The width of the $\omega$ meson in dense matter *

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We obtain the width of the $\omega$ meson in dense nuclear matter by taking into account (i) the free decay of the $\omega$ into three pions, which is dominated by $\rho\pi$ mode, (ii) the processes induced by a vector-baryon interaction dominated by vector meson exchange, and (iii) the $\omega \rightarrow KK$ mechanism in matter. The $\omega$ meson develops an important width in matter, coming from the dominant $\omega \rightarrow \rho\pi$ decay mode, with a value of $121 \pm 10$ MeV at normal nuclear matter density for an $\omega$ at rest. At finite momentum, the width of the $\omega$ meson increases moderately with values of 200 MeV at 600 MeV/c.

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Laura Tolos

1. Introduction

The interaction of vector mesons with nuclei has been a matter of much attention over the past decades. One of the more thoroughly investigated vector mesons is the $\omega$ meson.

From the experimental point of view, there are several investigations on the properties of the $\omega$ meson in matter with proton beams on nuclei at KEK by E325 Collaboration [1], photoproduction on nuclei by CBELSA/TAPS [2], photonuclear reactions looking for dileptons in the final state by CLAS [3] or dilepton production in p+p and p+Nb at HADES [4]. These experiments seem to point to the existence of a large width of the $\omega$ meson in the medium.

Different scenarios are present in the theoretical determination of the $\omega$ properties in matter. The obtained mass shifts range from an attraction of the order of 100-200 MeV [5, 6], through no changes in the mass [7], to a net repulsion [8]. As for the in-medium width of an $\omega$ meson at rest, the models of [5, 9] reported a value of about 40 MeV, while the width was found to be around 60 MeV in [10]. All these studies show a considerable increase of the $\omega$ width in the medium.

In this paper we study the $\omega$ width in dense matter, similarly to the $\bar{K}K^*$ meson [11, 12], paying a special attention to the decay of the $\omega$ into three pions via the dominant $\rho\pi$ decay mode [13].

2. Formalism: The $\omega$ self-energy in matter

Figure 1: The $\omega$ self-energy from the $\omega \rightarrow \bar{K}K$ channel in the nuclear medium including vertex corrections for the antikaon (left plot), and from the s-wave $\omega N$ interaction with vector mesons and baryons (right plot).

Figure 2: The $\omega$ meson self-energy from its decay into the $\rho\pi$ (a), where the $\rho$ meson decays into two pions (b) and the $\pi$ is dressed by its coupling to particle-hole and $\Delta$-hole including short-range correlations (c).

A free $\omega$ meson decays predominantly into three pions, most of the strength associated to the $\omega \rightarrow \rho\pi$ process with the subsequent decay of the $\rho$ meson into two pions. The $\omega$ width is small, $\Gamma^{(0)}_{\omega} = 8.49 \pm 0.08$ MeV, with 89.2% of this value corresponding to the $3\pi$ decay channel. This is due to the fact that the $\omega \rightarrow \rho\pi$ mechanism proceeds through the tail of the $\rho$-meson distribution. The situation, however, changes drastically in the nuclear medium.

First, the $\omega \rightarrow K\bar{K}$ mechanism is energetically open in matter when the medium modifications of the $\bar{K}$ and $K$ mesons are incorporated (see left plot of Fig. 1). The $\bar{K}$ self-energy in matter is
The width of the $\omega$ meson in dense matter

Laura Tolos

![Figure 3](image_url)

**Figure 3:** In-medium contribution to the width of the $\omega$ meson at zero momentum due to its coupling to $K\bar{K}$ (left plot) and the s-wave $\omega N \to VB$ interaction (right plot), at $\rho_0$ and as a function of the $\omega$ energy $P^0$.

obtained from the $\bar{K}N$ interaction within a chiral unitary approach [14, 15, 16]. For $K$, due to the much weaker $KN$ interaction, we use the low-density approximation [17, 18]. Moreover, because of gauge invariance of the model, it is necessary to include vertex corrections.

Second, the $\omega$ properties are modified due to quasielastic and inelastic vector-baryon processes dominated by vector meson exchange. The contribution to the $\omega$ self-energy coming from the s-wave $\omega N$ interaction with vector mesons and baryons is depicted on the right plot of Fig. 1. The $\omega N$ interaction is constructed within the hidden gauge formalism in coupled channels [19]. The vector meson-baryon scattering amplitudes are then obtained from the coupled-channel on-shell Bethe-Salpeter equation by incorporating medium modifications on the intermediate states [13].

Finally, the most important contribution to the $\omega$ width in matter comes from its decay into $\rho\pi$ in the nuclear medium due to the increase of the phase space available as compared to the free case. The self-energy for the $\omega \to \rho\pi$ process is depicted in Fig. 3(a), where the $\rho$- and $\pi$-meson lines correspond to their medium propagators shown in Figs. 3(b) and (c), respectively. The pion in matter is dressed via its self-energy which is strongly dominated by the $p$-wave coupling to particle-hole and $\Delta$-hole components and also contains a small repulsive $s$-wave contribution, as well as short-range correlations and contributions from $2p-2h$ excitations. For the $\rho$-meson we employ three different self-energy models, as we will see.

Note that in our calculation in matter we do not consider interference terms between the different physical states $\rho^+\pi^-$, $\rho^+\pi^-$ and $\rho^0\pi^0$. While in free space, we miss an important part of the free $\omega$ width, the interference terms are negligible in matter [13]. Moreover, we also need to incorporate the contribution of uncorrelated three pions. This contribution can be supplied by either introducing a contact term that provides a background to be added to the $\omega \to \rho\pi$ process, as done in Ref. [20], or by adjusting the coupling of $\omega \to \rho\pi$ to reproduce the complete free $\omega \to \pi\pi\pi$ width directly from the $\rho\pi$ mechanism. We analyze both mechanisms in the following.

3. Results: The width of the $\omega$ meson in matter

In left plot of Fig. 3 we show the in-medium $\omega$ width correction coming from its coupling to $K\bar{K}$ states in matter. At normal nuclear saturation density, $\rho_0 = 0.17\text{fm}^{-3}$, and around the free $\omega$ mass, this amounts for 2.9 MeV for an $\omega$ meson at rest. This correction to the width mainly comes from the $\omega N - KY$ processes, with $Y = \Lambda(\Sigma)$, that result from the $p$-wave coupling of $\bar{K}$ to $YN^{-1}$. 

We also present in the right plot of Fig. 3 the \( \omega \) width correction associated to the elastic and inelastic processes from the \( s \)-wave interaction of \( \omega N \) with vector mesons and baryons as a function of the \( \omega \) energy. We observe that this contribution produces a very small \( \omega \) width correction, about 0.5 MeV, for energies around the free \( \omega \) mass and at \( \rho_0 \). The small \( \omega \) width correction is associated to the \( \omega N \to \omega N \) and \( \omega N \to \rho N \) processes. Note that the implementation of pseudoscalar mesons, hence opening vector-baryon to pseudoscalar-baryon transitions such as \( \omega N \to \pi N \), might also add some width to the \( \omega \) in medium. For that purpose, we adopt the model independent view of Ref. [21], based on detailed balance and unitarity, and add 9 MeV to the width of the \( \omega \) meson.

In the right plot of Fig. 4 we show the in-medium width of an \( \omega \) meson at rest for \( \rho_0 \) as a function of the energy, from the \( s \)-wave interaction of \( \omega N \) with vector mesons and baryons as a function of the \( \omega \) energy. We observe that this contribution produces a very small \( \omega \) width correction, about 0.5 MeV, for energies around the free \( \omega \) mass and at \( \rho_0 \). The small \( \omega \) width correction is associated to the \( \omega N \to \omega N \) and \( \omega N \to \rho N \) processes. Note that the implementation of pseudoscalar mesons, hence opening vector-baryon to pseudoscalar-baryon transitions such as \( \omega N \to \pi N \), might also add some width to the \( \omega \) in medium. For that purpose, we adopt the model independent view of Ref. [21], based on detailed balance and unitarity, and add 9 MeV to the width of the \( \omega \) meson.

In summary, we find [13] that the width of the \( \omega \) meson at rest in nuclear matter at saturation density is \( \Gamma_\omega (\rho_0, m_\omega) = 7.6 \text{ MeV} \) (free width) + 101.2 MeV (\( \omega N \to \pi \pi N \), \( \omega NN \to \pi NN \)) + 2.9 MeV (\( \omega N \to KY \)) + 0.5 MeV (\( \omega N \to K^*Y \to \rho N \)) + 9 MeV (\( \omega N \to \pi N \)) = 121 \pm 10 \text{ MeV}. We note that one could add one more MeV to account for the other free decay channels of the \( \omega \) meson, \( \omega \to \pi^0 \gamma \) and \( \omega \to \pi^+ \pi^- \). With regards to the mass shift, no clear conclusion can be drawn due to the uncontrolled high-momentum components of the \( \pi \) and \( \rho \) propagators [13].

Our value of the width of the \( \omega \) meson at rest in nuclear matter is larger than that found by
The width of the \( \omega \) meson in dense matter

Laura Tolos

other works \([5][9][10]\), and similar to more recent calculations \([23]\). In order to compare with the experimental determination of the \( \omega \) width, we need to extend our calculation to finite momentum. We find that \( \Gamma_{\omega \to 3\pi} \) rises smoothly with momentum, and it can reach values of about 200 MeV at \( P = 600 \) MeV/c. The experimental width is quoted to be \( \Gamma_{\omega} \approx 130 - 150 \) MeV for an average 3-momentum of 1.1 GeV/c \([3]\). We obtain a good agreement within errors for 400 MeV/c and 600 MeV/c reported in Fig. 4 of Ref. \([2]\), where our results should be more accurate.

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