PROCEEDINGS OF SCIENCE

The phi meson in nuclear matter in a transport approach

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The status of theoretical studies dealing with the ϕ meson in nuclear matter is reviewed. Next, preliminary results of transport simulations of pA reactions measured at the past KEK E325 experiment are discussed. Corresponding di-lepton spectra are presented and compared with the E325 data.

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1. Introduction

The study of the behavior of vector mesons with a small decay width, such as ω and ϕ, in nuclear matter has attracted renewed interest recently, as their density-induced modifications are starting to be measured in several experiments. For recent reviews discussing, among other topics, the behavior of the ω and ϕ mesons at finite density, see Refs. [1–3].

These proceedings will focus on theoretical issues related to potential modification of the ϕ meson in nuclear matter. In Section 2, a few recent theoretical findings will be reviewed, after which first results of numerical transport simulations of the pA reactions studied at the KEK E325 experiment will be presented and discussed in Section 3. Section 4 contains a summary and conclusions.

2. Summary of recent theoretical results

With the persisting difficulty of lattice QCD to study non-zero density systems, QCD sum rules remain one of the few available tools to study the behavior of hadrons in nuclear matter directly from QCD [4]. This method has been further develped in recent years for instance by applying the maximum entropy method for its numerical analysis [5]. Making use of this approach, the QCD sum rules for the ϕ meson channel were analyzed in Ref. [6], finding the mass shift of the ϕ meson in nuclear matter (at rest) to be correlated with the strange sigma term $\sigma_{sN} = m_s \langle N|\bar{s}s|N\rangle$.

To take the effect of the ϕ meson momentum with respect to nuclear matter properly into account, a more advanced QCD sum rule study becomes necessary, especially by incorporating a complete set of non-scalar condensates into the analysis [7]. Computing first the Wilson coefficients of such condensates [8] and employing updated condensate estimates [9], a new analysis was performed recently [10]. Therein, predictions on the magnitude of the splitting between longitudinal and trasverse modes were given. This splitting can generally be understood from the breaking of Lorentz symmetry in nuclear matter and is within the QCD sum rule analysis more specifically caused by the existence of non-scalar condensates, such as $\mathcal{ST}\langle \bar{s}\gamma^{\mu} iD^{\nu} s\rangle_{\rho}$, where the operators $\mathcal{S}$ and $\mathcal{T}$ make the following structure symmetric and traceless with respect to open Lorentz indices. As is explained in more detail in Ref. [10], the two (longitudinal and transverse) modes move away from each other approximately quadratically in momentum $|\vec{q}|$. This behavior can be expressed as

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

where a stands for the zero momentum mass shift. The superscripts L and T represent longitudinal and transverse modes, respectively. The extracted numerical values for $b^{\mathrm{L/T}}$ are

$$b^{\mathrm{L}} = (-4.8 \pm 0.8) \cdot 10^{-3}, \tag{2}$$

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

It should be mentioned here that in an experiment, it is not possible to disentangle the longitudinal and transverse modes without any information about the angular distributions of the di-leptons originating from the decaying vector mesons. The more easily measurable angular averaged di-lepton spectrum will rather correspond to a weighted average of the two modes, somewhat tilted to the side of the transverse mode because there are two of them in contrast to the single longitudinal one. It will be instersting to see whether the new J-PARC E16 experiment [11] will be able to observe such a weighted average or even possibly the separate momentum dependences of the longitudinal and transverse modes.

3. Numerical pA reaction simulations

Let us here discuss some preliminary results obtained using the HSD transport approach [12] to simulate 12 GeV (lab frame) pA reactions with C and Cu targets, which were measured at the KEK E325 experiment [13]. HSD is a covariant, microscopic off-shell transport framework, in which the vector meson spectral functions and their density dependence can be specified freely. In our simulations, we use a relativistic Breit-Wigner parametrization, expressed as

$$A_V(M, \rho_N) = C\frac{2}{\pi}\frac{M^2\Gamma_V^*(M,\rho_N)}{[M^2 - M_0^{*2}(\rho_N)]^2 + M^2\Gamma_V^{*2}(M,\rho_N)}. \tag{4}$$

Here, C is a renormalization constant, while the in-medium mass $M_0^*(\rho_N)$ and width $\Gamma_V^*(M,\rho_N)$ are given as

$$M_0^*(\rho_N) = M_0\Big(1 - \alpha\frac{\rho_N}{\rho_0}\Big), \tag{5}$$

$$\Gamma_V^*(M,\rho_N) = \Gamma_V(M) + \alpha_{\text{coll}}\frac{\rho_N}{\rho_0}. \tag{6}$$

M_0 and $\Gamma_V(M)$ stand for the vacuum mass and width. Generally, $M_0^*(\rho_N)$ and $\Gamma_V^*(M,\rho_N)$ depend on the vector meson momentum (see the discussions at the end of Section 2). Such a dependence is neglected in the simulations discussed in these proceedings, will however be taken into account in future studies using a further develped HSD code (see, for instance, Ref. [14]).

pA simulations were performed for Cu and C targets and multiple ϕ meson modification scenarios [i.e. different values of α and α_{coll} in Eqs. (5) and (6)]. Some examples of the simulated di-lepton spectra in the ϕ meson mass region (for the Cu target) are given in Fig. 1. Note that these do not include finite resolution or any other experimental effects. Applying such effects (see Ref. [15]) to the obtained di-lepton spectra, it becomes possible to compare the experimental data of Ref. [13] with the simulation results. For this purpose we employ the ansatz

$$\rho(\omega) = a + b\omega + c\omega^2 + d\rho_{\phi,\text{HSD}}(\omega), \tag{7}$$

in which $\rho_{\phi,\text{HSD}}(\omega)$ is the acceptance and resolution corrected di-lepton spectrum of the ϕ meson, extracted from our HSD transport simulation. The second order polynomial is intended to approximate the background. Fitting the parameters a, b, c and d to the experimental di-lepton data, and comparing the χ^2/d.o.f. values for these fits, constraints provided by the data to the various mass shift and/or broadening scenarios at finite density can be deduced. The result of this procedure is shown in Fig. 2, with confidence levels of 95 % (pink line), 99 % (blue line) and 99.9 % (green line). One can conclude from this plot that while the scenario with a negative mass shift of around 34 MeV and no broadening is favored, some larger broadening scenarios cannot be entirely ruled out.

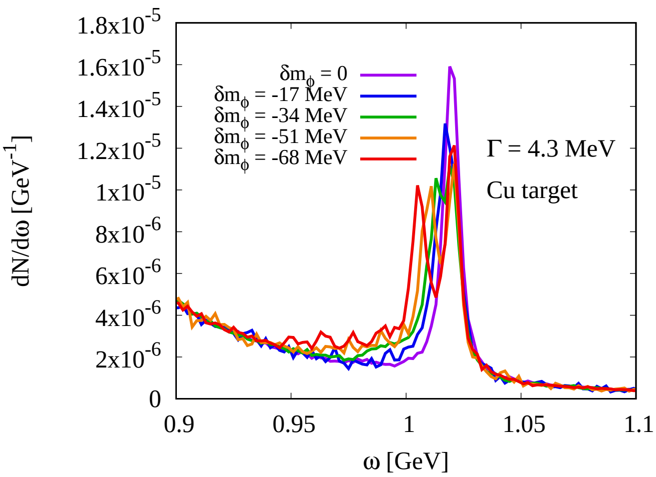

Figure 1: The di-lepton spectra in the ϕ meson mass region for scenarios of several negative mass shift magnitudes of the ϕ meson at finite density.

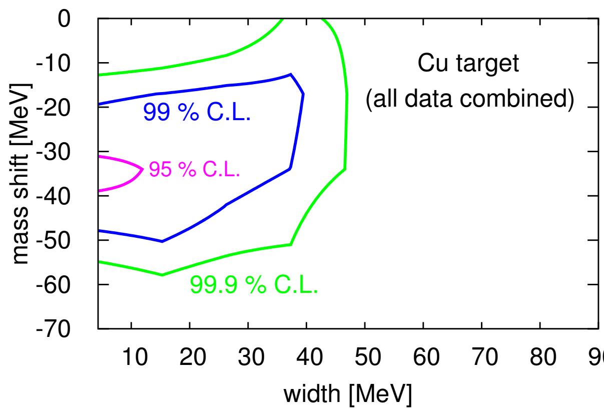

Figure 2: χ^2/d.o.f. values for various modification scenarios of the ϕ meson at normal nuclear matter density, obtained from a fit of the simulated di-lepton spectra to the experimental data of the KEK E325 experiment. The pink, blue and green lines correspond to the bounderies of regions which can be rejected with confidence levels of 95 %, 99 % and 99.9 %, respectively.

4. Summary and Conclusions

We have reviewed some recent theoretical results related to the behavior of the ϕ meson in nuclear matter, focusing on QCD sum rule studies, in which the author was involved. In particular, predictions for a modified dispersion relation in nuclear matter, related to the breaking of Lorentz symmetry, were highlighted. Furthermore, new results based on numerical simulations of pA reactions were discussed. By comparing the di-lepton spectra generated from these simulations with the experimental KEK E325 data, it is tentatively concluded that the data favor a scenario of a negative mass shift of the ϕ meson in nuclear matter with only small broadening. It remains to be seen how this conclusion can be reconciled with the predictions of many hadronic models, which usually favor relatively large broadening scenarios in nuclear matter.

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