\omega\int_0^\infty d\omega'\frac{\omega+\omega'}{(P^0)^2-(\omega+\omega')^2+i\eta} \times\int\frac{d^3q}{(2\pi)^3}S_\pi(\omega',\vec{P}-\vec{q})\big\{v_1(q,P)S^T_\rho(q) + v_2(q,P)\big[S^T_\rho(q)-S^L_\rho(q)\big]\big\}_{q^0=\omega} \tag{4}$$

with $S^{T,L}_\rho = -\frac{1}{\pi}\,\mathrm{Im}\,D^{T,L}_\rho$, $S_\pi = -\frac{1}{\pi}\,\mathrm{Im}\,D_\pi$ denoting the ρ and π spectral functions, respectively. The ω width follows from the imaginary part of the self-energy as $\Gamma_{\omega\to\rho\pi}(P) = -\,\mathrm{Im}\,\Pi_\omega(P)/P^0$. In vacuum, free spectral functions for the pion and the ρ meson are utilized,

$$S^{\rm vac}_\pi(\omega',\vec{q}) = \delta(\omega'^2 - \vec{q}^{\,2} - m^2_\pi),$$
$$S^{\rm vac}_\rho(\omega,\vec{q}) = -\frac{1}{\pi}\frac{\mathrm{Im}\,\Pi^{\rm vac}_{\rho\pi\pi}(q^2)}{|\omega^2-\vec{q}^{\,2}-M^2_\rho-\Pi^{\rm vac}_{\rho\pi\pi}(q^2)|^2}. \tag{5}$$

The $\rho\to\pi\pi$ self-energy is often approximated by reabsorbing the real part into the physical ρ mass, $m^2_\rho \equiv M^2_\rho - \mathrm{Re}\,\Pi^{\rm vac}_{\rho\pi\pi}$, and an imaginary part

$$\mathrm{Im}\,\Pi^{\rm vac}_{\rho\pi\pi}(q^2) = -\frac{g^2_{\rho\pi\pi}}{48\pi\sqrt{q^2}}(q^2-4m^2_\pi)^{\frac{3}{2}}\Theta(q^2-4m^2_\pi) \tag{6}$$

with $g_{\rho\pi\pi} \simeq 6$ to obtain $\Gamma_{\rho\to\pi\pi} = -\,\mathrm{Im}\,\Pi^{\rm vac}_{\rho\pi\pi}(q^2 = m^2_\rho)/m_\rho \simeq$ 150 MeV. Here, we use the microscopic vacuum spectral function underlying our in-medium model [29], which describes the low-mass tail of the ρ resonance more accurately, incorporating an energy dependence of $\mathrm{Re}\,\Pi^{\rm vac}_{\rho\pi\pi}$. With $g_{\omega\rho\pi} = 1.9/f_\pi$ (f_π = 92 MeV) [28,30], one obtains $\Gamma_{\omega\to\rho\pi} = 3.6$ MeV, i.e., about 1/2 of the total 3π width (2/3 when including interference effects [31]). Using a schematic Breit–Wigner ρ spectral function, $\Gamma_{\omega\to\rho\pi}(m_\omega)$ is reduced by approximately 30%. In Ref. [31] the partial $\pi\rho$ width was found to be 2.8 MeV. Rescaling our $g_{\omega\rho\pi}$ to obtain that value would entail an according 22% reduction of our in-medium widths reported below. Some of this would be recovered by medium effects of the accompanying increase in the direct 3π channel.

2.2. ρ and π propagators in nuclear matter

Before proceeding to calculate the ω meson width in nuclear matter caused by the dressing of the propagators in the $\pi\rho$ loop, $\Gamma^{\rm med}_{\omega\to\pi\rho}$, two comments are in order.

We first note that the unnatural-parity coupling in the $\omega\rho\pi$ Lagrangian (1) implies transversality of any contribution to the ω self-energy with at least one $\omega\rho\pi$ vertex with an external ω [26]. Thus, in-medium vertex corrections, as required to ensure transversality for the pion cloud of the ρ meson [29,32,33] (or chiral symmetry in the σ channel [34]), are not dictated here, but correspond to contributions to $\omega N \to \pi N, \pi\pi N$ scattering unrelated to the anomalous decay process. We will not include these in the present work.

Second, at finite 3-momentum relative to the nuclear medium, the ρ propagator splits into transverse and longitudinal modes. At $\vec{P} = \vec{0}$, the ω self-energy only depends on the transverse modes of the ρ, since the vertex function v_2 in Eq. (3) vanishes. However, for $\vec{P} \neq \vec{0}$, v_2 becomes finite and proportional to $S^T_\rho - S^L_\rho$. This contribution turns out to be appreciable due to the splitting of the in-medium T and L modes of the ρ [29] within the kinematics of the $\omega \to \rho\pi$ decay.

Let us turn to briefly reviewing the main ingredients to the evaluation of $\Gamma^{\rm med}_{\omega\to\pi\rho}$ from Eq. (4), which are the microscopic calculations of the in-medium pion and ρ propagators.

The pion spectral function is evaluated with standard P-wave nucleon–hole (NN^{-1}) and Delta–hole (ΔN^{-1}) excitations [35,36]. The corresponding irreducible P-wave pion self-energy,

$$\Pi_\pi(q^0,\vec{q};\varrho) = \frac{(\frac{f_N}{m_\pi})^2F_\pi(\vec{q}^{\,2})\vec{q}^{\,2}[U_{NN}+U_{\Delta N}-(g'_{11}-2g'_{12}+g'_{22})U_{NN}U_{\Delta N}]}{1-(\frac{f_N}{m_\pi})^2[g'_{11}U_{NN}+g'_{22}U_{\Delta N}-(g'_{11}g'_{22}-g'^2_{12})U_{NN}U_{\Delta N}]}, \tag{7}$$

is given by the Lindhard functions U_α for the loop diagrams [37]; they include transitions between the two channels through short-range correlations represented by Migdal parameters g'. The πNN and $\pi N\Delta$ coupling constants, $f_N \simeq 1$ and $f_\Delta/f_N \simeq 2.13$ (absorbed in the definition of $U_{\Delta N}$), are determined from pion–nucleon and pion–nucleus reactions. Finite-size effects on the πNN and $\pi N\Delta$ vertices are simulated via hadronic monopole form factors,

$$F_\pi(\vec{q}^{\,2}) = \Lambda^2_\pi/(\Lambda^2_\pi+\vec{q}^{\,2}). \tag{8}$$

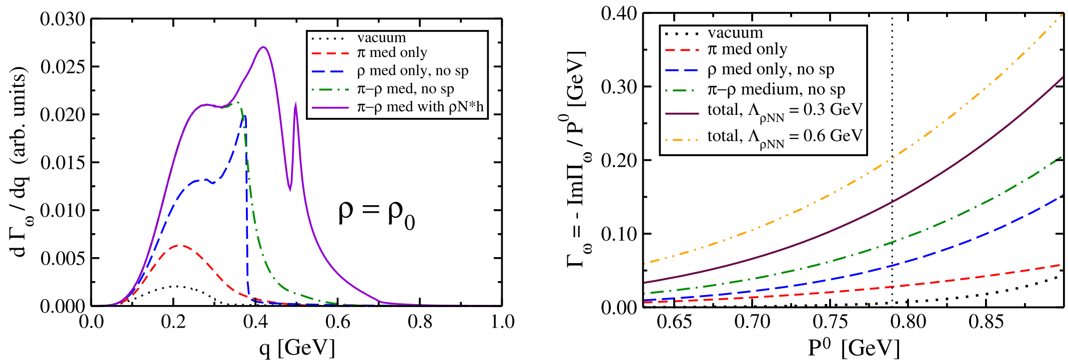

Fig. 1. Left: differential decay momentum distribution of the $\omega \to \rho\pi$ width (for $m_\omega = 782$ MeV) in vacuum (dotted line) and at saturation density when dressing either the pion (short-dashed line) or the ρ (long-dashed line), or both (dash-dotted line), without spacelike ρ modes. The solid line includes spacelike ρ's, where the two maxima beyond $q \simeq 0.4$ GeV correspond to ΔN^{-1} and NN^{-1} excitations ($\Lambda_{\rho NN} = 0.3$ GeV). Right: Energy dependence of $\Gamma_{\omega\to\rho\pi}$ at saturation density for different contributions as in the left panel.

Consistency with our model for the in-medium ρ discussed below dictates a soft cutoff, $\Lambda_\pi = 0.3$ GeV, following from constraints of $\pi N \to \rho N$ scattering data and the non-resonant continuum in nuclear photo-absorption [38] (e.g., with $\Lambda_\pi = 0.5$ GeV one overestimates the measured $\pi N \to \rho N$ cross section by a factor of $\sim$2). Especially the former probe similar kinematics of the virtual πNN vertex as figuring into $\omega N \to \rho N$ processes. The Migdal parameters are $g'_{11} = 0.6$ and $g'_{12} = g'_{22} = 0.2$.

The in-medium ρ spectral function is taken from Refs. [29, 39], which start from a realistic description of the ρ in free space (reproducing P-wave $\pi\pi$ scattering and the pion electromagnetic form factor). The self-energy in nuclear matter contains two components: pisobars (NN^{-1}, ΔN^{-1}) in the two-pion cloud, $\Pi_{\rho\pi\pi}$, and direct baryon resonance excitations in ρN scattering, $\Pi_{\rho BN^{-1}}$ ("ρ-sobars"). The latter have been evaluated using effective Lagrangians in hadronic many-body theory (in analogy to the pion) [29,40,41], including ca. 10 baryonic resonances. In $\Pi_{\rho\pi\pi}$, the in-medium pion propagator described above is supplemented with vertex corrections to preserve the Ward–Takahashi identities of the ρ propagator; it extends to finite 3-momentum of the ρ which is essential for the $\pi\rho$ loop in Π_ω. The total ρ self-energy is quantitatively constrained by nuclear photo-absorption and $\pi N \to \rho N$ scattering, dictating the soft $\pi NN(\Delta)$ form factor quoted above [38]. The resulting ρ spectral function in nuclear matter is substantially broadened, with a (non-Breit–Wigner) shoulder around $M \simeq 0.5$ GeV; this is precisely the region where most of the free $\omega \to \rho\pi$ decays occur. Note that spacelike parts of the π and ρ spectral functions (i.e., with negative 4-momenta squared, $q^2 < 0$) contribute to $\Gamma^{\rm med}_{\omega\to\pi\rho}$; they correspond to t-channel exchanges in ωN scattering (e.g., ρ exchange in $\omega N \to \pi N^*$). For the pion these are encoded in the Lindhard functions in the self-energy, Eq. (7). For the ρ they also turn out to be dominated by the low-lying P-wave ρ-sobars, ρNN^{-1} and $\rho\Delta N^{-1}$. The latter is well constrained by nuclear photo-absorption ($f^2_{\rho\Delta N}/4\pi = 16.2$, $\Lambda_{\rho\Delta N} = 0.7$ GeV), but the purely spacelike NN^{-1} mode (generating Landau damping of the exchanged ρ) is not. An analysis of ρ photo-production cross sections, $\gamma p \to \rho p$ [42], gave indications for a rather soft form factor, $\Lambda_{\rho NN} \simeq 0.6$ GeV ($f^2_{\rho NN}/4\pi = 6.0$), but it might be as soft as the πNN form factor in the pion cloud of the ρ. This needs to be investigated in future analysis of ωN scattering data. Here, we bracket the uncertainty by varying $\Lambda_{\rho NN} = 0.3$–0.6 GeV and $g'_{NN} = 0$–0.6. We find that the ω coupling to spacelike S-wave rhosobars (e.g., $N^*(1520)N^{-1}$, corresponding to $\omega N \to \pi N^*(1520)$) is already much less important.

In addition to modifications of the $\pi\rho$ cloud, pion dressing in the direct $\omega \to \pi\pi\pi$ channel and $\omega N^* N^{-1}$ excitations occur. The direct 3π decay has considerable phase space in vacuum, and thus we expect its in-medium modification to be smaller than for the $\pi\rho$ channel, especially if the latter dominates in vacuum and with our soft form factors for the pion dressing; for $\Lambda_{\pi NN(\Delta)} = 0.3$ GeV we estimate $\Gamma^{\rm med}_{\omega\to 3\pi}(\varrho_0) < 20$ MeV based on recent work in Ref. [43]. For the ω-sobars, e.g., $N^*(1535)$, $N^*(1520)$ or $N^*(1650)$ [19,21], we cannot simply adopt the couplings from the literature, since they were adjusted to fit ωN scattering data without the inclusion of $\pi\rho$ cloud effects. If the latter are present, the direct-resonance contributions need to be suppressed to still describe ωN scattering, and thus their contribution to the in-medium width will be (much) smaller than in Refs. [19,21].

3. *ω* width in nuclear matter

Let us first examine the differential distribution of the ω width, $d\Gamma_\omega/dq$, over the center-of-mass decay momentum, $|\vec{q}|$, of the π and ρ spectral functions, recall Eq. (4). In vacuum, the fixed pion mass uniquely determines the (off-shell) ρ mass (M) at given q. The maximum of the distribution occurs at $q_{\rm max} \simeq 0.2$ GeV, corresponding to $M \simeq 0.5$ GeV (see Fig. 1 left). Consequently, the enhancement of the in-medium ρ spectral function around this mass strongly increases the phase space and thus $\Gamma^{\rm med}_{\omega\to\pi\rho}$. A similar, albeit less pronounced effect is caused by the in-medium pion. A further remarkable increase in decay width is generated by spacelike ρ-sobars above $q \simeq 0.4$ GeV, which, for a free pion ($m = m_\pi$), marks the $M = 0$ boundary. The low-lying collective excitations are sensitive to the ρNN form factor. For a conservative choice of $\Lambda_{\rho NN} = 0.3$ GeV, about 40% of the in-medium ω width is generated by the spacelike ρ modes.

The energy dependence of $\Gamma^{\rm med}_{\omega\to\pi\rho}$ is rather pronounced (Fig. 1 right), a remnant of the (nominal) vacuum $\pi\rho$ threshold together with the $\vec{q}^{\,2}$ dependence of the $\omega\pi\rho$ vertex. The density dependence of $\Gamma^{\rm med}_{\omega\to\pi\rho}$ (Fig. 2 left) exhibits significant nonlinearities. At normal nuclear matter density, the dominant uncertainty is due the ρNN form factor, quantified as $\Gamma^{\rm med}_{\omega\to\pi\rho} = 130$–$200$ MeV.

The 3-momentum dependence of the on-shell ω width (i.e., for $P^2 = (P^0)^2 - \vec{P}^2 = m^2_\omega$), relative to the nuclear rest frame, turns out to be moderate (Fig. 2 right), as generally expected from cloud effects with soft form factors counter-acting the momentum dependence of the vertices. A fair agreement with CBELSA/TAPS data [16] is found, apparently preferring the lower values of $\Lambda_{\rho NN}$, leaving room for (smaller) contributions from direct 3π and interference terms, as well as from ω-sobars which are expected to come in at higher 3-momenta [21]. However, we recall the somewhat larger in-medium width of $\sim$200 MeV found by CLAS [15].

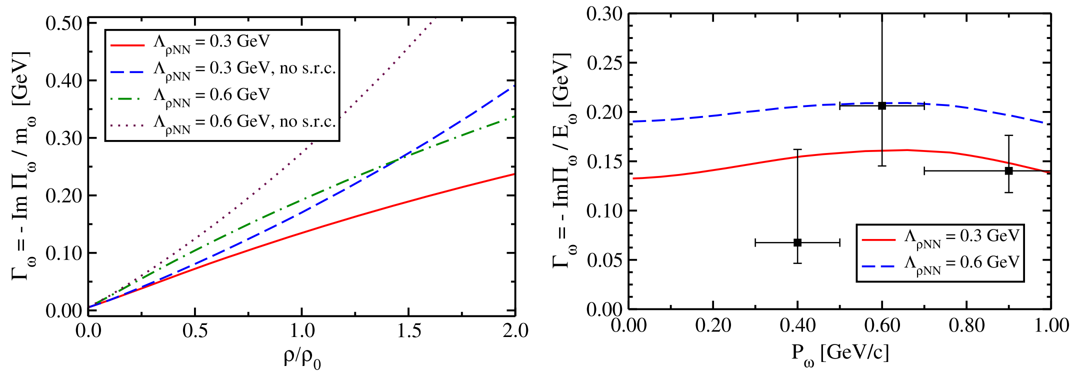

Fig. 2. Left: Density dependence of the $\omega \to \rho\pi$ width at $P^0 = m_\omega$, $\vec{P} = \vec{0}$, and for different ρNN form factors and short-range correlations. Right: Three-momentum dependence of $\Gamma_{\omega\to\rho\pi}$ at saturation density for on-shell ω mesons ($P^2 = m_\omega^2$, i.e., $E_\omega^2 = m_\omega^2 + P_\omega^2$), compared to CBELSA/TAPS data [16].

In the very recent work of Ref. [43], the total ω width in nuclear matter is computed with similar methods. At $\varrho_N = \varrho_0$ and $\vec{P} = \vec{0}$, $\Gamma_\omega^{\text{med}} = 129 \pm 10$ MeV is reported, predominantly due to the $\rho\pi$ cloud modification and with a more pronounced momentum dependence. The ρ spectral function employed in there exhibits a factor of ∼2 less broadening than in our input, while the pion modifications are stronger due to a harder πNN form factor. We recall that the latter is fixed in our approach as part of the quantitatively constrained ρ spectral function. It was also argued in Ref. [43] that medium effects in interference terms of 3π final states from direct 3π and $\rho\pi$ decays, which we neglected here, are small. Thus both our work and Ref. [43] identify the $\pi\rho$ cloud as the main agent for the ω's in-medium broadening, albeit with some differences in the partitioning into π and ρ modifications, and in the 3-momentum dependence.

4. Summary

We have studied the width of the ω meson in cold nuclear matter focusing on the role of its $\pi\rho$ cloud. We have employed hadronic many-body theory utilizing pion and ρ propagators evaluated with the same techniques, constrained and applied previously in both elementary and heavy-ion reactions. The low-mass shoulder in the in-medium ρ spectral function, together with spacelike contributions in the $\pi\rho$ intermediate states, induce large effects, along with non-linear density dependencies, not captured in previous calculations based on T–ϱ approximations. For an ω at rest at saturation density, we find $\Gamma_\omega^{\text{med}} = 130$–$200$ MeV, where the uncertainty is largely due to the ρNN vertex form factor which could not be accurately constrained before from ρ properties alone. Together with a rather weak 3-momentum dependence of the on-shell ω width, our calculations compare favorably with data from recent absorption experiments. The present uncertainties can be reduced by systematic analyses of vacuum ω scattering data (similar to the πNN form factor in the ρ cloud), where also contributions from direct 3π couplings and ωN resonances (ω-sobars) need to be included. Work in this direction is in progress. The emergence of a large ω width from ρ and pion propagators in nuclear matter is encouraging, and corroborates the quantum many-body approach as a suitable tool to assess the properties of hadrons in medium.

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References

[1] I. Tserruya, in: R. Stock (Ed.), Relativistic Heavy-Ion Physics, in: Landolt Börnstein (Springer), New Series, vol. I/23A, 2010, 4-2, arXiv:0903.0415 [nucl-ex].
[2] H.J. Specht, for the NA60 Collaboration, AIP Conf. Proc. 1322 (2010) 1.
[3] F. Geurts, et al., STAR Collaboration, Nucl. Phys. A 904–905 (2013) 217c.
[4] R. Rapp, J. Wambach, H. van Hees, in: R. Stock (Ed.), Relativistic Heavy-Ion Physics, in: Landolt Börnstein (Springer), New Series, vol. I/23A, 2010, 4-1, arXiv:0901.3289 [hep-ph].
[5] R. Rapp, PoS CPOD 2013 (2013) 008.
[6] S. Leupold, V. Metag, U. Mosel, Int. J. Mod. Phys. E 19 (2010) 147.
[7] F. Riek, R. Rapp, Y. Oh, T.-S.H. Lee, Phys. Rev. C 82 (2010) 015202.
[8] G.M. Huber, et al., TAGX Collaboration, Phys. Rev. C 68 (2003) 065202.
[9] M.H. Wood, et al., CLAS Collaboration, Phys. Rev. C 78 (2008) 015201.
[10] D. Trnka, et al., CBELSA/TAPS Collaboration, Phys. Rev. Lett. 94 (2005) 192303.
[11] M. Naruki, et al., E325 Collaboration, Phys. Rev. Lett. 96 (2006) 092301.
[12] M. Nanova, et al., CBELSA/TAPS Collaboration, Phys. Rev. C 82 (2010) 035209.
[13] M. Kaskulov, E. Hernandez, E. Oset, Eur. Phys. J. A 31 (2007) 245.
[14] T. Ishikawa, et al., LEPS Collaboration, Phys. Lett. B 608 (2005) 215.
[15] M.H. Wood, et al., CLAS Collaboration, Phys. Rev. Lett. 105 (2010) 112301.
[16] M. Kotulla, et al., CBELSA/TAPS Collaboration, Phys. Rev. Lett. 100 (2008) 192302.
[17] F. Klingl, N. Kaiser, W. Weise, Nucl. Phys. A 624 (1997) 527.
[18] M. Post, U. Mosel, Nucl. Phys. A 688 (2001) 808.
[19] M.F.M. Lutz, G. Wolf, B. Friman, Nucl. Phys. A 706 (2002) 431;
M.F.M. Lutz, G. Wolf, B. Friman, Nucl. Phys. A 765 (2006) 431 (Erratum).
[20] S. Zschocke, O.P. Pavlenko, B. Kämpfer, Phys. Lett. B 562 (2003) 57.
[21] P. Muehlich, V. Shklyar, S. Leupold, U. Mosel, M. Post, Nucl. Phys. A 780 (2006) 187.
[22] A.T. Martell, P.J. Ellis, Phys. Rev. C 69 (2004) 065206.
[23] F. Eichstaedt, S. Leupold, U. Mosel, P. Muehlich, Prog. Theor. Phys. Suppl. 168 (2007) 495.
[24] T.E. Rodrigues, J.D.T. Arruda-Neto, Phys. Rev. C 84 (2011) 021601.
[25] S. Ghosh, S. Sarkar, Eur. Phys. J. A 49 (2013) 97.
[26] M. Wachs, PhD thesis, TU Darmstadt, 2000, http://tuprints.ulb.tu-darmstadt.de/epda/000050/.
[27] F. Riek, J. Knoll, Nucl. Phys. A 740 (2004) 287.
[28] P. Jain, R. Johnson, U.G. Meissner, N.W. Park, J. Schechter, Phys. Rev. D 37 (1988) 3252.
[29] M. Urban, M. Buballa, R. Rapp, J. Wambach, Nucl. Phys. A 641 (1998) 433.
[30] F. Klingl, N. Kaiser, W. Weise, Z. Phys. A 356 (1996) 193.
[31] D.G. Gudino, G.T. Sanchez, Int. J. Mod. Phys. A 27 (2012) 1250101.
[32] G. Chanfray, P. Schuck, Nucl. Phys. A 555 (1993) 329.
[33] M. Herrmann, B.L. Friman, W. Nörenberg, Nucl. Phys. A 560 (1993) 411.
[34] H.C. Chiang, E. Oset, M.J. Vicente-Vacas, Nucl. Phys. A 644 (1998) 77.
[35] E. Oset, H. Toki, W. Weise, Phys. Rep. 83 (1982) 281.
[36] A.B. Migdal, E.E. Saperstein, M.A. Troitsky, D.N. Voskresensky, Phys. Rep. 192 (1990) 179.

[37] E. Oset, P. Fernandez de Cordoba, L.L. Salcedo, R. Brockmann, Phys. Rep. 188 (1990) 79.
[38] R. Rapp, J. Wambach, Adv. Nucl. Phys. 25 (2000) 1.
[39] R. Rapp, M. Urban, M. Buballa, J. Wambach, Phys. Lett. B 417 (1998) 1.
[40] M. Urban, M. Buballa, R. Rapp, J. Wambach, Nucl. Phys. A 673 (2000) 357.
[41] R. Rapp, J. Wambach, Eur. Phys. J. A 6 (1999) 415.
[42] F. Riek, R. Rapp, T.-S.H. Lee, Y. Oh, Phys. Lett. B 677 (2009) 116.
[43] A. Ramos, L. Tolos, R. Molina, E. Oset, arXiv:1306.5921v3 [nucl-th].