The phi meson in nuclear matter from dilepton and $K^+K^-$ decays

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Based on work done in collaboration with
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and ongoing discussions with
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Contents

- Introduction: $\varphi$ meson in nuclear matter
- Transport Simulations of $pA$ reactions with density dependent vector meson spectral functions
- Measuring the $\varphi$ meson in nuclear matter: dilepton vs. $K^+K^-$ channels
- Considering electromagnetic and experimental rescattering effects on the dilepton spectra
Why should we be interested?

The $\varphi$ meson mass in nuclear matter probes the strange quark condensate at finite density!

| $\langle \bar{ss} \rangle_\rho$ | $\mathcal{M}_\varphi$ | $\sigma_N$ |


$|\langle \bar{ss} \rangle_\rho| = |\langle \bar{ss} \rangle_0| - \frac{\rho}{m_s} \sigma_{SN} + \ldots$
What does lattice QCD say about the strange sigma term?

\[ \sigma_{SN} = m_s \langle N | \bar{s}s | N \rangle \]

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

See also the most recent result of the BMW collaboration: Sz. Borsanyi et al., arXiv:2007.03319 [hep-lat].
Combine QCD sum rules with lattice QCD

No mass shift in nuclear matter ??

Previous experimental results

KEK E325

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

Measurement is being repeated with ~100x increased statistics at the J-PARC E16 experiment!

\[ \beta \gamma = \frac{|p|}{m_\phi} \]

More recent experiments

**HADES:** 1.7 GeV $\pi^-A$-reaction

$K^+K^-$ - invariant mass spectrum

**ALICE:** pp

Measurement of $\phiN$ correlation

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How compare theory with experiment?

Information useful for theory

- Spectral function as a function of density
- Mass at normal nuclear matter density
- Decay width at normal nuclear matter density

Experimental data

Realistic simulation of pA reaction is needed!
Our tool: transport simulation HSD (Hadron String Dynamics)


Off-shell dynamics of vector mesons and kaons is included  
(dynamical modification of the mesonic spectral function during the simulated reaction)

Testparticle approach:
Treatment of KN-interactions

Density dependent cross sections based on the chiral unitary model
(including coupled channels and s-/p-wave of $\bar{K}N$ interactions)

See talk by Taesoo Song
Advantage: vector meson spectra can be chosen freely

Our choice: a Breit-Wigner with density dependent mass and width

$$A_{\phi}(M, \rho) = C \frac{2}{\pi} \frac{M^2 \Gamma^*_{\phi}(M, \rho)}{[M^2 - M^*_{\phi}^2(\rho)]^2 + M^2 \Gamma^*_{\phi}^2(M, \rho)}$$

with

$$\begin{cases} 
M^*_{\phi}(\rho) = M^\text{vac}_{\phi} \left(1 - \alpha^\phi \frac{\rho}{\rho_0}\right), \\
\Gamma^*_{\phi}(M, \rho) = \Gamma^\text{vac}_{\phi} + \alpha^\phi_{\text{coll}} \frac{\rho}{\rho_0}
\end{cases}$$

Simulated scenarios:

- E325 result

$\delta M^*_{\phi}(\rho_0) [\text{MeV}]$

$\Gamma^*_{\phi}(\rho_0) [\text{MeV}]$
What density does the $\varphi$ feel in the reaction ($p+$Cu at 12 GeV)?

Majority of $\varphi$ mesons are produced at densities around $\rho_0$.

Majority of $\varphi$ mesons decay in free space (note the log-scale!).
What density does the $\varphi$ feel in different pA ($p+Cu$) reactions?

Larger densities are reached for larger incoming proton energy.

Majority of $\varphi$ mesons decay in free space (note the log-scale!)
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)

A significant negative mass shift is needed to reproduce the slow $\varphi$ data

Favors relatively large negative mass shift

No strong constraints for any modification scenario

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

Confidence levels of combined Copper data

Conclusion of the E325 Collaboration
Best fit to E325 data
(p + Cu at 12 GeV)

\[ \delta m_\phi (\rho_0) = -34 \text{ MeV} \quad \Gamma (\rho_0) = 4.3 \text{ MeV} \]

slow \( \phi \)s
intermediate \( \phi \)s
fast \( \phi \)s
What about the $K^+K^-$ decay channel?

(new J-PARC proposal P88)

Kaons feel the strong interaction
- Distorted in-medium $\phi$ meson signal
- Large branching ratio
- Good statistics

Kaons do not feel the strong interaction
- Clear in-medium $\phi$ meson signal
- Small branching ratio
- Bad statistics
Distortion of the in-medium $\phi$ meson signal in the $K^+K^-$ channel
($p + Cu$ at $30$ GeV)

Small distortion effect from the strong KN interaction !?
Absorption of kaons in nuclear matter

(p + Cu at 30 GeV)

Stronger absorption for lower momenta

Suppression due to repulsive K⁺N interaction??
Expected $K^+K^-$ invariant mass spectrum (incl. background)

$\text{p + Cu at 30 GeV}$

- No acceptance corrections!
- No finite resolution effects!

Is a sufficiently precise measurement possible?
What about other effects?

- Electromagnetic corrections to the dilepton spectrum?
- Rescattering effects of dileptons on experimental environment?

Detailed information about the experiment is needed
Evidence for in-medium modification of the φ meson at normal nuclear density

Ryotaro Muto

Old PhD Thesis from the early 2000s

Both effects contribute roughly equally

Rescattering effect
Evidence for in-medium modification of the $\phi$ meson at normal nuclear density

Ryotaro Muto

Old PhD Thesis from the early 2000s

$\beta\gamma$-dependence of electromagnetic + rescattering effects
How do the electro + rescattering effects change the fits (Cu target)?

Before

- Slow $\varphi$s
- Intermediate $\varphi$s: All allowed!
- Fast $\varphi$s

After
All $\beta\gamma$-regions combined (Cu target)

Before

After

No modification scenario favored??

![Graph showing mass shift vs. width for Cu target before and after modification with different confidence levels.](image-url)
How do the electro + rescattering effects change the fits (C target)?

Before

slow ϕs

All allowed!

intermediate ϕs

fast ϕs

After
All $\beta\gamma$-regions combined (C target)

Before

After

Small modification scenario favored?
New fits to experimental Copper target data (E325)

- **Slow $\varphi$s**
- **Intermediate $\varphi$s**
- **Fast $\varphi$s**
Possible solution?

Momentum dependent mass shift

Summary and Conclusions

- Relating modification of QCD condensates with hadron properties in nuclear matter is a non-trivial multi-step process.

  ![Diagram](QCD condensates <-> Hadronic spectrum <-> Experimental data)

- For studying the modification of the \( \phi \) meson spectral function experimentally at finite density, a good understanding of the underlying reactions is needed.

- We conducted numerical simulations of the \( pA \) reactions measured at the E325 experiment at KEK, using the HSD transport code.

  ![Diagram](Estimation of electromagnetic and rescattering effect is ongoing)

- New J-PARC proposal P88 to measure the \( \phi \) meson \( K^+K^- \) decay channel.

  ![Diagram](Distortion effects due to the strong KN interaction appears to be small)
Backup slides
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


\[
\sigma_{\text{nucleon}}^{\text{scalar}} = \frac{8G_F^2}{\pi} M_Z^2 m_h^2 \left( \frac{F_{H_h}}{m_h^2} + \frac{F_{H_H}}{m_H^2} \right) \frac{M_Z}{2} \sum_q \langle N | \bar{q}q | N \rangle \sum_i P_q \left( A_{q_i}^2 - B_{q_i}^2 \right) \]

most important contribution dominates

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

\[
g_d = \frac{2}{27} \left( m_N + \frac{23}{4} \sigma_{\pi N} + \frac{25}{2} \sigma_{SN} \right)
\]

Structure of QCD sum rules for the $\phi$ meson channel

(after application of the Borel transform)

$$\chi(x) = \bar{s}(x)\gamma_\mu s(x)$$

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

In Vacuum

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

Dim. 2: \quad c_2(0) = -6m_s^2

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

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

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

At finite density

(lexical with the linear density approximation)

\[
\langle \bar{s}s \rangle_\rho = \langle 0 | \bar{s}s | 0 \rangle + \langle N | \bar{s}s | N \rangle \rho + \ldots
\]

Dim. 0: \quad c_0(\rho) = c_0(0)

Dim. 2: \quad c_2(\rho) = c_2(0)

Dim. 4: \quad 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 + \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_2^q M_N \right]

Dim. 6: \quad 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^4 M_N^3 \right]
Results for the $\phi$ meson mass at rest

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

Strangeness content of the nucleon

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

Recent experimental results

HADES: 1.7 GeV $\pi^{-}A$-reaction

- Larger suppression of $K^{-}$ in the Tungsten target compared to the Carbon target
- $K^{-}/\phi$ ratio is similar for both Tungsten and Carbon targets
- Observation of large suppression (broadening?) of the $\phi$ meson in large nuclei

New experimental results

ALICE (Femtoscopy)

The observable to be measured: the correlation function:

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

Emission source (Gaussian)
Relative momentum of the particle pair

New experimental results
ALICE

Measurement of $\phi N$ correlation

Extracted $\phi N$ 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/broadening?

New experimental results

ALICE

Fit of the correlation function data to two simple phenomenological potentials

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

\[ A = 0.021 \pm 0.009 \text{ (stat.)} \pm 0.006 \text{ (syst.)} \]
\[ \alpha = 65.9 \pm 38.0 \text{ (stat.)} \pm 17.5 \text{ (syst.) MeV} \]

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

\[ V_{\text{eff.}} = 2.5 \pm 0.9 \text{ (stat.)} \pm 1.4 \text{ (syst.) MeV} \]
\[ \mu = 0.14 \pm 0.06 \text{ (stat.)} \pm 0.09 \text{ (syst.) fm}^{-2} \]

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

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

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

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].
Our tool: a transport approach

Basic Ingredient 1: Solve a Boltzmann-Uehling-Uhlenbeck (BUU) type equation for each particle type

\[ \left( \frac{\partial}{\partial t} + \vec{v}_p \cdot \nabla_r - \vec{v}_r \cdot \nabla_p \right) f_a(\vec{r}, \vec{p}; t) = I_{\text{coll}}[f_a(\vec{r}, \vec{p}; t)] \]

Includes mean field (tuned to reproduce nuclear matter properties)

Basic Ingredient 2: "Testparticle" approach

\[ f_h(r, p; t) = \frac{1}{N_{\text{test}}} \sum_i N_h(t) \delta(r - r_i(t)) \delta(p - p_i(t)) \]
Example of a transport calculation

Au+Au collision at $s^{1/2} = 200$ GeV, $b = 2$ fm

nucleons
quarks
gluons

will not be included in the simulations shown in this talk
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:

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

- Background
- $\phi$ meson signal

Fitted to the experimental dilepton spectrum independently for each $\beta\gamma$-region
Reason for large modification for fast $\phi$ mesons

Initial stage of $\phi$ meson production

$\phi$ mesons are generated from high energy collisions (via strings)

- large momentum
- high density

$\phi$ mesons are generated from low energy hadronic collisions

- small momentum
- low density
Density and $\beta\gamma$ distributions for the different production mechanisms

Density distribution at production

Low energy hadronic production occurs dominantly at the nuclear surface

$\beta\gamma$ distribution at production

For $\beta\gamma > 1.5$, high energy $\phi$ meson production via strings dominates