Simulating pA reactions to study the phi meson in nuclear matter at J-PARC

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Work done in collaboration with
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φ meson

\[ m_\phi = 1019 \text{ MeV} \]
\[ \Gamma_\phi = 4.3 \text{ MeV} \]
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:

strong 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?
φ meson mass at finite density from QCD sum rules

Most important parameter, that determines the behavior of the φ meson mass at finite density:

Strangeness content of the nucleon

\[ \sigma_{sN} = m_s \langle N | \bar{s}s | N \rangle \]
Vector mesons in experiment

One method: proton induced interactions on nuclei

- low (zero?) temperature
- no strong interaction
- no distortion of signal due to interaction with nuclear medium

- approximate density: normal nuclear density $\rho_0$

E325 (KEK)
E16 (J-PARC)
However, some caution is needed

Non-trivial non-equilibrium process??

large probability of vector meson decay outside of the nucleus

density much below $\rho_0$
Experimental di-lepton spectrum

outside decay + inside decay = Experimentally observed spectrum

di-electron invariant mass
Experimental results
(E325, KEK)

Pole mass:
\[ \frac{m_\phi(\rho)}{m_\phi(0)} = 1 - k_1 \frac{\rho}{\rho_0} \]
\[ 0.034 \pm 0.007 \]

Pole width:
\[ \frac{\Gamma_\phi(\rho)}{\Gamma_\phi(0)} = 1 + k_2 \frac{\rho}{\rho_0} \]
\[ 2.6 \pm 1.5 \]

How compare theory with experiment?

Theory

Experiment

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


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

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

mean field (tuned to reproduce nuclear matter properties)
particle distribution function

Basic Ingredient 2: „Testparticle“ approach

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

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

nucleons
quarks
 gluons
Example of a PHSD calculation

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Advantage: vector meson spectra can be chosen freely

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

\[ A_V(M, \rho_N) = C \frac{2}{\pi} \frac{M^2 \Gamma^*_V(M, \rho_N)}{(M^2 - M_0^*(\rho_N))^2 + M^2 \Gamma^*_V(M, \rho_N)} \]

with

\[ M_0^*(\rho_N) = M_0 \left(1 - \alpha \frac{\rho_N}{\rho_0} \right) \]

\[ \Gamma^*_V(M, \rho_N) = \Gamma_V(M) + \alpha_{\text{coll}} \frac{\rho_N}{\rho_0} \]

and

\[ \alpha^\phi = 0.034, \]
\[ \alpha_{\text{coll}}^\phi = 11 \text{ MeV} \]

(corresponds to the result found in the E325 experiment)
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

Preliminary

pA reaction with 30 GeV protons
A: Copper

Average of 400 simulated reactions

nucleon target after collision
projectile proton after collision
A first look at a reaction to be probed at J-PARC:
pA collisions with initial proton energy of 30 GeV

Due to the large collision energy, the incoming proton passes through the target nucleus.
What happens with the $\phi$?

Production

$p + Cu$ at 12 GeV

Almost all $\phi$ mesons are created at early collision time and at large density

Decay

$p + Cu$ at 12 GeV

Only $\phi$ mesons which decay early, decay in a dense environment
The dilepton spectrum

p+Cu at 12 GeV

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

$p+Cu$ at 12 GeV

no acceptance corrections
no finite resolution effects
The dilepton spectrum in the $\varphi$ meson region

$\rho$+Cu at 12 GeV

Preliminary
Discriminate between different $\beta \gamma$ regions

$p+Cu$ at 12 GeV

with acceptance corrections

with finite resolution effects
To be done

★ Accumulate more statistics

★ Determine which spectral function best reproduces the E325 experimental data (might not be unique)

★ Make predictions for the E16 experiment at J-PARC

★ Incorporate non-trivial (Lorentz violating) momentum dependence of the spectral function into the simulation
Summary and Conclusions

★ To experimentally the modification of the $\phi$ meson spectral function at finite density is non-trivial. A good understanding of the underlying pA reaction is needed!

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

★ Results will provide important insights for the future E16 experiment at J-PARC
Backup slides
Our tool: a transport code
PHSD (Parton Hadron String Dynamics)


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

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

- mean field (tuned to reproduce nuclear matter properties)
- particle distribution function

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

Makes use of the analytic properties of the correlation function:

\[ \Pi(q^2) = i \int d^4 x e^{i q x} \langle T[\chi(x)\bar{\chi}(0)] \rangle \]

After the Borel transformation:

\[ M.A. \text{ Shifman, A.I. Vainshtein and V.I. Zakharov,} \]
\[ \text{Nucl. Phys. B147, 385 (1979); B147, 448 (1979).} \]
More on the operator product expansion (OPE)

\[ i \int d^4x e^{iqx} \langle 0 | T \{ \chi(x) \bar{\chi}(0) \} | 0 \rangle = C_I(q^2)I + \sum_n C_n(q^2) \langle 0 | O_n | 0 \rangle \]

\[ \langle 0 | O_n | 0 \rangle = \langle 0 | \bar{q}q | 0 \rangle, \]
\[ \quad \langle 0 | G^{a}_{\mu\nu} G^{a}_{\mu\nu} | 0 \rangle, \]
\[ \quad \langle 0 | \bar{q} \sigma_{\mu\nu} \frac{\lambda^a}{2} G^{a}_{\mu\nu} q | 0 \rangle, \]
\[ \quad \langle 0 | \bar{q} q \bar{q} q | 0 \rangle, \ldots \]

Change in hot or dense matter!
Structure of QCD sum rules for the phi meson

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

In Vacuum

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

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

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

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:**
\[ c_4(\rho) = c_4(0) + \rho\left[ -\frac{2}{27} M_N + \frac{56}{27} m_s \langle N|\bar{s}s|N \rangle \right. \]
\[ + \frac{4}{27} m_q \langle N|\bar{q}q|N \rangle + A_2^s M_N - \frac{7}{12} \frac{\alpha_s}{\pi} A_2^g M_N \]

**Dim. 6:**
\[ c_6(\rho) = c_6(0) + \rho\left[ -\frac{896}{81} \kappa_N \pi^3 \alpha_s \langle \bar{s}s \rangle \langle N|\bar{s}s|N \rangle - \frac{5}{6} A_4^s M_N^3 \right] \]
The strangeness content of the nucleon: results from lattice QCD

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

**Two methods**

- **Direct measurement**

  \[ \sigma_{sN} = m_s \frac{\partial m_N}{\partial m_s} \]

- **Feynman-Hellmann theorem**


Recent results from lattice QCD

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

Table 5: Recent \(\sigma_{sN}\) values from lattice QCD and ChPT fits to lattice QCD data.

<table>
<thead>
<tr>
<th>Method</th>
<th>Collaboration, Year</th>
<th>(\sigma_{sN}) [MeV]</th>
<th>Reference</th>
</tr>
</thead>
<tbody>
<tr>
<td>Lattice QCD (Feynman-Hellmann)</td>
<td>BMW, 2016</td>
<td>105(41)(37)</td>
<td>[121]</td>
</tr>
<tr>
<td>Lattice QCD (direct)</td>
<td>(\chi)QCD, 2016</td>
<td>40.2(11.7)(3.5)</td>
<td>[122]</td>
</tr>
<tr>
<td>Lattice QCD (direct)</td>
<td>ETM, 2016</td>
<td>41.1(8.2)(7.8)</td>
<td>[123]</td>
</tr>
<tr>
<td>Lattice QCD (direct)</td>
<td>RQCD, 2016</td>
<td>35(12)</td>
<td>[124]</td>
</tr>
<tr>
<td>Lattice QCD (direct)</td>
<td>JLQCD, 2018</td>
<td>17(18)(9)</td>
<td>[125]</td>
</tr>
<tr>
<td>Lattice QCD data + ChPT</td>
<td>2012</td>
<td>22(20)</td>
<td>[126]</td>
</tr>
<tr>
<td>Lattice QCD data + ChPT</td>
<td>2013</td>
<td>21(6)</td>
<td>[128]</td>
</tr>
<tr>
<td>Lattice QCD data + ChPT</td>
<td>2015</td>
<td>27(27)(4)</td>
<td>[130]</td>
</tr>
</tbody>
</table>

Compare Theory with Experiment

Not consistent?

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

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

$$\sigma_{SN} \sim 160 \pm 50 \text{ MeV}$$
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 $T$:

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

Measured at SPring-8 (LEPS)


Measured at COSY-ANKE


Theoretical calculation:


Theoretical calculation:

Starting point

\[ \Pi_{\mu\nu}(q) = i \int d^4x e^{iqx} \langle T[j_\mu(x)j_\nu(0)] \rangle_\rho \]

\[ j_\mu(x) = \frac{1}{3} \bar{s}(x) \gamma_\mu s(x) \]

Rewrite using hadronic degrees of freedom (vector dominance model)

\[ \Pi(q^2) = \frac{1}{3q^2} \Pi^\mu(\mu) \]

\[ \text{Im}\Pi(q^2) = \frac{\text{Im}\Pi_\phi(q^2)}{q^2 g^2_\phi} \left| \frac{(1-a_\phi)q^2 - \tilde{m}^2_\phi}{q^2 - \tilde{m}^2_\phi - \Pi_\phi(q^2)} \right|^2 \]

\[ \text{Kaon loops} \]
Vacuum spectrum

\[
\frac{\sigma(e^+e^- \rightarrow K^+K^-)}{\sigma(e^+e^- \rightarrow \mu^+\mu^-)}
\]  
(Vacuum)

How is this spectrum modified in nuclear matter?

Is the (modified) spectral function consistent with QCD sum rules?

Data from

More on the free KN and $\bar{K}N$ scattering amplitudes

For KN: Approximate by a real constant ($\leftrightarrow$ repulsion)


For $\bar{K}N$: Use the latest fit based on SU(3) chiral effective field theory, coupled channels and recent experimental results ($\leftrightarrow$ attraction)


K-p scattering length obtained from kaonic hydrogen (SIDDHARTA Collaboration)
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 Superpartners of the Higgs, the photon and the Z-boson

Adapted from:

In-nucleus decay fractions for E325 kinematics

<table>
<thead>
<tr>
<th></th>
<th>C (%)</th>
<th>Cu (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\rho$</td>
<td>46</td>
<td>61</td>
</tr>
<tr>
<td>$\omega$</td>
<td>5</td>
<td>9</td>
</tr>
<tr>
<td>$\phi$</td>
<td>$6^a$</td>
<td></td>
</tr>
</tbody>
</table>

$^a$For slow $\phi$ mesons with $\beta\gamma<1.25$.

Taken from: R.S. Hayano and T. Hatsuda, Rev. Mod. Phys. 82, 2949 (2010).