Phi meson properties in nuclear matter

Philipp Gubler
Japan Atomic Energy Agency (JAEA)

Work done in collaboration with
Elena Bratkovskaya (Frankfurt U./GSI)
HyungJoo Kim (APCTP/Yonsei U.)
Keisuke Ohtani (Tokyo Tech)

Talk at the “APCTP Focus Program in Nuclear Physics 2021 Part I: Hadron properties in a nuclear medium from the quark and gluon degrees of freedom”, online
July 15, 2021
$\phi$ meson

$m_\phi = 1019$ MeV

$\Gamma_\phi = 4.3$ MeV
Many theoretical works about the $\varphi$ meson at finite density in recent years

Spectral functions from hadronic models


Possibility of $\varphi$-nucleus bound state


Mass shift in nuclear matter from QCD sum rules


Previous experimental results

KEK E325

12 GeV pA-reaction

Pole mass:

\[ \frac{m_\phi(\rho)}{m_\phi(0)} = 1 - k_1 \frac{\rho}{\rho_0} \]

0.034 ± 0.007

Pole width:

\[ \frac{\Gamma_\phi(\rho)}{\Gamma_\phi(0)} = 1 + k_2 \frac{\rho}{\rho_0} \]

2.6 ± 1.5

To be measured again at the J-PARC E16 experiment with 100x increased statistics!

Recent experimental results
HADES: 1.7 GeV π-A-reaction

★ Larger suppression of K- in the Tungsten target compared to the Carbon target

★ K-/φ ratio is similar for both Tungsten and Carbon targets

★ Observation of large suppression (broadening?) of the φ meson in large nuclei

New experimental results
ALICE (Femtoscopy)

The observable to be measured: the correlation function:

\[
C(k) = N \frac{N_{\text{Same}}}{N_{\text{Mixed}}} = \int S(\vec{r}) |\Psi(\vec{k}, \vec{r})|^2 d^3 \vec{r}
\]

- Emission source (Gaussian)
- Relative momentum of the particle pair

S. Acharya et al. (ALICE Collaboration), arXiv:2105.05578 [nucl-ex].
New experimental results

ALICE

Measurement of $\phi N$ the correlation function

Information about the $\phi N$ scattering length

Real part:
$$\text{Re}(f_0) = 0.85 \pm 0.34\text{(stat.)} \pm 0.14\text{(syst.)}\text{ fm}$$
Attractive

Imaginary part:
$$\text{Im}(f_0) = 0.16 \pm 0.10\text{(stat.)} \pm 0.09\text{(syst.)}\text{ fm}$$
Small absorption?

S. Acharya et al. (ALICE Collaboration), arXiv:2105.05578 [nucl-ex].
New experimental results

ALICE

Fit of the correlation function data to two simple phenomenological potentials

\[
V_{\text{Yukawa}}(r) = -\frac{A}{r} e^{-\alpha r}
\]

\[A = 0.021 \pm 0.009 \text{ (stat.)} \pm 0.006 \text{ (syst.)} \]

\[\alpha = 65.9 \pm 38.0 \text{ (stat.)} \pm 17.5 \text{ (syst.) MeV} \]

\[
V_{\text{Gaussian}}(r) = -V_{\text{eff}} e^{-\mu r^2}
\]

\[V_{\text{eff.}} = 2.5 \pm 0.9 \text{ (stat.)} \pm 1.4 \text{ (syst.) MeV} \]

\[\mu = 0.14 \pm 0.06 \text{ (stat.)} \pm 0.09 \text{ (syst.) fm}^{-2} \]

\[
E_{\text{int}} = \int d^3\vec{r} \int d^3\vec{r}^\prime \rho_N(\vec{r}) V(\vec{r} - \vec{r}^\prime) \rho_\phi(\vec{r}^\prime)
\]

\[
\rho_0 \\
\delta^3(\vec{r}^\prime)
\]

\[
E_{\text{int}} = -\frac{4\pi A \rho_0}{\alpha^2} \\
= -79.3 \pm 108.8 \text{ MeV}
\]

\[
\bar{E}_{\text{int}} = -\frac{\pi^{3/2} V_{\text{eff}} \rho_0}{\mu^{3/2}} \\
= -45.2 \pm 61.5 \text{ MeV}
\]

Larger attraction than what was observed at KEK 325, but large statistical and systematic uncertainties

S. Acharya et al. (ALICE Collaboration), arXiv:2105.05578 [nucl-ex].
Recent results from theory
Results for the $\phi$ meson mass at rest (from QCD sum rules)

Most important parameter, that determines the behavior of the $\phi$ meson mass at finite density:

Strangeness content of the nucleon

$$\sigma_{sN} = m_s \langle N | \bar{s}s | N \rangle$$

$$\langle \bar{s}s \rangle_{\rho} = \langle \bar{s}s \rangle_0 + \langle N | \bar{s}s | N \rangle \rho + \ldots$$

What does lattice QCD say about $\sigma_s$?

http://flag.unibe.ch/2019/

See also the most recent results of the BMW collaboration: Sz. Borsanyi et al., arXiv:2007.03319 [hep-lat].
Compare Theory with Experiment

Not consistent?

Will be measured again with better statistics at the E16 experiment at J-PARC!

\[ \frac{m_\phi(0)}{m_\phi(0)} = 0.966 \pm 0.007 \]

\[ \sigma_{SN} \sim 160 \pm 50 \text{ MeV} \]
Effect of momentum

vector meson at rest in nuclear matter

spin direction does not change physics (rotational symmetry)

vector meson moving in nuclear matter

spin direction changes physics (broken rotational symmetry)
Results for the $\phi$ meson mass with non-zero momentum depends on 
\[
\langle N|\bar{s}s|N\rangle
\]
computed at normal nuclear matter density

caused by
\[
\langle N|S\mathcal{T}\gamma^\alpha iD^\beta s|N\rangle 
\]
\[
+ \langle N|S\mathcal{T}G^{a\alpha}_\mu G^{a\mu\beta}|N\rangle
\]

The angle-averaged di-lepton spectrum

The angle-averaged di-lepton spectrum

Momentum-dependent mass and width

Results of one-peak fits

How compare theory with experiment?

Realistic simulation of pA reaction is needed!
Our tool: a transport approach
PHSD (Parton Hadron String Dynamics)


Most important feature for our purposes:
Off-shell dynamics of vector mesons
(dynamical modification of the vector meson spectral
function during the simulated reaction)

Testparticle approach:

\[
\begin{align*}
\frac{d\bar{X}_i}{dt} &= \frac{1}{1-C(i)} \frac{1}{2\varepsilon_i} \left[ 2\bar{P}_i + \bar{\nabla} P_i \text{ Re } \Sigma_{i}^{\text{ret}} + \frac{\varepsilon_i^2 - \bar{P}_i^2 - M_0^2 - \text{ Re } \Sigma_{i}^{\text{ret}}}{\bar{\Gamma}_{i}} \bar{\nabla} P_i \bar{\Gamma}_{i} \right], \\
\frac{d\bar{P}_i}{dt} &= -\frac{1}{1-C(i)} \frac{1}{2\varepsilon_i} \left[ \bar{\nabla} X_i \text{ Re } \Sigma_{i}^{\text{ret}} + \frac{\varepsilon_i^2 - \bar{P}_i^2 - M_0^2 - \text{ Re } \Sigma_{i}^{\text{ret}}}{\bar{\Gamma}_{i}} \bar{\nabla} X_i \bar{\Gamma}_{i} \right], \\
\frac{d\varepsilon_i}{dt} &= \frac{1}{1-C(i)} \frac{1}{2\varepsilon_i} \left[ \frac{\partial}{\partial t} \text{ Re } \Sigma_{i}^{\text{ret}} + \frac{\varepsilon_i^2 - \bar{P}_i^2 - M_0^2 - \text{ Re } \Sigma_{i}^{\text{ret}}}{\bar{\Gamma}_{i}} \frac{\partial}{\partial t} \bar{\Gamma}_{i} \right],
\end{align*}
\]
Advantage: vector meson spectra can be chosen freely
Our choice: a Breit-Wigner with density dependent mass and width

\[
A_\phi(M, \rho) = C' \frac{2}{\pi} \frac{M^2 \Gamma_\phi^*(M, \rho)}{[M^2 - M_\phi^*(\rho)]^2 + M^2 \Gamma_\phi^*(M, \rho)}
\]

with

\[
\begin{align*}
M_\phi^*(\rho) &= M_\phi^{\text{vac}} \left( 1 - \alpha_\phi \frac{\rho}{\rho_0} \right), \\
\Gamma_\phi^*(M, \rho) &= \Gamma_\phi^{\text{vac}} + \alpha_{\text{coll}}^\phi \frac{\rho}{\rho_0}
\end{align*}
\]

Simulated scenarios:

\[
\begin{align*}
\delta M_\phi^*(\rho_0) &\text{[MeV]} \\
\Gamma_\phi^*(\rho_0) &\text{[MeV]}
\end{align*}
\]
What density does the $\phi$ feel in the reaction ($p+Cu/C$ at 12 GeV)?

Production

Decay
The dilepton spectrum in the $\phi$ meson region

$p + Cu$ at 12 GeV

No acceptance corrections!
No finite resolution effects!
Fits to experimental Copper target data (E325)

Favors relatively large negative mass shift!

Favors small mass shift!
Fits to experimental Copper target data (E325)

Confidence levels of combined Copper data

Conclusion of the E325 Collaboration
Fits to experimental Carbon target data (E325)

Confidence levels of combined Carbon data

$\pi + C$ at 12 GeV
Best fit to E325 data

(p + Cu at 12 GeV)

$\delta m_\phi(\rho_0) = -34 \text{ MeV}$

$\Gamma(\rho_0) = 4.3 \text{ MeV}$

slow $\varphi$s

intermediate $\varphi$s

fast $\varphi$s
Summary and Conclusions

★ A lot of new experimental information about the φN interaction is becoming available (HADES, LHC, J-PARC)

★ Studying the modification of the φ meson spectral function experimentally at finite density is non-trivial. A good understanding of the underlying reactions is needed!

★ Numerical simulations of the pA reactions to measured at the E325 experiment at KEK, using the PHSD transport code, are in progress.

Frist results indicate that the experimental data favor a **negative mass shift with none or only small broadening**!
Backup slides
The experimental situation

The E325 Experiment (KEK)

Slowly moving $\phi$ mesons are produced in 12 GeV $p+A$ reactions and are measured through di-leptons.

No effect (only vacuum)

$\phi$-meson

Our tool: a transport code
PHSD (Parton Hadron String Dynamics)


Example:
Au+Au collision at 200 GeV
b = 2 fm

nucleons
quarks
gluons
The importance of off-shell contributions

Only on-shell contributions: Vacuum spectral function are not recovered at late time of the reaction

Off-shell contributions included: correct behavior

What density does the \( \phi \) feel in the reaction (p+Cu/C at 12 GeV)?

### Production

- Cu target
- C target
- \( \phi \) mesons are on average created at a density significantly below \( \rho_0 \)

### Decay

- \( \phi \) mesons on average decay at a density significantly below \( \rho_0 \)

---

**Graphs:**

- **Production Graph:**
  - \( \delta m_\phi(p_0) = 0, \Gamma(p_0) = 4.3 \text{ MeV} \)
  - \( \delta m_\phi(p_0) = 0, \Gamma(p_0) = 59.3 \text{ MeV} \)
  - \( \delta m_\phi(p_0) = -68 \text{ MeV}, \Gamma(p_0) = 4.3 \text{ MeV} \)
  - \( \delta m_\phi(p_0) = -68 \text{ MeV}, \Gamma(p_0) = 59.3 \text{ MeV} \)

- **Decay Graph:**
  - Average \( \phi \) decay baryon density
The dilepton spectrum

$p+$Cu at 12 GeV

The $\phi$ meson peak is clearly visible.
The dilepton spectrum in the $\phi$ meson region

$p + \text{Cu at } 12 \text{ GeV}$

No acceptance corrections!

No finite resolution effects!
The dilepton spectrum in the $\varphi$ meson region

$p + Cu$ at 12 GeV

With acceptance corrections!

With finite resolution effects!
Final step: comparison to experimental data

Potential issues:

★ Experimental background is not included in the simulation

★ Normalization of the experimental dilepton spectrum is not given

Fit to experimental data is necessary!

Dilepton spectrum:

$$\rho(\omega) = a\omega^2 + b\omega + c + A\rho_{\phi, PHSD}(\omega)$$

Background

ϕ meson signal

Fitted to the experimental dilepton spectrum independently for each βγ-region
Experimental di-lepton spectrum

outside decay + inside decay = Experimentally observed spectrum
A first look at a reaction to be probed at J-PARC: pA collisions with initial proton energy of 30 GeV

A first look at the reaction: Rapidity distribution of protons/mesons

Due to the large collision energy, the incoming proton passes through the target nucleus

nucleon target after collision  projectile proton after collision
Recent theoretical works about the $\phi$ based on hadronic models

Forward $\bar{K}N$ (or KN) scattering amplitude

Recent theoretical works about the $\phi$

based on hadronic models

large dependence on details of the model incorporating Baryon - Vector meson interaction

SU(6): Spin-Flavor Symmetry extension of standard flavor SU(3)

HLS: Hidden Local Symmetry

Common features:

dstrong broadening, small negative mass shift

See also:
Recent theoretical works about the $\phi$ based on the quark-meson coupling model

Some $\phi A$ bound states might exist, but they have a large width → difficult to observe experimentally?
Our tool: a transport code
PHSD (Parton Hadron String Dynamics)


Basic Ingredient 1: Solve a Vlasov-Uehling-Uhlenbeck type equation for each particle type

\[
\left( \frac{\partial}{\partial t} + \frac{p_1}{m} \cdot \frac{\partial}{\partial r} - \frac{\partial}{\partial r} U_{\text{BHF}}(r; t) \cdot \frac{\partial}{\partial p_1} \right) f(r, p_1; t) = \left( \frac{\partial f}{\partial t} \right)_{\text{coll}}
\]

mean field
(tuned to reproduce nuclear matter properties)

particle distribution function

Basic Ingredient 2: „Testparticle“ approach

\[
f_h(r, p; t) = \frac{1}{N_{\text{test}}} \sum_i \frac{N_h(t) \times N_{\text{test}}}{N_{\text{test}}} \delta(r - r_i(t)) \delta(p - p_i(t))
\]
Structure of QCD sum rules for the phi meson

\[ \frac{1}{M^2} \int_0^\infty ds e^{-s/M^2} \rho(s) = c_0(\rho) + \frac{c_2(\rho)}{M^2} + \frac{c_4(\rho)}{M^4} + \frac{c_6(\rho)}{M^6} + \ldots \]

**In Vacuum**

**Dim. 0:** \[ c_0(0) = 1 + \frac{\alpha_s}{\pi} \]

**Dim. 2:** \[ c_2(0) = -6m_s^2 \]

**Dim. 4:** \[ c_4(0) = \frac{\pi^2}{3} \langle \frac{\alpha_s}{\pi} G^2 \rangle + 8\pi^2 m_s \langle \bar{s}s \rangle \]

**Dim. 6:** \[ c_6(0) = -\frac{448}{81} \kappa \pi^3 \alpha_s \langle \bar{s}s \rangle^2 \]
Structure of QCD sum rules for the phi meson

\[ \frac{1}{M^2} \int_0^\infty ds \, e^{-s/M^2} \rho(s) = c_0(\rho) + \frac{c_2(\rho)}{M^2} + \frac{c_4(\rho)}{M^4} + \frac{c_6(\rho)}{M^6} + \ldots \]

In Nuclear Matter

Dim. 0: \[ c_0(\rho) = c_0(0) \]

\[ \langle \bar{s}s \rangle_\rho = \langle \bar{s}s \rangle_0 + \langle N|\bar{s}s|N \rangle_\rho + \ldots \]

Dim. 2: \[ c_2(\rho) = c_2(0) \]

Dim. 4: \[ c_4(\rho) = c_4(0) + \rho \left[ -\frac{2}{27} M_N + \frac{56}{27} m_s \langle N|\bar{s}s|N \rangle \right. \\
\left. + \frac{4}{27} m_q \langle N|\bar{q}q|N \rangle + A_s^2 M_N - \frac{7}{12} \frac{\alpha_s}{\pi} A_s^g M_N \right] \]

Dim. 6: \[ c_6(\rho) = c_6(0) + \rho \left[ -\frac{896}{81} \kappa_N \pi^3 \alpha_s \langle \bar{s}s \rangle \langle N|\bar{s}s|N \rangle - \frac{5}{6} A_s^s M_N^3 \right] \]
The strangeness content of the nucleon: $\sigma_{sN} = m_s \langle N|\bar{s}s|N \rangle$

Important parameter for dark-matter searches!

Neutralino: Linear superposition of the Super-partners of the Higgs, the photon and the Z-boson

Adapted from:

\[ \sigma_{\text{nucleon}}^{\text{scalar}} = \frac{8G_F^2}{\pi} M_Z^2 m_\phi^2 \left[ \frac{F_h I_h}{m_h^2} + \frac{F_H I_H}{m_H^2} \frac{M_Z^2}{2} \sum_q \langle N|\bar{q}q|N \rangle \sum_i P_{q_i} (A_{q_i}^2 - B_{q_i}^2) \right]^2 \]

most important contribution dominates

\[ I_{h,H} = k_{u\text{-type}} H + k_{d\text{-type}} H \]

Adapted from:
Other experimental results

There are some more experimental results on the $\phi$-meson width in nuclear matter, based on the measurement of the transparency ratio $T$:

$$T = \frac{\sigma_{\gamma A \rightarrow \phi X}}{A \sigma_{\gamma N \rightarrow \phi X}}$$

Measured at SPring-8 (LEPS)

- $\Gamma_\phi(\rho_0) \simeq 30 \text{ MeV}$


Measured at COSY-ANKE

- $\Gamma_\phi(\rho_0) \simeq 27 \text{ MeV}$


Theoretical calculation:


Theoretical calculation:


Theoretical calculation: