"Medium Modification of Light Vector Mesons in Nuclei"

C. Djalali (USC), M. Wood (Canesius College), R. Nasseripour (GWU), D. P. Weygand (JLab) and CLAS Collaboration

- Physics Motivations
  - Why study in medium hadrons?
  - Models and Predictions
- Some key experiments
- Photo-production of vector mesons at JLab
  - $\rho$ meson mass spectra
  - $\omega$ and $\phi$ absorption
- Summary and Outlook on Medium Modifications
The study of medium modifications of hadrons has a long history in hadronic physics. Widespread theoretical and experimental work.

- The spontaneous breaking of Chiral Symmetry in vacuum is at the origin of 98% of the mass of hadrons.

- The properties of hadrons (“excitations of the QCD vacuum”) depend on these condensates.

- Changes in the medium of the properties of hadrons may signal:
  - Chiral symmetry restoration
  - Exotic state of matter, …

As $< 0 | q \bar{q} | 0 > \Rightarrow 0$, Restoration of chiral symmetry.

Mass, decay, coupling constants will change.
Model predictions of the in medium properties of vector mesons

Bernard and Meissner, NPA 489 (1988) 647

Scale invariance in effective Lagrangian:

\[ \frac{m_V^*}{m_V} = \frac{m_N^*}{m_N} = \frac{f_{\pi}^*}{f_{\pi}} \approx 0.8 \quad \text{at } \rho_0 \]


QCD sumrules:

\[ \frac{m_V^*}{m_V} = 1 - \alpha \frac{\rho_B}{\rho_0} \quad \alpha \approx 0.16 \pm 0.06 \]


Many body effects:


Hatsuda & Lee

 rho meson: }
Medium modification of vector mesons properties in nuclei

The predicted medium modifications are large enough that even at normal nuclear density, one can expect to observe them, so:
• Vector mesons can be produced in nuclei with probes that leave the nucleus in almost an equilibrium state $\gamma, \pi, \rho$
• $(\text{probe}) + A \rightarrow V X \rightarrow e^+e^- X$ (no FSI)

<table>
<thead>
<tr>
<th>Vector mesons</th>
<th>$\rho$:</th>
<th>$M=768$ MeV</th>
<th>$\Gamma = 149$ MeV</th>
<th>$c\tau \sim 1.3$ fm</th>
</tr>
</thead>
<tbody>
<tr>
<td>$J^P=1^-$</td>
<td>$\omega$:</td>
<td>$M=782$ MeV</td>
<td>$\Gamma = 8$ MeV</td>
<td>$c\tau \sim 23.4$ fm</td>
</tr>
<tr>
<td></td>
<td>$\phi$:</td>
<td>$M=1020$ MeV</td>
<td>$\Gamma = 4$ MeV</td>
<td>$c\tau \sim 44.4$ fm</td>
</tr>
</tbody>
</table>

Need very low $p$

C. Djalali  Nov 13, 2008
### Elementary reactions  
*(not exhaustive list):*

<table>
<thead>
<tr>
<th>Experiment</th>
<th>Reactions</th>
<th>Results</th>
</tr>
</thead>
<tbody>
<tr>
<td>TAGX</td>
<td>$\gamma + ^3\text{He} \rightarrow \rho + X \ (\rho \rightarrow \pi^+\pi^-)$</td>
<td>full BR, $\alpha \sim 0.06$</td>
</tr>
<tr>
<td>KEK</td>
<td>$p+A \rightarrow \rho,\omega,\phi + X \ (\rho,\omega \rightarrow e^+e^-)$</td>
<td>$\alpha = 0.092 \pm 0.002$</td>
</tr>
<tr>
<td>KEK</td>
<td>$p+A \rightarrow \phi + X \ (\phi \rightarrow e^+e^-)$</td>
<td>$\alpha \sim 0.04$</td>
</tr>
<tr>
<td>SPring-8</td>
<td>$\gamma + A \rightarrow \phi + A^* \ (\phi \rightarrow K^+K^-)$</td>
<td>no effect</td>
</tr>
<tr>
<td>TAPS</td>
<td>$\gamma + A \rightarrow \omega + X \ (\omega \rightarrow \pi^0 \gamma)$</td>
<td>$\alpha \sim 0.13-015$ (?)</td>
</tr>
<tr>
<td>JLab-g7a</td>
<td>$\gamma + A \rightarrow (\rho,\omega,\phi) + A^* \ (\text{VM} \rightarrow e^+e^-)$</td>
<td>$\alpha = 0.02 \pm 0.02$</td>
</tr>
<tr>
<td>JPARC</td>
<td>$p+A \rightarrow \rho,\omega,\phi + X \ (\rho,\omega,\phi \rightarrow e^+e^-)$</td>
<td>proposal #16</td>
</tr>
<tr>
<td>HADES</td>
<td>$p+p,d \rightarrow \rho,\omega,\phi + X \ (\rho,\omega,\phi \rightarrow e^+e^-)$</td>
<td>(running)</td>
</tr>
</tbody>
</table>

*Only g7 with EM interaction in entrance and exit channels*

*TAGX, Spring8 and TAPS have hadronic FSI.*
## Experimental Results

### Elementary Reactions

<table>
<thead>
<tr>
<th>KEK</th>
<th>CBELSA/TAPS</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Reaction</strong></td>
<td><strong>Condition</strong></td>
</tr>
<tr>
<td>$pA \rightarrow (\rho,\omega,\phi)A'$</td>
<td>$\rho=0.53\rho_0$, $T\sim 0$ MeV</td>
</tr>
<tr>
<td>$VM \rightarrow e^+e^-$</td>
<td>$\rho=0.55\rho_0$, $T\sim 0$ MeV</td>
</tr>
<tr>
<td><strong>Mass</strong></td>
<td><strong>Width</strong></td>
</tr>
<tr>
<td>$\Delta m_{\rho} \sim -9%$</td>
<td>$\Delta \Gamma_{\rho} = 0$ MeV</td>
</tr>
<tr>
<td>$\Delta m_{\omega} \sim -4%$</td>
<td>$\Gamma_{\phi}(\rho=\rho_0) = 47$ MeV</td>
</tr>
<tr>
<td><strong>Note</strong></td>
<td><strong>Experimental Results</strong></td>
</tr>
<tr>
<td>No direct extraction of $\rho$ meson (BKGD)</td>
<td>$\pi^0$ FSI</td>
</tr>
<tr>
<td></td>
<td>Large background</td>
</tr>
</tbody>
</table>

### Rel. Heavy-Ion

<table>
<thead>
<tr>
<th>CERES</th>
<th>NA 60</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Reaction</strong></td>
<td><strong>Condition</strong></td>
</tr>
<tr>
<td>$p+Au, Pb+Au$</td>
<td>$\rho=0.55\rho_0$, $T\sim 0$ MeV</td>
</tr>
<tr>
<td>$\rho \rightarrow e^+e^-$</td>
<td>$\rho \rightarrow \mu^+\mu^-$</td>
</tr>
<tr>
<td>$158$ A GeV</td>
<td>$158$ A GeV</td>
</tr>
<tr>
<td><strong>Mass</strong></td>
<td><strong>Width</strong></td>
</tr>
<tr>
<td>$\Delta m$ not favored</td>
<td>$\Gamma_{\omega}(\rho=\rho_0) \approx 140$ MeV</td>
</tr>
<tr>
<td><strong>Note</strong></td>
<td><strong>Experimental Results</strong></td>
</tr>
<tr>
<td>$\rho$, $T$ not constant</td>
<td>$\rho$, $T$ not constant</td>
</tr>
</tbody>
</table>

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M. Naruki et al, PRL96 (2006)  
R. Muto et al., PRL98 (2007)  
D. Trnka et al., PRL 94 (2005)  
M. Kotulla et al, PRL 100 (2008)  
Photoproduction of Vector Mesons off Nuclei “looking for medium modifications”

\[ \gamma A \rightarrow VX \rightarrow e^+e^- \]

- Original idea:
- Jlab Experiment E01-112 (also called g7)
  Spokespersons: C. Djalali (USC), M. Kossov (ITEP), D. Weygand (Jlab)
- Photon beam (minimal disturbance to initial state):
  \( E_\gamma \sim 0.6 \) to 3.8 GeV (tagged \( \gamma \))
  Targets: LD2, C, Ti, Fe, (Pb)
- Leptonic decay:
  Almost no final state interaction! HOWEVER (NO FREE LUNCH!)

Low branching ratio: \(~5 \times 10^{-5}\)

needs high photon flux: \(5 \times 10^7\) tagged \(\gamma/s\)
- Toroidal magnetic field
  (6 superconducting coils),
- Drift chambers, Scintillators, Cerenkovs, Electromagnetic Calorimeter.

Hall B @ Jlab (CLAS)

>150 physicists,
>10 countries
Multi-Segment Nuclear Target

- Contains materials with different average densities.
- LD2 and seven solid foils of C, Fe, Pb, and Ti.
- Each target material 1 g/cm$^2$ and diameter 1.2 cm
- Approximately same number of nucleons/target

Proper spacing 2.5 cm to reduce multiple scattering
- Deuterium target as reference, small nucleus, no modification expected.
Particle Detection with CLAS

coincident electron pairs in the CLAS

- Momentum corrections
- Target energy loss corrections
- Lepton momentum cuts

**Caution:** The treatment of the background may change the estimation of the signal ($\rho$).

**Excellent \( \pi/e \) discrimination:** 5.4x10^{-4} for one and 2.9x10^{-7} for two arms.
Possible channels that contribute to e+e- mass spectrum

**Correlated:**
- Monte-Carlo simulations using a model (BUU) by Mosel et al. (*Nucl. Phys. A671, 503 (2000)*) including various decay channels and nuclear effects, and CLAS detector simulation package (GSIM) Simulations with BUU includes all the e+e- decay channels with same strength.
  - $\omega \rightarrow e^+e^-$, $\rho \rightarrow e^+e^-$, $\phi \rightarrow e^+e^-$
  - $\eta \rightarrow \gamma e^+e^-$
  - $\omega \rightarrow \pi^0 e^+e^-$

**“Semi-correlated”:**
- Bethe-Heitler calculated by Mosel’s group $\rightarrow$ negligible
- $\gamma A \rightarrow \pi^0 \pi^0 X \rightarrow \gamma e^+e^- \gamma e^+e^-$ 2 $\pi^0$ Dalitz decay mixed $\rightarrow$ negligible
- $\pi^0 \rightarrow e^+e^- e^+e^-$ double Dalitz $\rightarrow$ low mass

**Uncorrelated:**
- Mixed event technique. Pairs of identical (e+e+, e-e-) leptons, which are produced only by combinatorial background provide a natural normalization and samples of uncorrelated particles.
Combinatorial Background (mixed events and same sign pairs)

μ+μ− measurement: at CERN-SPS IPNO-DR-02.015 (2002)
The vacuum properties of the $\rho$ meson are: $m=770$ MeV/c$^2$ and $\Gamma=150$ MeV. Broadening of the width is consistent with many-body effects.
Our result ($\alpha = 0.02 \pm 0.02$) is compatible with no mass shift.
- Result does not confirm the KEK results ($\alpha \sim 0.09$).
- Rule out $\Delta m$ à la Brown/Rho (20%) and Hatsuda/Lee ($\alpha \sim 0.16$).
- Width reproduced by GiBUU.
- Mass spectra not directly comparable with spectral function!
- Momentum of $\rho$ between 0.8 and 2 GeV.
- Need to study momentum dependence.

Giessen group (U. Mosel):
W. Peters et al., *NPA 632 (1998) 109*
M. Post et al., *NPA 741 (2004) 81*
BUU model of $\rho$ meson production and propagation with nucleon resonance-hole contributions.

Planned $g7b$
Conditionally approved
Absorption of $\omega$ Meson and its in-medium width

The in-medium width is $\Gamma = \Gamma_0 + \Gamma_{\text{coll}}$ where $\Gamma_{\text{coll}} = \gamma \rho v \sigma^*_{VN}$

Transparency ratio:

$$T_A = \frac{\sigma_{\gamma A \rightarrow \omega X}}{A \cdot \sigma_{\gamma N \rightarrow \omega X}}$$

$$T_{\text{norm}} = \frac{12 \cdot \sigma_{\gamma A \rightarrow \omega X}}{A \cdot \sigma_{\gamma^{12}\text{C} \rightarrow \omega X}}$$

Kaskulov, Hernandez & Oset EPJ A 31 (2007) 245


Latest TAPS $\Gamma_\omega \sim 130-150$ MeV

JLAB preliminary results $\rightarrow$ larger width!

C. Djalali

Nov 13, 2008
\( \rho - \omega \) Interference

The \( e^+e^- \) amplitude is modeled as

\[
F = f_\rho + ie^{iq} f_\omega
\]

where \( f_{\rho,\omega} \) are relativistic BW shapes.

Interference after subtracting the \( \rho \)

Data from the \( ^2H \) target

Work in progress

preliminary

C. Djalali

Nov 13, 2008
Comparison to Theory – $\phi$-Meson

Spring8 $\gamma$ A $\rightarrow \phi$ A' $\rightarrow$ K$^+$K$^-$ A' ($E_\gamma$=1.5-2.4 GeV)

Normalized to carbon

$T_A / T_{12C}$

**Giessen calculations**

**Giessen calculations w/ Spring8 absorption strengths**

**Spring8**

**Proposed Jlab run**

$\sigma_{\phi N} \sim 25 - 55$mb

Large statistical error bars.

C. Djalali

Nov 13, 2008
Summary and Conclusions (Medium Modifications)

CLAS excellent tool for these studies:
- $e^+e^-$ from rare leptonic decay of light vector mesons are identified.
- Clear $\rho$, $\omega$ and $\phi$ signals in the invariant mass spectrum.
- “Mixed-event” technique gives both shape and normalization of the combinatorial background

The $\rho$ meson (Final):
- Correct mass shape is extracted.
- No mass shift and width increased by 40% in Fe (as predicted by GiBUU)

The $\omega$ meson (preliminary):
- From transparency ratios, width $\sim$ 200 – 250 MeV!

The $\phi$ meson (preliminary):
- From transparency ratios, in medium total cross section $\sim$ 25 - 55 mb

Medium modification studies continue to be a hot topic!

Next at Jlab by g7 group:
- High Statistics measurement of $e^+e^-$ production on $H_2$
- Conditionally approved g7b high statistics data on $LD_2$, C, Fe, Nb and Sn to measure the $\rho$ meson mass spectra in four momentum bites from 0.4 to 2 GeV/c and transparency ratios.