Studying ϕ meson properties in nuclear matter from dilepton and K^+K^- decays

Philipp Gubler[1,*] and *Elena* Bratkovskaya[2,3,4,**]

[1]Advanced Science Research Center, Japan Atomic Energy Agency, Tokai, Ibaraki 319-1195, Japan
[2]GSI Helmholtzzentrum für Schwerionenforschung GmbH, Planckstrasse 1, 64291 Darmstadt, Germany
[3]Institute for Theoretical Physics, Johann Wolfgang Goethe Universität, Frankfurt am Main, Germany
[4]Helmholtz Research Academy Hesse for FAIR (HFHF), GSI Helmholtz Center for Heavy Ion Physics, Campus Frankfurt, 60438 Frankfurt, Germany

Abstract. After briefly reviewing the state of theoretical knowledge related to the behavior of the ϕ meson in nuclear matter, preliminary results of transport simulations of pA reactions corresponding to the KEK E325 experiment are presented. Finally, an outlook to current and future developments in the field is given.

1 Introduction

The behavior of the ϕ meson in hot and/or dense matter has for a long time been of interest from the point of view of probing the in-medium strange quark condensate [1, 2] and strangeness production in heavy-ion collisions [5, 6]. Recently, it has also attracted attention because its degree of its polarization [7] and the behavior of its polarization modes can provide information about the vorticity [8, 9] and the potential breaking of Lorentz symmetry of the medium [10, 11].

In these proceedings, we will particularly focus on the finite density behavior of the ϕ meson, by first reviewing some recent theoretical results obtained within a QCD sum rule approach in Section 2 and next by discussing preliminary results of numerical transport simulations of the pA reactions studied at the KEK E325 experiment in Section 3. A summary and outlook follow in Section 4.

2 Recent theory results

The QCD sum rule method is one of the few tools available to study finite density systems directly from QCD [1]. The method provides relations between the various QCD condensates and the spectral properties of hadrons, both in vacuum and in hot and/or dense matter. It was for instance shown in Ref. [2] that the mass of the ϕ meson in nuclear matter can be related to the strange sigma term $\sigma_{sN} = m_s\langle N|\bar{s}s|N\rangle$, which governs the finite density behavior of the

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[*] e-mail: gubler@post.j-parc.jp
[**] e-mail: brat@fias.uni-frankfurt.de

strange quark condensate $\langle \bar{s}s \rangle_\rho$ within the linear density approximation: $\langle \bar{s}s \rangle_\rho \simeq \langle 0|\bar{s}s|0\rangle + \frac{\sigma_{sN}}{m_s}\rho$. Specifically, the relation between σ_{sN} and the ϕ meson mass $m_\phi(\rho)$ was determined as

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

ρ_0 being the normal nuclear matter density and $b_0 = (1.00 \pm 0.34)\cdot 10^{-2}$, $b_1 = (2.86 \pm 0.48)\cdot 10^{-4}$.

The above result shows that an experimental measurement of $m_\phi(\rho)$ would allow to constrain the value of σ_{sN}. Equation (1), however, does not take finite momentum effects into account, which cannot simply be ignored in an actual experimental situation. Such effects were considered in Ref. [11], where it was found that the longitudinal and transverse modes, which cannot be distinguished at zero momentum, will split with increasing momentum. The origin of this splitting is the breaking of Lorentz symmetry in nuclear matter, which in QCD sum rules leads to the emergence of non-scalar condensates, such as $\mathcal{ST}\langle \bar{s}\gamma^\mu iD^\nu s\rangle_\rho$ ($\mathcal{S}$ and $\mathcal{T}$ make the following structures symmetric and traceless with respect to open Lorentz indices). These, in turn, cause the two polarizations modes to behave differently. A specific calculation leads to [11]

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

where a is the zero momentum mass shift [which depends on σ_{sN}, as shown in Eq. (1)]. The superscripts L and T stand for longitudinal and transverse modes, respectively. The numerical values for $b^{\mathrm{L/T}}$ are calculated as $b^{\mathrm{L}} = (-4.8 \pm 0.8)\cdot 10^{-3}$, $b^{\mathrm{T}} = (6.7 \pm 3.4)\cdot 10^{-3}$. It will be interesting to see whether the E16 experiment at J-PARC [12] will in the future be able to measure these two polarization modes independently.

3 Numerical pA reaction simulations

In this work, we use the PHSD transport approach [3, 4] (in the HSD version [5], i.e. ignoring the possible QGP droplet formation) which is a covariant, microscopic off-shell framework, in which the vector meson (and recently also kaon [13]) spectral functions and their density dependence can be consistently incorporated into the numerical simulation. We simulate 12 GeV pA reactions with C and Cu targets, that were studied at the E325 experiment [14] at KEK. For parametrizing the ϕ meson spectral function and its density dependence, we use a relativistic Breit-Wigner form

$$A_V(M,\rho) = C\frac{2}{\pi}\frac{M^2\Gamma_V^*(M,\rho)}{[M^2 - M_0^{*2}(\rho)]^2 + M^2\Gamma_V^{*2}(M,\rho)}, \tag{3}$$

where C is a renormalization constant and the in-medium mass $M_0^*(\rho)$ and width $\Gamma_V^*(M,\rho)$ are assumed to depend linearly on density ρ,

$$M_0^*(\rho) = M_0\Big(1 - \alpha\frac{\rho}{\rho_0}\Big), \tag{4}$$

$$\Gamma_V^*(M,\rho) = \Gamma_V(M) + \alpha_{\mathrm{coll}}\frac{\rho}{\rho_0}, \tag{5}$$

M_0 ($\Gamma_V(M)$) are the vacuum mass (width).

The simulations were carried out with multiple ϕ meson modification scenarios, that is, with changing values of α and α_{coll} in the above parametrization. A few preliminary examples

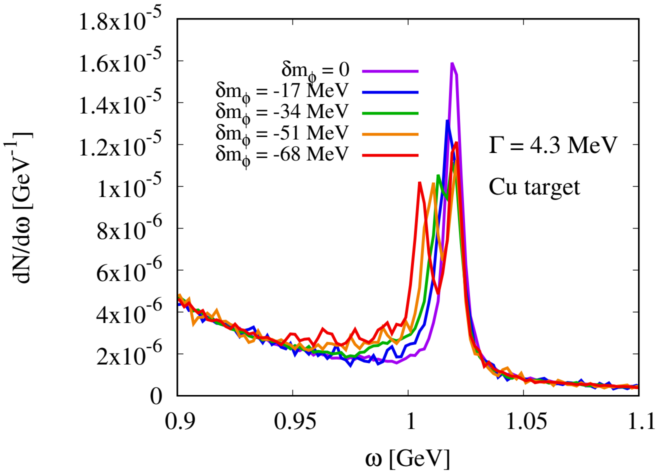

Figure 1. The di-lepton spectra in the ϕ meson mass region, obtained in simulations of 12 GeV pCu reactions for scenarios of different negative mass shift magnitudes for the ϕ meson at finite density.

of the di-lepton spectra in the ϕ meson mass region, obtained for a Cu target and scenarios with different finite density mass shifts (and no broadening) are given in Fig. 1. Experimental effects such as acceptance, limited resolution and rescattering effects of the dileptons emerging from the reaction, are not included in this plot. It is furthermore important to include final state QED radiation effects, which can deform the spectrum in a similar manner as one would expect for a mass shift case [15]. Only after taking all these effects properly into account, can a realistic comparison with experimental data become possible. Such an analysis, with the final goal of determining which mass shift and/or broadening scenarios can best reproduce the experimental data of Ref. [14], is presently ongoing.

4 Conclusions and outlook

In these proceedings, recent theoretical results related to the behavior of the ϕ meson in nuclear matter were reviewed, emphasizing especially the effects of Lorentz symmetry breaking in medium, which leads to a splitting of the longitudinal and transverse polarization modes and to a modified dispersion relation. First results based on numerical simulations of pA reactions using the microscopic PHSD transport approach were also discussed and the importance of considering all experimental and theoretical (QED) effects than can distort the dilepton spectrum before making a direct comparison with experimental data, was highlighted.

As an outlook, let us mention here some interesting directions of research, that are currently being pursued by multiple theoretical and experimental groups. Very recently, two new results regarding the ϕN scattering length have been reported from a femtoscopy measurement by ALICE at LHC [16] and a lattice QCD calculation by the HAL QCD Collaboration [17]. The scattering length can at low density can be related to a first order nuclear optical potential and hence to the nuclear matter ϕ meson mass shift and width. These new results suggest for the ϕ meson a rather strong attraction of several tens of MeV at normal nuclear matter density. It remains to be seen whether this conclusion holds in future more precise measurements and calculations. Another new development is the J-PARC E16 experiment [12], which 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. At a later stage, the K^+K^- decay channel will also be studied in the same experiment, which in combination with the dilepton measurement could be especially useful to disentangle the two polarization modes discussed in Section 2.

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