Systematic study of the vector meson spectral modification in the nuclear medium at J-PARC

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Outline

• Introduction
• Motivation of the J-PARC E16 experiment
• Detector performance
• Simulation results
• Summary
Introduction

- Chiral symmetry is considered as the origin of hadron mass. chiral condensates: \( <\bar{q}q> \neq 0 \)
- Chiral symmetry is predicted to be partially restored in hot and/or dense matter.
- The mass spectra of vector mesons in hot and/or dense environment have been investigated.
- Many experiments report the results of the spectral modification, but the origin is not figured out yet.
Experimental efforts

- The mass spectra of vector mesons in medium are investigated using reactions induced by heavy-ion, photon beam and proton beam.

<table>
<thead>
<tr>
<th>Experiment</th>
<th>Reaction</th>
<th>$\sqrt{s}$ NN [GeV/c$^2$]</th>
<th>Vector meson</th>
</tr>
</thead>
<tbody>
<tr>
<td>SPS-CERES</td>
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<td>17.3</td>
<td>$\rho$</td>
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<tr>
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<tr>
<td>RHIC-PHENIX</td>
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<td>$\gamma$ 0.64–2.53</td>
<td>$\omega$</td>
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<tr>
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<td>$\gamma$+A</td>
<td>$\gamma$ 0.7–2.5</td>
<td>$\rho$</td>
</tr>
<tr>
<td>KEK-E325</td>
<td>p+A</td>
<td>5.1</td>
<td>$\rho$, $\omega$, $\phi$</td>
</tr>
<tr>
<td>GSI-HADES</td>
<td>p+A</td>
<td>3.2</td>
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Experimental efforts

- The mass spectra of vector mesons in medium are investigated using reactions induced by heavy-ion, photon beam and proton beam.

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- Broadening
- Enhancement
- No shift, No broadening (Sensitivity is not enough)
- No shift, but broadening
- $\rho/\omega$ 9% shift
- $\phi$ 3.4% shift, width x3.6

Excess in slow dilepton in p+Nb
KEKPS-E325 results

- 12 GeV p+A→φ + X, φ→e⁺e⁻, C and Cu targets.
- Excess is observed for slowly moving φ meson on Cu target.

[Diagram showing electron decay inside and outside the nucleus with references to R. Muto et al., PRL 98(2007) 042581]

Blue line is the expected shape of φ meson including all experimental effects.
Model fit: parameters

- Generation point is uniform.
  - Woods-Saxon density distribution
  - Momentum is calculated by JAM.

- Decay in-flight
  - Based on Breit-Wigner shape.
  - Change of pole mass
    \[ m(\rho) = (1 - k_1 \frac{\rho}{\rho_0}) m(0) \]
  - Width broadening
    \[ \Gamma(\rho) = (1 + k_2 \frac{\rho}{\rho_0}) \Gamma(0) \]

\[ \tau(\rho) = \frac{\Gamma(0)}{\Gamma(\rho)} \tau(0) \]
KEKPS-E325 results: Model fit

Red line is a fit result.

- Significant excess in only $\beta\gamma\phi<1.25$ with Cu target data.
- Model Fit (six spectra simultaneously)
  $\Delta m (k1) \sim 0.034$, $\Delta \Gamma (k2) \sim 2.6$
- Model Fit only slow $\phi$ with Cu:
  $\Delta m (k1) \sim 0.031$, $\Delta \Gamma (k2) \sim 6.1$

※ These two parameter sets are used in the following simulation.

R. Muto et al., PRL 98(2007) 042581

R. Muto Doctor thesis.
Motivation: What is important for further study?

- Mass spectrum itself. (Not only “shift” and/or “broadening”)
- Dependence on target nucleus size and momentum of φ mesons.

φ meson is a good probe!
- Narrow natural width
- No other resonance nearby
- φ->ee is free from final state interaction

But ...
- Branching ratio of φ->ee is small. (~10⁻⁴)
- Life time of φ is relatively long.

High statistics is necessary.

New experiment, J-PARC E16 is proposed!
- New spectrometer at new beam line.
- High intensity 30 GeV proton beam 10¹⁰/spill.
- High statistics
- High mass resolution

In this presentation, the expected sensitivity of the J-PARC E16 experiment is reported.
J-PARC (Proton Accelerator Research Complex)

Linac 400MeV

RCS 3GeV

Neutrino beams to Super K (T2K)

MLF (Material and Life science experimental Facility)

MR 30 GeV

Hadron Hall

30GeV proton Slow extraction

Switch Yard

Bird's eye photo in Jan. 2008

Borrowed from Tadashi Koseki’s slide
Beam Line at J-PARC Hadron Hall

Proton beam (30GeV) LINE-A

T1 target

High-p (LINE-B)

~$10^{10}$ ppp is stealed from LINE-A

1x$10^{10}$ proton/pulse

2 sec duration

5.52〜6.0 sec cycle

Switch Yard

Hadron Hall

K1.8BR

K1.8

K_0

E16 spectrometer
Spectrometer

• Detectors are installed in a magnet.
• Mass resolution $< 10 \text{ MeV/c}^2$.
• $\pi$ rejection $<10^{-3}$.
Spectrometer

• Detectors are installed in a magnet.
• Mass resolution < 10 MeV/c^2.
• π rejection <10^{-3}.
Spectrometer

- Detectors are installed in a magnet.
- Mass resolution < 10 MeV/c².
- $\pi$ rejection < $10^{-3}$.

In this presentation, the expected sensitivity for the first run is reported.
GEM Tracker

- Tracking with three layers of position sensitive chambers in a magnetic field.
- Gas Electron Multiplier (GEM) is used. The sizes are 10 cm x 10 cm, 20 cm x 20 cm and 30 cm x 30 cm.
- Triple GEM + 2D readout strips / chamber.
- We fabricated GEM domestically.
- Electronics: APV25-s1 chips.
- CFRP made frame
• Tracking with three layers of position sensitive chambers in a magnetic field.
• Gas Electron Multiplier (GEM) is used. The sizes are 10 cm x 10 cm, 20 cm x 20 cm, and 30 cm x 30 cm.
• Triple GEM + 2D readout strips/chamber.
• We fabricated GEM domes.
• Electronics: APV25 chips.
• CFRP made frame
GEM Tracker: position resolution

- Analysis method for angled tracks
  - Timing information
- Sufficient performance event in a magnetic field.
- Required position resolution of 100 μm is achieved up to the incidence angle of 30 °.
Hadron Blind Detector

- Mirrorless and Windowless Čerenkov Detector. Based on PHENIX HBD[3].
- Photocathode is developed successfully.
- ~11 p.e. is obtained for electron beam.
- Cluster size (# of hit pads) cut improves π rejection.
- π rejection power of 120 at e efficiency of 83% is achieved at beam test.


300 mm x 300 mm CsI GEM
Lead-glass calorimeter (LG)

- LG is placed behind HBD.
- eID with HBD. Separate $e$ and $\pi$ by signal amplitudes.
- Response to $e$ and $\pi$ is measured at J-PARC K1.1BR beam line.

Note: In offline analysis, threshold is changed according to $\pi$ momentum. $\pi$ rejection factor of ~10 at 90% $e$ efficiency (online).
Summary of detector performance

- **GEM Tracker**: Position resolution of $100 \, \mu m$ is achieved for the incidence angle up to $30^\circ$.

- **HBD & LG**:
  - online trigger
    - eID eff 61% / $\pi$ survival rate 0.2%
    - (rejection 99.8%)
  - offline analysis
    - eID eff 57% / $\pi$ survival rate 0.03%
    - (rejection 99.97%)

**Detector development is completed!**

Next, we simulated the expected mass spectrum based on the achieved detector performance.
Monte–Carlo simulation

- Mass spectra of $\phi$ and background are simulated using Geant4.
- Detector material and detector performances are implemented.
- Background hits (5 kHz/mm$^2$ at $1 \times 10^{10}$ proton/spill)
  - Beam halo, tracks from the target, room background, etc.
- Tracking
  - Signal response of GEM tracker is simulated and it reproduces the position resolution of the GEM tracker.
  - COG + Timing method
  - Algorithm for clustering and track finding.
- Combinatorial background
  - Uncorrelated pairs of $e^+$ from $\pi^0$ Dalitz decay and $\gamma$ conversions, and mis-identified $\pi^{+-}$.
  - Momentum distributions of $\pi^{+-}0$ are taken from JAM.
Simulation of mass spectrum  
Modification assumed for $\phi$ meson  

- Same model used for fitting E325 results.  
- Change of pole mass  
  
  \[ m(\rho) = (1 - k_1 \frac{\rho}{\rho_0}) m(0) \]  
- Width broadening  
  
  \[ \Gamma(\rho) = (1 + k_2 \frac{\rho}{\rho_0}) \Gamma(0) \]  

In the simulation,  
\[ \text{ave. } k_1 = 0.034, \quad k_2 = 2.6 \] 
\[ \text{slow } k_1 = 0.031, \quad k_2 = 6.1 \] 
are used.
Simulated spectrum

- Expected spectrum for the first run of J-PARC E16 exp.
- Limited number of detector modules. (8/26)
- Beam intensity is 0.33x10^{10} proton/spill. (1/3 of planned intensity.)
- Target: Cu 80 μm x2
- 66 days of data taking is assumed. (same as E325.)
- Trigger eff., eID eff., Tracking eff., Beam available eff., and DAQ live time are included.
Simulated spectrum: Fit with vacuum $\phi$ shape

- All $\beta\gamma$. Statistics of $\phi$ is $\sim4$ of E325.
- Left: Fit in 0.85-1.2 GeV/c$^2$, Right: exclude 0.906-1.004 GeV/c$^2$ from fit.
- Rejection power of $\chi^2$/ndf is significantly different.
- Unlike E325, we have sensitivity without selecting $\beta\gamma$. 

\[ \chi^2/\text{ndf} = 75/47 \]

\[ \chi^2/\text{ndf} = 26/33 \]
\[ \frac{N_{\text{ex}}}{(N_\phi + N_{\text{ex}})} \]

- Background component of fit result (exclude fit) is subtracted.

- Number of excess \( N_{\text{ex}} \) is counted between green lines.

- \( N_\phi \) is an integral of fit result. (red line.)

- \( \frac{N_{\text{ex}}}{(N_\phi + N_{\text{ex}})} \) is evaluated.

\[ \frac{N_{\text{ex}}}{(N_\phi + N_{\text{ex}})} = 0.06 \pm 0.01 \text{ (stat.)} \]

→ Dependence of \( \frac{N_{\text{ex}}}{(N_\phi + N_{\text{ex}})} \) on \( \beta \gamma \) region is examined.
Relative abundance in slow region with Cu target is large.

- $N_{ex}/(N_{\phi} + N_{ex})$ is apart from zero significantly in only slow $\phi$ with Cu.
- Error bars are statistical.
\[ \frac{N_{\text{ex}}}{(N_\Phi + N_{\text{ex}})} \]  
\( \beta \gamma \) dependence

- **E16, Cu(ave.):** \( k_1 = 0.034 \) and \( k_2 = 2.6 \).
- **E16, Cu(slow):** \( k_1 = 0.031 \) and \( k_2 = 6.1 \).
- In E16 with Cu, error bars are reduced compared to E325.
\[
\frac{N_{ex}}{(N_\phi + N_{ex})}
\]
\(\beta\gamma\) dependence

- **E16, Cu(ave.):** \(k1 = 0.034\) and \(k2=2.6\).
- **E16, Cu(slow):** \(k1 = 0.031\) and \(k2=6.1\).
- In E16 with Cu, error bars are **reduced compared to E325.**
Summary

• Many experiments report spectral modification in dilepton spectra, but more systematic study is necessary.
• J-PARC E16 experiment is in preparation to measure $\phi$ meson mass in medium with high statistics and high mass resolution for the systematic studies.
  - System size dependence / dispersion relation
• Detector R&D is completed and the production is in progress.
• Sensitivity is evaluated by MC simulation for the expected E16 first run with limited detectors and beam intensity.
  - Even in these limited conditions, higher sensitivity to the spectral modification than KEK-PS E325.
• Outlook:
  Sensitivity on various predictions of spectral modification.
backup
Sensitivity for modification

- Number of $\phi$ w/o modification ($=N_\phi$) and excess ($=N_{\text{ex}}$) are counted.
- Integral of the difference between the simulation data and fit result is $N_{\text{ex}}$.

\[
N_\phi = 3265\pm 157 \text{ (stat.)}
\]

\[
N_{\text{ex}} = 773\pm 94 \text{ (stat.)}
\]

\[
N_{\text{ex}}/(N_\phi+N_{\text{ex}}) = 0.19\pm 0.02 \text{ (stat.)}
\]

$N_{\text{ex}}$ is $\sim 6$ times larger than KEK-PS E325.
Significance (statistical) of $N_{\text{ex}}/(N_\phi+N_{\text{ex}})$ is $9.5\sigma$. 
KEKPS-E325 results: Model fit

- Significant excess in $\beta \gamma < 1.25$ with Cu target.
- Model Fit (six spectra simultaneously)
  \[ \Delta m (k1) \approx 0.034, \quad \Delta \Gamma (k2) \approx 2.6 \]
- Model Fit only Cu in $\beta \gamma < 1.25$:
  \[ \Delta m (k1) \approx 0.031, \quad \Delta \Gamma (k2) \approx 6.1 \]
  \( (\chi^2/\text{ndf} = 66/48 \text{ (simul.)} \rightarrow 63.4/48) \)

R. Muto Doctor thesis.
\[ \frac{N_{ex}}{(N_\phi + N_{ex})} \]

\( \beta \gamma \) dependence

- E16, Cu(ave.): \( k_1 = 0.034 \) and \( k_2 = 2.6 \).
- E16, Cu(slow): \( k_1 = 0.031 \) and \( k_2 = 6.1 \).
- Error bars are statistical.
- In E16, Cu(slow), error bar is reduced compared to (ave.) and also better than E325 Cu. S/N is improved by a cut on charge and hit modules.
$k1 = 0.034, \ k2 = 2.6, \ bg<1.25, \ 8\text{mod}, \ w \ LRCut$

$N_{\phi} = 644 \pm 44$

$N_{ex} = 75 \pm 23$

$\frac{N_{ex}}{(N_{\phi} + N_{ex})} = 0.10 \pm 0.03$
Simulated mass spectrum

\[ \begin{align*} 
\phi + \text{BG} & \\
\phi & \\
\text{ee BG} & \\
\text{e\pi BG} & \\
\pi\pi \text{ BG} & 
\end{align*} \]

- Modification parameter: measured by KEK-PS E325 for slow $\phi$
- Beam intensity is $0.33 \times 10^{10}$ proton/spill
- Yield (66 days, same as E325.) $\phi: \sim 4000$
  (cf). $N_{\text{ex}} + N_{\phi} = 597$
  @KEK-PS E325)
  BG sum: $\sim 14000$
- Trigger eff., eID eff., Tracking eff., Beam available eff., and DAQ live time are included.
Sensitivity for modification

• Mass spectrum is fitted with exponential + vacuum φ.
• $\chi^2$/ndf are investigated for different fit regions.
• Mass spectrum cannot be fitted including the excess at the confidence level of 99.9%.
• The difference of rejection power shows a significance of the existence of mass modification.

Fit region: 0.85 – 1.2 GeV/c$^2$

Fit region: 0.85 – 0.906, 1.018–1.2 GeV/c$^2$