EPJ Web of Conferences **291**, 04003 (2024)
MESON 2023
https://doi.org/10.1051/epjconf/202429104003

The ϕ meson in nuclear matter from theory and experimental data

Philipp Gubler[1,*], *Elena* Bratkovskaya[2,3,4], *Masaya* Ichikawa[1,5], and *Taesoo* Song[2]

[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
[5]Department of Physics, Kyoto University, Kitashirakawa Oiwakecho, Kyoto, Kyoto 606-8502, Japan

Abstract. We first review recent theoretical results related to the ϕ-N and ϕ-nucleus interactions. Thereafter, preliminary results of transport simulations of 12 GeV pA reactions to study the corresponding dilepton spectrum measured at the KEK E325 experiment are presented.

1 Introduction

Until not too long ago, the ϕ-N and ϕ-nucleus interactions were thought to be rather weak and dominated by strong absorbtion effects [1–6], even though there were some experimental results pointing towards a stronger attractive interaction [7]. This picture may have to be revised due to recent experimental and theoretical findings, which indicate that the ϕ is strongly attracted to both single nucleons and larger nuclei.

The measurement of the ϕN scattering length within the femtoscopy technique as reported by the ALICE Collaborations at LHC [8] and a lattice QCD calculation of a closely related quantity by the HAL QCD Collaboration [9] both obtain scattering lenghs that are attractive and more than an order of magnitude larger that the value reported from previous photo production measurements [6]. An analysis combining the ALICE and HAL QCD Collaboration results (in which the former provides a scattering length that is a combination of the ϕN spin 1/2 and 3/2 channels, while the latter gives a result of only the pure spin 3/2 scattering length) even provided evidence for the existence of a ϕN bound state in the spin 1/2 channel [10]. Furthermore, a recent analysis by Paryev [11] of the pion-induced ϕ meson production cross sections on nuclear targets measured at HADES [12] led to a ϕ-nucleus potential depth of 50-100 MeV, which is larger than earlier predictions of hadronic effective theory calculations [1–5] and is also not compatible with results obtained when combining QCD sum rule calculations [13, 14] with the newest values of the strangeness sigma term (see for instance Ref.[15] and the references cited therein). From all this, it is clear that the ϕ-N and ϕ-nucleus interactions are not well understood from a theoretical point of view. The experimental contradictions among the measurements of the ϕN scattering length [6, 8] furthermore remain unresolved.

*e-mail: philipp.gubler1@gmail.com

This complicated state of the field has motivated us to study again the old dilepton data of the KEK E325 experiment, which were generated from 12 GeV p-C and p-Cu reactions [7], making use of a modern transport approach. This study is further motivated by the upcoming J-PARC E16 experiment, which will measure the same reactions with a 30 GeV incoming proton [16], which we also plan to study in the near future.

This proceeding contribution is organized as follows. After having given a brief review of the current status of the field in this introductory Section 1, we discuss preliminary results of our transport simulations of pA reactions measured at the KEK E325 experiment in Section 2. The paper is concluded in Section 3 with a summary and outlook.

2 Numerical transport simulations of pA reactions

In this work, the PHSD transport approach [17, 18] (in the HSD version [19], that is, ignoring quark and gluon degrees of freedom) is used to numerically simulate the pA reactions of of interest. PHSD is a covariant, microscopic off-shell framework, in which the spectral functions of light vector mesons and kaons [20] (including their density dependence) are treated consistently while the particles move through regions of high baryonic density.

The ultimate goal of this study is to determine which degree of in-medium modification (mass shift and/or broadening) of the ϕ meson can best reproduce the dilepton data measured at the corresponding pA reactions. For this purpose, we parametrize the ϕ meson spectral function including its density dependence as a relativistic Breit-Wigner form

$$A_V(M,\rho) = C\frac{2}{\pi}\frac{M^2\Gamma^*_V(M,\rho)}{[M^2 - M^{*2}_0(\rho)]^2 + M^2\Gamma^{*2}_V(M,\rho)}, \tag{1}$$

where the in-medium ϕ meson pole mass $M^*_0(\rho)$ and width $\Gamma^*_V(M,\rho)$ are taken to have a linear dependence on the density ρ,

$$M^*_0(\rho) = M_0\Big(1 - \alpha\frac{\rho}{\rho_0}\Big), \tag{2}$$

$$\Gamma^*_V(M,\rho) = \Gamma_V(M) + \alpha_{\mathrm{coll}}\frac{\rho}{\rho_0}, \tag{3}$$

with M_0 and $\Gamma_V(M)$ being the vacuum mass and width and ρ_0 the normal nuclear matter density. C in Eq. (1) is a simple normalization constant. α and α_{coll} in Eqs. (2) and (3) will be adjusted to the various mass shift and broadening scenarios.

As first results of our simulations, we show the ϕ meson contribution to the di-lepton spectrum, extracted from p-C and p-Cu collisions in Fig. 1. In these plots, we include a scenario without any in-medium modifications ($\alpha = \alpha_{\mathrm{coll}} = 0$) and two scenarios with mass shifts of different magnitudes, but no broadening effects. A shoulder effect on the negative side of the peak can be seen for the mass shift scenarios, which is obviously more prominent for the larger copper nucleus. Note that the peak is still generated at the original ϕ meson mass for all modification scenarios, through ϕs that decay outside of the target nucleus.

To eventually compare these results with the experimental data of the KEK E325 experiment, a few additional steps will have to be taken. First, experimental acceptance, finite energy resolution and rescattering effects of the dilepton measurement have to be included. Especially the rescattering effects are important as they lead to shoulder effect on the left side of the peak, which is similar to the one caused by a negative mass shift [21]. Next, final state QED radiation effects also have to be taken into account, which, even though QED effects are small, lead to a similar shoulder effect on the left side of the peak [22]. An analysis including all these effects is currently ongoing.

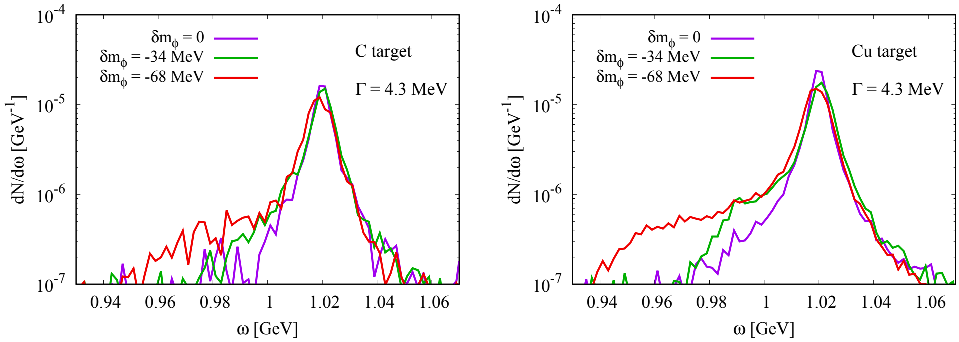

Figure 1. The ϕ meson contribution to the dilepton spectrum, obtained in simulations of 12 GeV p-C (left plot) and p-Cu (right plot) reactions for a scenario without any in-medium modifications (purple lines) and two scenarios with negative mass shifts of 34 MeV (green lines) and 68 MeV (red lines) at normal nuclear matter density.

3 Conclusions and outlook

We have in these proceedings discussed currently ongoing numerical simulations of 12 GeV p-C and p-Cu reactions, making use of the microscopic PHSD transport approach, to study what kind of in-medium modification scenarios of the ϕ meson can best reproduce the KEK E325 dilepton data [7].

Let us here give an outlook on future directions of our own project and research work of other groups. As mentioned in Sec. 1, a number of new experimental measurements and theoretical analysis have come out in recent years, which may change our understanding of the ϕ-N and ϕ-nucleus interaction, which could be stronger and more attractive than expected. It will be interesting to see whether these findings hold as more precise measurements and calculations become available. An important benchmark will for example be, whether the ϕ-N bound state predicted in Ref. [10] can be confirmed in a direct measurement.

On the other hand, the J-PARC E16 experiment [16] will start with its first physics data taking in the near future as a follow up experiment of KEK E325, similarly studying dileptons from pA reactions to determine in-medium modification effects of vector mesons. With significantly increased statistics compared to the KEK E325 measurement, this will hopefully make it possible to strongly constrain the ϕ meson modification in nuclear matter, including (for the first time) the momentum dependence of a potential mass shift and broadening effects. E16 will be followed by the E88 experiment [23], which plans to measure the K^+K^- channel in addition to dileptons from the same pA reactions, as done previously at E325 [24] and at HADES [12]. One difference from the dilepton measurement is that for the K^+K^- channel, complete coverage of all possible decay angles of the kaons in the lab frame will be possible for the measurement at the J-PARC facility. This will be crucial for measuring the longitudinal and transverse polarization modes of the ϕ [25], which can generally have different in-medium modifications [26].

P.G. thanks Su Houng Lee, Wolfram Weise, HyungJoo Kim, Daisuke Satow, In Woo Park, Kazuya Aoki, Hiroyuki Sako and Keisuke Ohtani for the fruitful collaborations that are mentioned in these proceedings. P.G. is supported by KAKENHI under Contract No. JP20K03940. E.B. acknowledges support by the Deutsche Forschungsgemeinschaft (DFG, German Research Foundation) through the grant CRC-TR 211 “Strong-interaction matter under extreme conditions” - project number 315477589 - TRR 211.

References

[1] F. Klingl, T. Waas, W. Weise, Phys. Lett. B **431**, 254 (1998), hep-ph/9709210
[2] P. Gubler, W. Weise, Phys. Lett. B **751**, 396 (2015), 1507.03769
[3] P. Gubler, W. Weise, Nucl. Phys. A **954**, 125 (2016), 1602.09126
[4] D. Cabrera, A.N. Hiller Blin, M.J. Vicente Vacas, Phys. Rev. C **95**, 015201 (2017), 1609.03880
[5] D. Cabrera, A.N. Hiller Blin, M.J. Vicente Vacas, P. Fernández De Córdoba, Phys. Rev. C **96**, 034618 (2017), 1706.08064
[6] I.I. Strakovsky, L. Pentchev, A. Titov, Phys. Rev. C **101**, 045201 (2020), 2001.08851
[7] R. Muto et al. (KEK-PS-E325), Phys. Rev. Lett. **98**, 042501 (2007), nucl-ex/0511019
[8] S. Acharya et al. (ALICE), Phys. Rev. Lett. **127**, 172301 (2021), 2105.05578
[9] Y. Lyu, T. Doi, T. Hatsuda, Y. Ikeda, J. Meng, K. Sasaki, T. Sugiura, Phys. Rev. D **106**, 074507 (2022), 2205.10544
[10] E. Chizzali, Y. Kamiya, R. Del Grande, T. Doi, L. Fabbietti, T. Hatsuda, Y. Lyu (2022), 2212.12690
[11] E.Y. Paryev, Nucl. Phys. A **1032**, 122624 (2023), 2212.13778
[12] J. Adamczewski-Musch et al. (HADES), Phys. Rev. Lett. **123**, 022002 (2019), 1812.03728
[13] T. Hatsuda, S.H. Lee, Phys. Rev. C **46**, R34 (1992)
[14] P. Gubler, K. Ohtani, Phys. Rev. D **90**, 094002 (2014), 1404.7701
[15] P. Gubler, D. Satow, Prog. Part. Nucl. Phys. **106**, 1 (2019), 1812.00385
[16] K. Aoki et al., Few Body Syst. **64**, 63 (2023)
[17] W. Cassing, E.L. Bratkovskaya, Phys. Rev. C **78**, 034919 (2008), 0808.0022
[18] W. Cassing, E.L. Bratkovskaya, Nucl. Phys. A **831**, 215 (2009), 0907.5331
[19] W. Cassing, E.L. Bratkovskaya, Phys. Rept. **308**, 65 (1999)
[20] T. Song, L. Tolos, J. Wirth, J. Aichelin, E. Bratkovskaya, Phys. Rev. C **103**, 044901 (2021), 2012.05589
[21] R. Muto, Ph.D. thesis, Kyoto U. (2007)
[22] A. Spiridonov (2005), hep-ex/0510076
[23] H. Sako et al., *Proposals for nuclear and particle physics experiments at J-PARC “P88: Study of in-medium modification of ϕ mesons inside the nucleus with $\phi \to K^+K^-$ measurement with the E16 spectrometer”*, https://j-parc.jp/researcher/Hadron/en/pac_2107/pdf/P88_2021-12.pdf
[24] F. Sakuma et al. (E325), Phys. Rev. Lett. **98**, 152302 (2007), nucl-ex/0606029
[25] I.W. Park, H. Sako, K. Aoki, P. Gubler, S.H. Lee, Phys. Rev. D **107**, 074033 (2023), 2211.16949
[26] H. Kim, P. Gubler, Phys. Lett. B **805**, 135412 (2020), 1911.08737