ϕ meson properties in nuclear matter from dilepton spectra in a transport approach

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Abstract. The current status of research related to the behavior of the ϕ meson in nuclear matter is reviewed. First, recent theoretical works based of QCD sum rules and effective theory approaches are discussed. Next, preliminary results of transport simulations of pA reactions, with the goal of reproducing the dilepton spectra of the KEK E325 experiment are presented.

1 Introduction

The finite density behavior of vector mesons with small decay widths, such as ω and ϕ, is attracting renewed interest in recent years, as their in-medium modifications as well as their fundamental meson-nucleon interactions are being measured in multiple experiments. For previous reviews, see Refs. [1–3], and also Refs. [4, 5] for the most recent experimental results.

The focus of these proceedings will be the behavior of the ϕ meson in dense matter. It has been shown theoretically, that the ϕ meson in matter can be viewed as a probe of the in-medium strange quark condensate [6, 7] and strangeness production in heavy-ion collisions [8, 9]. Furthermore, its longitudinal and transverse polarization modes could in the future be used to measure the degree of Lorentz symmetry breaking in nuclear matter [10, 11] and the vorticity of matter created in non-central heavy-ion collisions [12, 13]. On the experimental side, it is worth mentioning the dilepton measurement of the KEK E325 Collaboration [14], which observed a signal that was claimed to be compatible with a negative mass shift of 3.4 % at normal nuclear matter density and the recently started J-PARC E16 experiment [15], which is attempting to conduct a similar measurement with significantly increased statistics. Providing an accurate and physically reasonable interpretation for the corresponding dilepton data is the main motivation for conducting the transport simulations discussed in the latter half of these proceedings.

This work is organized as follows. In Section 2, we first recapitulate theoretical results obtained within a QCD sum rule approach and hadronic effective theories. We move on

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to Section 3, to discuss preliminary results of numerical transport simulations of the pA reactions studied at the KEK E325 experiment. Section 4 concludes the proceedings with a summary and outlook.

2 Results from QCD sum rules and effective field theory

While it is currently still not possible to apply lattice QCD to low-temperature, high-density density systems, the QCD sum rule method remains one of the few available tools to study the in-medium behavior of hadrons based on QCD [6]. This approach has been generalized some time ago in Ref. [16] to make use of the maximum entropy method. The same technique was employed in Ref. [7], which found the following relation between the ϕ meson mass shift in nuclear matter and the strange sigma term $\sigma_{sN} = m_s\langle N|\bar{s}s|N\rangle$,

$$\frac{m_\phi(\rho)}{m_\phi(0)} - 1 = \left[b_0 - b_1\Big(\frac{\sigma_{sN}}{1\,\mathrm{MeV}}\Big)\right]\frac{\rho}{\rho_0}, \tag{1}$$

with parameter values $b_0 = (1.00 \pm 0.34) \times 10^{-2}$ and $b_1 = (2.86 \pm 0.48) \times 10^{-4}$ and ρ_0 standing for the normal nuclear matter density. This shows that the ϕ meson mass shift vanishes at $\sigma_{sN} = b_0/b_1 = 34.9 \pm 13.1$ MeV and becomes negative for larger σ_{sN} values. Note here that the strange sigma term determines the behavior of the strange quark condensate $\langle\bar{s}s\rangle_\rho$ within the linear density approximation as

$$\langle\bar{s}s\rangle_\rho \simeq \langle 0|\bar{s}s|0\rangle + \frac{\sigma_{sN}}{m_s}\rho, \tag{2}$$

where m_s is the strange quark mass.

Furthermore, QCD sum rules have been used to extend the above result to include non-zero momentum effects that were ignored in Eq. (1). Such effects are potentially important when making comparisons to experimental measurements, where (at least in the experiments done so far) the ϕ meson momentum with respect to the surrounding nuclear matter is of the order of 1 GeV [14]. Following the pioneering work of Ref. [10], the momentum effects were studied in Ref. [11], making use of the earlier OPE calculation carried out in Refs. [17, 18]. Finite momentum effects in fact do not only change the magnitude of the ϕ meson mass shift of Eq. (1), but also lead to a splitting of its two (longitudinal and transverse) polarization modes, which depict the two independent configurations of the ϕ meson spin in relation to its momentum direction. The splitting of the polarization modes is caused by the breaking of Lorentz symmetry in nuclear matter, which leads to the emergence of non-scalar condensates such as $\langle\mathcal{S}\mathcal{T}\,\bar{s}\gamma^\mu iD^\nu s\rangle_\rho$ and $\langle\mathcal{S}\mathcal{T}\,G^{\alpha\mu}_\alpha G^{\alpha\nu\alpha}\rangle_\rho$ ($\mathcal{S}$ and $\mathcal{T}$ here symmetrize the following open Lorentz indices and make them traceless, respectively). These lead to differences in the OPE of the two polarization components. An analysis of the corresponding pole masses then found [11]

$$\frac{m_\phi^{\mathrm{L/T}}(\rho)}{m_\phi(0)} - 1 = \left[a + b^{\mathrm{L/T}}\Big(\frac{|\vec{q}|^2}{1\,\mathrm{GeV}^2}\Big)\right]\frac{\rho}{\rho_0}, \tag{3}$$

where $\vec{q}$ is the ϕ meson three-momentum and a contains the mass shift for vanishing momentum, as given in Eq. (1), which depends on σ_{sN}. The letters L and T represent the longitudinal and transverse modes, respectively. The values for $b^{\mathrm{L/T}}$ were obtained as

$$b^{\mathrm{L}} = (-4.8 \pm 0.8) \cdot 10^{-3}, \tag{4}$$

$$b^{\mathrm{T}} = (6.7 \pm 3.4) \cdot 10^{-3}, \tag{5}$$

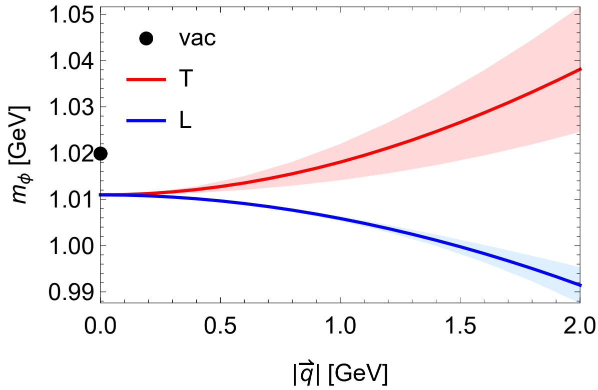

Figure 1. The ϕ meson pole mass, shown as a function of momentum $|\vec{q}|$ for longitudinal (blue curve) and transverse (red curve) modes, at normal nuclear matter density ρ_0. Adapted from Ref. [11].

showing that the respective poles are modified in opposite directions. This is also illustrated in Fig. 1, where the pole masses are shown as a function of momentum $|\vec{q}|$.

One goal of the J-PARC E16 experiment is the measurement of the dispersion relation of the ϕ meson in nuclear matter [15]. Depending of in-medium ϕ meson decay width, the above two modes will either be seen as one smeared single peak slightly tilted toward the transverse direction (because there are two transverse degrees of freedom compared to only one longitudinal), or as two independent peaks that move away from each other with increasing momentum. Furthermore, if the experiment turns out to be accurate enough to measure the angular dependence of the dilepton (or K^+K^-) decay with sufficient precision, it might even be possible to observe the two polarization modes independently.

Next, let us briefly discuss studies of the ϕ meson behavior in nuclear matter based on hadronic effective field theory. This approach allows one to directly compute the detailed structure of the spectral function in vacuum and at finite density, in contrast to QCD sum rules which can only determine the mass and (at most) width of the particle of interest. On the other hand, results obtained from effective field theories usually carry some degree of model dependence. In Refs. [19, 20] an improved vector dominance model [21] was employed to calculate the ϕ meson spectral function and its modification in nuclear matter. The finite density effects were assumed to be dominated by the modification of the the $K\bar{K}$ loops contributing to the ϕ meson self-energy through S-wave and P-wave KN and $\bar{K}N$ interactions. The resulting spectral function turned out to have only a small and negative mass shift, but exhibited a strong broadening tendency with a decay width increased by about a factor of 10 compared to the vacuum value. Refs. [22, 23] furthermore included direct vector meson - baryon interactions using two different models (based on the hidden local symmetry and SU(6) spin flavor symmetry), but obtained a roughly similar result: a small negative mass shift and strong broadening for the ϕ meson at normal nuclear matter density.

3 Numerical pA reaction simulations

In this study, we employ the PHSD transport approach [24, 25] (in the HSD version [8], that is, ignoring quark and gluon degrees of freedom), a covariant, microscopic off-shell framework, in which the vector meson (and recently also kaon [26]) spectral functions and their density dependence are consistently treated as the particles move through regions of

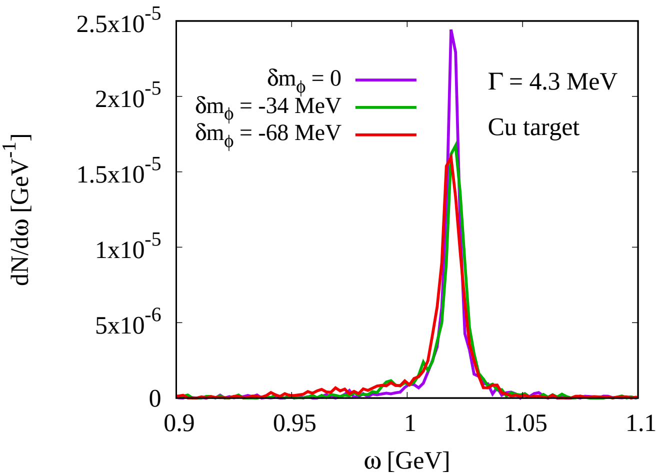

Figure 2. The ϕ meson contribution to the dilepton spectrum, obtained in simulations of 12 GeV pCu reactions for scenarios of different negative mass shift magnitudes for the ϕ meson at finite density.

varying density. To simulate the reactions measured at the KEK E325 experiment [14], we study 12 GeV pC and pCu reactions, with various in-medium modification scenarios for the ϕ meson. The ϕ meson spectral function and its density dependence is parametrized using a relativistic Breit-Wigner form

$$A_V(M,\rho) = C\frac{2}{\pi}\frac{M^2\Gamma_V^*(M,\rho)}{[M^2 - M_0^{*2}(\rho)]^2 + M^2\Gamma_V^{*2}(M,\rho)}, \tag{6}$$

in which C stands for a renormalization constant. The in-medium ϕ meson mass $M_0^*(\rho)$ and width $\Gamma_V^*(M,\rho)$ are assumed to depend linearly on density ρ,

$$M_0^*(\rho) = M_0\Big(1 - \alpha\frac{\rho}{\rho_0}\Big), \tag{7}$$

$$\Gamma_V^*(M,\rho) = \Gamma_V(M) + \alpha_{\rm coll}\frac{\rho}{\rho_0}, \tag{8}$$

where M_0 and $\Gamma_V(M)$ are the vacuum mass and width, respectively.

In the numerical calculations, α and $\alpha_{\rm coll}$ in Eqs. (7) and (8) can be changed to simulate various mass shift and broadening scenarios. Examples of the corresponding ϕ meson contribution to the di-lepton spectrum, extracted from pCu collisions and different mass shifts at normal nuclear matter density (but no broadening), are shown in Fig. 2. Note that experimental acceptance, finite energy resolution and rescattering effects of the dilepton measurement are not taken into account in this plot. For making an accurate comparison with the experimental dilepton data, final state QED radiation effects should also be included, as these can lead to a enhancement of the spectrum on the small-energy side of the peak and can thus deform the spectrum in a manner that is resembling a mass shift case [27]. An analysis, which takes all these effects into account, and eventually aims to determine which mass shift and/or broadening scenario can best reproduce the experimental data of Ref. [14] is ongoing.

4 Conclusions and outlook

We have in these proceedings first reviewed recent theoretical findings related to the behavior of the ϕ meson in nuclear matter. The effect of Lorentz symmetry breaking in medium, leading to a splitting of the longitudinal and transverse polarization modes and to a modified dispersion relation, was discussed within a QCD sum rule approach. Furthermore, the basic properties of the ϕ meson spectral functions computed from hadronic models were briefly recapitulated. Even though the detailed features of the obtained spectral functions are model dependent, all of them suggest that the ϕ receives only a small and negative mass shift in nuclear matter, while it gets broadened rather strongly, leading to decay widths of the order of 40 MeV.

Next, ongoing numerical simulations of pC and pCu reactions using the microscopic PHSD transport approach with the eventual goal of reproducing the KEK E325 dilepton data of Ref. [14] were discussed, highlighting especially the importance of considering all experimental and theoretical corrections, which can distort the dilepton spectrum.

Let us finally discuss here some topics closely related to this work, that are currently under discussion by various groups. New results regarding the ϕN scattering length, firstly from a femtoscopy measurement by ALICE at LHC [5] and secondly from a lattice QCD calculation by the HAL QCD Collaboration [28], were reported recently. The scattering length can in a low-density-approximation be related to the first order nuclear optical potential and hence to the nuclear matter ϕ meson mass shift and width. The new ALICE and HAL QCD findings can thus be translated into a ϕ meson mass shift, that turns out to be as large as several tens of MeV at normal nuclear matter density. It will be interesting to see whether these conclusions hold with more precise measurements and calculations.

The J-PARC E16 experiment [15], on the other hand, is scheduled to start with its first physics data taking in 2024 and will, similar to the KEK E325 experiment, measure dilepton spectra generated by pA reactions to study potential in-medium modification effects of vector mesons. It is now planned that, at a later stage, the K^+K^- decay channel will additionally be investigated in the same experiment, as it was also done at E325 [29] and more recently at HADES [4]. In contrast to the dilepton measurement, the K^+K^- decay channel will have full coverage of all possible decay angles in the lab frame. The measurement of this decay will hence be crucial for extracting the two polarization modes discussed in Section 2 independently and to determine their respective pole masses. To make sure that the potentially strong final state KN and $\bar{K}N$ interactions do not distort the initial ϕ meson signal, a careful and accurate evaluation of these final state interactions will, however, have to be carried out, which we leave as a task for future study.

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