ϕ mesons in cold nuclear matter with resonant ϕN interactions

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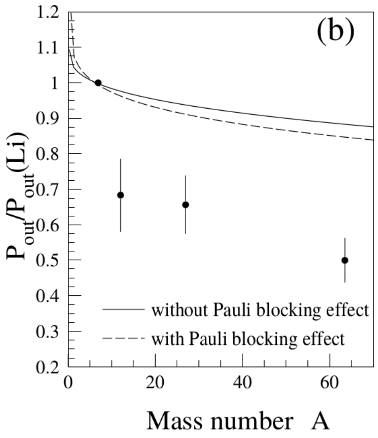
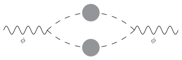
Motivation

LEPS photoproduction

$\phi \to K^+K^-$ Ishikawa et al., PLB 608 (2005) 215



- Experimental observation of the ϕ in-medium transparency much lower than theoretical predictions.



Cabrera et al., NPA 733 (2004) 130

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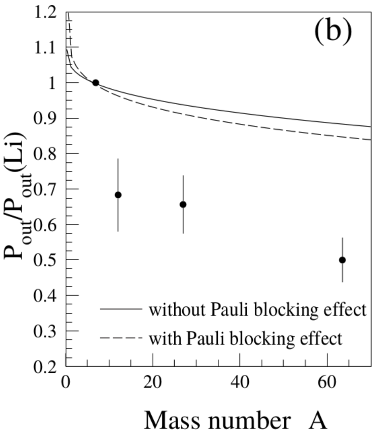

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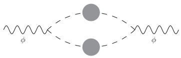


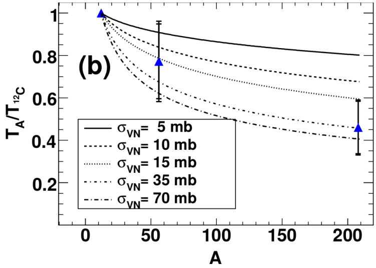
Cabrera et al., NPA 733 (2004) 130

- Additional mechanisms needed.

ϕ nuclear transparency ratio

CLAS photoproduction

$\phi \rightarrow e^+e^-$ Wood et al., PRL 105 (2010) 112301

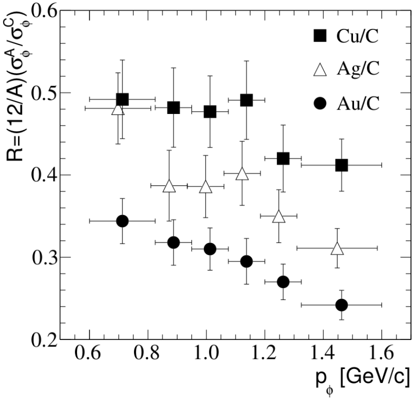


- The higher the atomic mass, the lower the transparency.
- This corresponds to Glauber calculations with ever growing cross sections.
- High in-medium absorption effects!

Momentum dependence

COSY-ANKE@Jülich $p\ A$ collisions

$\phi \to K^+K^-$ Hartmann et al., PRC 85 (2012) 035206

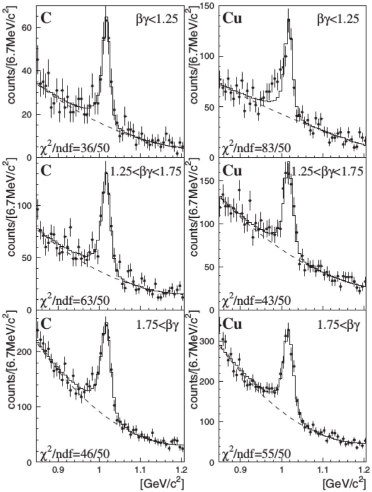


- Recent results with momentum binning!
- The transparency ratio decreases with momentum.

Invariant mass distribution

KEK-PS-E325 $p\ A$ collisions

$\phi \to e^+e^-$ Muto et al., PRL 98 (2007) 042501



- For small velocities a shoulder appears to the left of the peak.
- Possible explanation: in-medium mass shift and some broadening!
- Fits with these assumptions reproduce data well.

Summary of photoproduction and proton collision

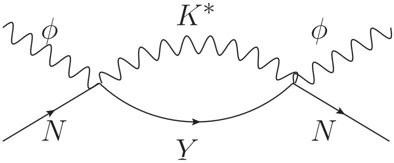
- Large absorption in nuclei — widths one order of magnitude higher than dominant decay in vacuum: $15 \sim 100\ \mathrm{MeV}$.
- Small in-medium mass shift.
- Medium effects larger than predicted by theoretical models from in-medium decay to $\bar{K}\ K$. (In vacuum 83% of the contribution.)

Vector mesons in nuclear medium

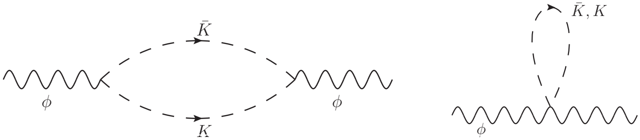
- ρ, ω and ϕ decay into l^+l^- and photons:
  No strong interaction $\Rightarrow$ probes with little distortion!
- The in-medium dynamics of ϕ is strongly connected to K and $\bar{K}$: Good probe of chiral dynamics, exotic atoms and properties of compact stellar objects
- In-medium properties of vector mesons in recent HICs:
  BES at RHIC Blume and Markert, PPNP 66 (2011) 834
  HADES at GSI Agakishiev et al., EPJA 49 (2013) 34
  ALICE at LHC Abelev et al., PRC 91 (2015) 024609
- Recent measurement shows deep sub-threshold ϕ production:
  $1.23\mathrm{AGeV}$ Au+Au collisions Lorenz et al., NPA 931 (2014) 785
  Missing mechanisms (ϕ production reactions, broadening, mass shift)

Further mechanisms explored in this work

- Direct coupling to nucleon: OZI forbidden! Highly suppressed.
- BUT! ϕ N interactions via hyperon loops have been studied: generation of resonances close to threshold!
- **In this work we include these channels.**



Previously done: ϕ self-energy from $\phi \to \bar{K}K$ decay



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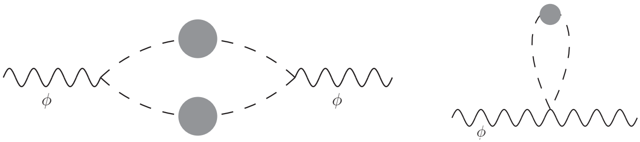

- The kaon propagators have to be dressed.

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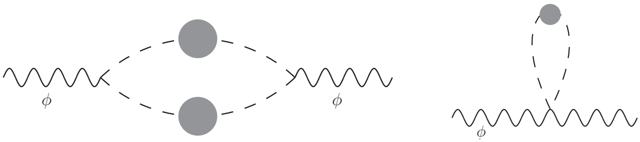
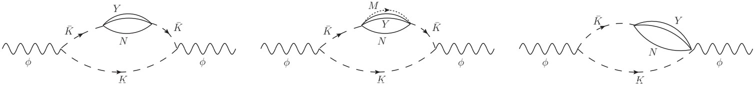
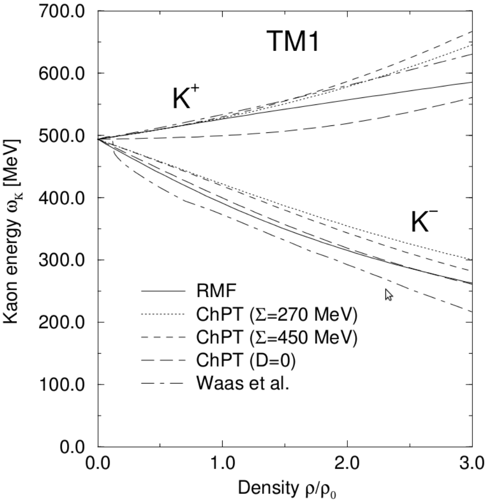


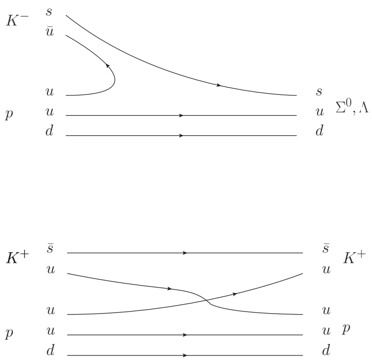
- The kaon propagators have to be dressed.
- The $\bar{K}YN(M)$ $P(S)$-wave couplings have to be considered.
- Recourse to $SU(3)$ meson-baryon ChPT.



Ko et al., PRC 45 (1992) 1400
Kuwabara and Hatsuda, PTP 94 (1995) 1163
Klingl et al., NPA 624 (1997) 527
Klingl et al., PLB 431 (1998) 254
Oset and Ramos, NPA 679 (2001) 616
Oset et al., PLB 508 (2001) 237
Alvarez-Ruso and Koch, PRC 65 (2002) 054901
Cabrera and Vicente Vacas, PRC 67 (2003) 045203
Cabrera et al., NPA 733 (2004) 130

In-medium splitting of kaon properties





Schaffner et al., NPA 625 (1997) 325

Theoretical status of in-medium kaons

- s-wave interaction relevant at low energies.
  - K N smooth, mild repulsion at normal density.
  - $\bar{K}$ N strongly dominated by sub-threshold $\Lambda(1405)$: attraction and broadening.
- higher waves at higher energies: $\bar{K}$ $N \to Y$ excitations.

Lutz, PLB426 (1998) 12
Ramos and Oset, NPA671 (2000) 481
Tolos et al., NPA690 (2001) 547
Tolos et al., PRC74 (2006) 015203
Lutz et al., NPA808 (2008) 124
Tolos et al., PRC78 (2008) 045205
Lutz et al., NPA808 (2008) 124
Tolos et al., PRC78 (2008) 045205
Cabrera et al., PRC 90 (2014) no.5 055207

The $\phi \to \bar{K}K$ self-energy

$$\Pi_\phi^{K\bar{K}}(q) =$$

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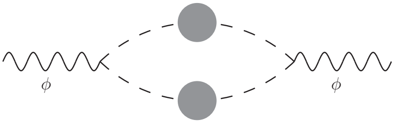
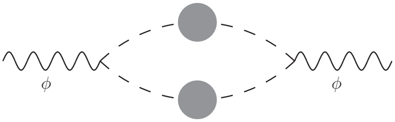


$$\Pi_{\phi}^{K\bar{K}}(q) = 2\mathrm{i}g_{\phi}^{2}\frac{4}{3}\int\frac{\mathrm{d}^4k}{(2\pi)^4}\left[\frac{(q\cdot k)^2}{q^2} - k^2\right] D_K(q-k)D_{\bar{K}}(k)$$

The $\phi \to \bar{K}K$ self-energy



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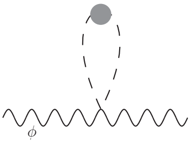
$$-2\mathrm{i}g_\phi^2 \int \frac{\mathrm{d}^4 k}{(2\pi)^4} \left[D_K(k) + D_{\bar{K}}(k)\right]$$



In-medium kaon propagator and spectral function

Dressed propagator

$$D_{\bar{K}(K)}(q^0, \vec{q}; \rho) = \int_0^\infty \mathrm{d}\omega \left(\frac{S_{\bar{K}(K)}(\omega, \vec{q}; \rho)}{q^0 - \omega + \mathrm{i}\eta} - \frac{S_{K(\bar{K})}(\omega, \vec{q}; \rho)}{q^0 + \omega - \mathrm{i}\eta} \right)$$

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Spectral function

$$S_{\bar{K}(K)}(q^0,\vec{q};\rho) = -\frac{1}{\pi} \frac{\mathrm{Im}\Pi_{\bar{K}(K)}(q^0,\vec{q};\rho)}{|(q^0)^2-\vec{q}^2-m_K^2-\Pi_{\bar{K}(K)}(q^0,\vec{q};\rho)|^2}$$

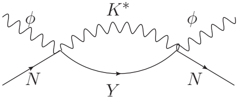
In-medium ϕ self-energy from ϕB interactions

New work

In-medium ϕ self-energy from ϕ B interactions

New work

- Additional contribution to ϕ self-energy from direct interactions with baryons.



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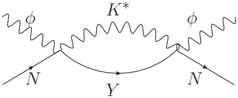
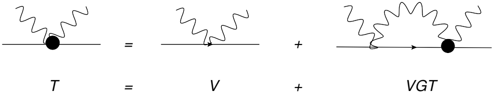


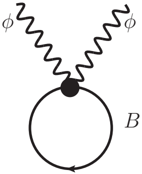
- Comparing two unitarized coupled-channel models:
  - HLS formalism. Oset and Ramos, EPJA 44 (2010) 445
    Vector-meson exchange dominates interactions with baryons.
  - $SU(6)$ spin-flavor symmetry extension of the chiral Lagrangian.
    Romanets et al., PRD 85 (2012) 114032



Contribution from resonant meson-baryon interaction

N^* resonances are generated directly above $\phi\ N$ threshold
$\sqrt{s_{\phi\ N}} \sim 2 - 2.1\ \mathrm{GeV}$.
For $SU(6)$ non-degenerate in $J^P = 1/2^-, 3/2^-$!

ϕ self-energy contribution $\Pi_\phi^{\phi N} = \int \frac{\mathrm{d}^3 p}{(2\pi)^3} n(\vec{p})\, T_{\phi N}$ ✓ Fermi motion



Medium modifications on ϕ N scattering amplitude

Additionally included in this work

✓ Pauli blocking (affects only nucleons)

Reminder! $T = V + VGT$

$$\delta G^{\text{Pauli}}(P,\rho) = -\int \frac{\mathrm{d}^3 q}{(2\pi^3)} \frac{M_N}{E_N(\vec{p})} \frac{n(\vec{p})}{[P^0 - E_N(\vec{p})]^2 - \omega_\phi^2(\vec{q}) + \mathrm{i}\epsilon}\Big|_{\vec{p}=\vec{P}-\vec{q}}$$

Future work

✗ Baryon binding potentials

✗ Self-consistency: dressing of ϕ propagator in ϕN loop

Calculated quantities

ϕ nuclear optical potential

$$V_{\text{opt}} = \frac{\Pi_\phi}{2\omega}$$

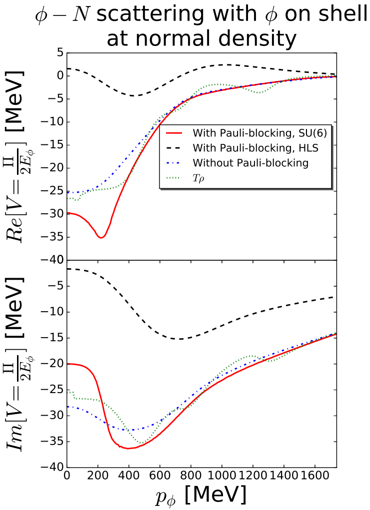
$$\text{Re}(V_{\text{opt}}) \sim \text{mass shift}$$

$$\text{Im}(V_{\text{opt}}) \sim \text{width enhancement}$$

Spectral function

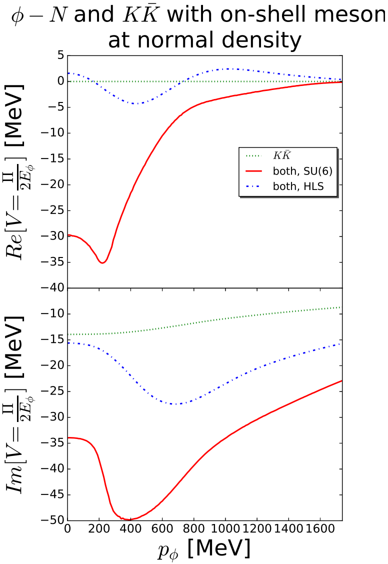
$$S(\omega, \vec{q}) = -\frac{1}{\pi} \frac{\text{Im}\Pi_\phi(\omega, \vec{q})}{|\omega^2 - \vec{q}^2 - m_\phi^2 - \Pi_\phi(\omega, \vec{q})|^2}$$

ϕ optical potential: ϕ N contribution



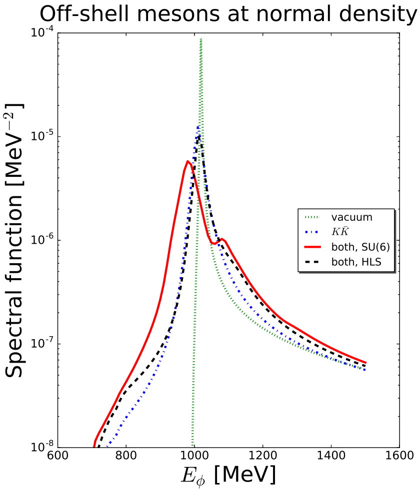
- ϕ N interaction induces an attractive potential.
- Considerable energy dependence due to resonant states above threshold.
- The T ρ approximation smoothens when including fermi motion.

ϕ optical potential: $\phi\ N + \bar{K}K$



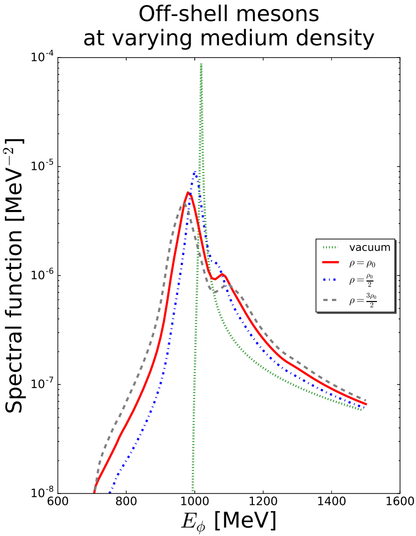
- The contributions from $\phi\ N$ interactions appear to be **larger** than those from $\bar{K}\ K$!
- Widths up to ~ 70 MeV at $\rho = \rho_0$ for ϕ mesons at rest.

Spectral function



- Broadening of the vacuum spectral function due to $K\bar{K}$ cloud, with vanishing mass shift.
- Further broadening due to ϕN interaction, new structure.
- Negative mass shift in $SU(6)$ model.
- Second shoulder above the ϕ mass — excitation of $N^* N^{-1}$ modes.

Spectral function at different matter densities



Evolution with density:

- Shift of the peak to lower ϕ energies with rising medium density.
- Further broadening.

Summary and outlook

- Resonant ϕN **interactions** are implemented as **novel mechanisms** of ϕ in-medium properties.
- Strength similar to $K\bar{K}$-cloud effects (or even stronger).
- N^*-like states are generated immediately above ϕN threshold.
- **Large ϕ broadening in line with recent nuclear production experiments.**

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- Baryon binding potentials.
- Finite temperature effects: heavy-ion collisions.
- Evaluation of transparency ratio with updated ϕ self-energy.

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ありがとう　ございます!