Experimental studies on medium modification of vector mesons

Megumi Naruki (Kyoto Univ.)

- Introduction
- Dilepton measurement so far
- Near future project at J-PARC
Hadron Mass

- spontaneous chiral symmetry breaking
  - mechanism to generate hadron mass: really visible in universe. ~98% of protons’ mass.
  - experimental fact: parity doublet patterns
- origin of order parameter not a priori given
  - quark condensate: \( <q\bar{q}> \leftrightarrow f_\pi m_\pi \)
  - four-quark condensate, strong gluonic interaction
Experimental Approach

- **bound system**
  - pionic atom
    - S236 experiment @ GSI

- **nuclear mass number dependence**
  - width modification

- **dilepton measurement**
  - mass of vector meson in hot/dense matter
pionic atom spectroscopy


S236 experiment @ GSI

$\pi$ bound state is observed in Sn(d, $^3$He) pion transfer reaction.

Reduction of the pion decay constant $f^*(\rho)^2/f^2_\pi \approx 0.64$ at the normal nuclear matter density ($\rho = \rho_0$)

$\leftarrow$ W-T relation: $b_1/b_1(\rho_e) \approx f_\pi(\rho_e)^2/f^2_\pi$

from the p-nucleus scattering data, this can be connected to quark condensate in the medium.

$$\frac{\langle \bar{q}q \rangle^*}{\langle \bar{q}q \rangle} \approx \left( \frac{b_1}{b_1^*} \right)^\frac{1}{2} \left( 1 - \gamma \frac{\rho}{\rho_0} \right)$$


37% decrease of $\langle \bar{q}q \rangle$ at $\rho_0$

$\Rightarrow$ chiral symmetry restoration?
Dilepton Measurement

directly access to the properties of vector mesons

Low Mass Range $M_{ee} < 1.1 \text{ GeV/c}^2$

in-medium modification of vector mesons
possible connection to CSB

<table>
<thead>
<tr>
<th></th>
<th>Width</th>
<th>$c\tau$</th>
<th>$\rho, \omega \text{ vs } \phi$</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\rho$</td>
<td>149.2 MeV</td>
<td>1.3 fm</td>
<td>large effect overlap</td>
</tr>
<tr>
<td>$\omega$</td>
<td>8.44 MeV</td>
<td>24 fm</td>
<td></td>
</tr>
<tr>
<td>$\phi$</td>
<td>4.26 MeV</td>
<td>47 fm</td>
<td>single peak</td>
</tr>
</tbody>
</table>
Density dependence of Mass

Hatsuda & Lee, PRC46('92)R34 base on QCDSR

Lutz&Friman, NPA706('02)

M. Post et al, NPA741('04)

Rapp & Wambach, ANP25 ('00)

Klingl,Kaiser&Weise, NPA624('97)

broadening, shift, low-mass peak :ρN*N
Temperature dependence

many-body theory: $\pi$-clouds w/ $\pi$BN,$\pi$BB + anti-baryon $\pi\pi$ heat bath (for $\rho$)

SPS

RHIC

melting at high temperature

van Hees & Rapp NPA806(2008)
HIC vs. cold nuclear matter

Relativistic Heavy Ion Collisions

large modification
complicate space-time evolution

Critical point

Quark Gluon Plasma

Hadron Gas

Color Superconductor

nuclei

Neutron Stars

stable system
rather small modification

T_c ~ 170 MeV

RHIC

SPS

FAIR300

KEK/J-PARC/JLAB

HADES

Baryon Density
Dilepton Measurements

History vs. Energy scale

- KEK E325
- CERES
- NA60
- HADES
- PHENIX
- STAR
- ALICE
- CBM
- J-PARC E16

Energy scales:
- $\sqrt{s} = 7$ TeV
- $\sqrt{s} = 200$ GeV
- 158 AGeV
- 12 GeV
- 1-4 GeV

Year:
- 1990
- 1995
- 2000
- 2005
- 2010
- 2015
- 2020
Experimental results at high temperature
CERES @ SPS

e+e− pair measurement in central Pb–Au collisions at 158A GeV/c

2000 data

- Rapp & Wambach
- Brown & Rho

both scenarios are possible within the systematic uncertainty

invariant mass of $\mu^+\mu^-$ in In-In at 158 AGeV ($\sqrt{s_{NN}}=19.6$ GeV)

PRL 96, 162302 (2006)

$\Delta M = 23$ MeV at the $\phi$

$\rho$ spectrum is reproduced with broadening of $\rho$ (Rapp & Wambach)

space-time evolution: thermal fireball model
invariant mass of $e^+e^-$ at $\sqrt{s_{NN}} = 200$ GeV

strong enhancement in $150 < m_{ee} < 750$ MeV:
$4.7 \pm 0.4\,\text{(stat.)} \pm 1.5\,\text{(syst.)} \pm 0.9\,\text{(model)}$
Comparison w/ Models

- thermal fireball model by Rapp & vanHees
- Hydro dynamical evolution model by Dusling & Zahed
- Transport model by Bratkovskaya & Cassing

All models and groups that successfully described the SPS data fail in describing the PHENIX results
Centrality dependence

Strong centrality dependence in the Low-Mass Region.
p_T dependence of low mass enhancement

Low mass excess in Au-Au concentrated at low p_T
clear enhancement over the hadronic cocktail
weak centrality dependence
Comparison w/ Model

Thermal model by R. Rapp (priv. comm.) cf. PRC 63 (2001) 054907

Transport model by Linnyk et al. PRC85, 024910(2012)

rough agreement in $M_{ee} > 0.4 \text{GeV}$ but overshoot in low-mass side

rough agreement with STAR central but not with PHENIX
Scaled by all the yields from PHENIX result, STAR reproduces the PHENIX cocktail.
Experimental Results in cold nuclear matter
The superposition will be observed.
CBELSA/TAPS experiment

\( \omega \to \pi^0\gamma \) in \( \gamma + A \)

\[
m_\omega = \sqrt{(p_\pi + p_\gamma)^2}
\]

Advantage:
- \( \pi^0\gamma \) large branching ratio (8%)
- no \( \rho \)-contribution (\( \rho \to \pi^0\gamma : 7 \cdot 10^{-4} \))

disadvantage:
- \( \pi^0 \)-rescattering

Nanova et al., PRC82(2010)035209
In-medium Width of $\omega$

estimated from transparency ratio

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

comparison to data $\Gamma(\rho_0, <|p_\omega|> \approx 1.1 \text{ GeV/c}) \approx 130-150 \text{ MeV}$

PRL100,192302(2008)
Induce photons to Liquid deuterium, Carbon, Titanium and Iron targets, generate vector mesons, and detect e+e- decays with large acceptance spectrometer.

R. Nasseripour et al., PRL 99 (2007) 262302

\[ m_\rho = m_0 (1 - \alpha \rho/\rho_0) \]

for \( \alpha = 0.02 \pm 0.02 \)

No peak shift of \( \rho \) consistent with collisional broadening.
the excess over the known hadronic sources on the low mass side of $\omega$ peak has been observed.
$\rho/\omega$ ratio is consistent with zero. 95% C.L. allowed regions:

- $N_\rho/N_\omega < 0.04\text{(stat.)} + 0.09\text{(sys.)}$
- $N_\rho/N_\omega < 0.10\text{(stat.)} + 0.21\text{(sys.)}$

Most of $\rho$ decay in nucleus due to their short lifetime; $\tau \sim 1.3\text{fm}$.
Comparison w/ Model

\[ \frac{m^*}{m} = 1 - f_1 \frac{\rho}{\rho_0}, \quad f_1: \text{fitting parameter} \]

well reproduced with the 9% mass decrease at \( \rho_0 \).
Invariant mass spectra of $\phi \rightarrow e^+e^-$

$\beta_\gamma < 1.25$ (Slow)  
$1.25 < \beta_\gamma < 1.75$  
$1.75 < \beta_\gamma$ (Fast)

Rejected at 99% confidence level

PRL 98(2007)042501
Comparison w/ Model Calc.

\[ \beta \gamma < 1.25 \text{ (Slow)} \quad 1.25 < \beta \gamma < 1.75 \quad 1.75 < \beta \gamma \text{ (Fast)} \]

\[ \chi^2 / \text{ndf} = 37/50 \quad \chi^2 / \text{ndf} = 66/50 \quad \chi^2 / \text{ndf} = 45/50 \quad \chi^2 / \text{ndf} = 58/50 \]

Large Nucleus

Small Nucleus

reproduced with \( m^*/m = 1 - 3.4\% \rho / \rho_0 \) & \( \Gamma / \Gamma_0 = 1 + 2.6\rho / \rho_0 \)
• large acceptance at small \( M_{e^+e^-} \) and \( p \) (<1 GeV/c) (first measurement at low \( p \) !)

• \( p+p \) data are cocktail: based on known sources fixed to data \( \pi^0/\eta/\omega/\rho \), \( \Delta \) with constant eTFF

 underestimated \( e^+e^- \) yield below VM pole \( \rightarrow \) higher resonances (\( \Delta, N^* \))
Summary & Outlook

• **Solid Statement**: spectral modification of vector meson have been observed in various reactions at various energies.

• **BUT** there is no general consensus on the theoretical interpretations.

• “shift” vs. ‘broadening” is too naïve. The real effect might be a composition of shift, broadening, dip-like structure etc.

• The spectral modification will largely depend on momentum.

→ **precise measurement w/ high statistics & resolution**
  o systematic study: dispersion relation, system size dependence
J-PARC bird’s-eye view

Materials & Life Science Facility

3GeV PS (RCS)

Hadron Experimental Facility

30GeV PS (MR)

400MeV LINAC

slow extraction section

Tokai, Ibaraki, Japan
Hadron Physics at J-PARC

Strangeness Physics

$\Xi$ hypernuclei in $^{12}$C($K^-,K^+$) double-$\Lambda$

Pentaquark $\Theta^+$

Origin of Hadron Mass

Charmed Baryon production

Target

MC

production

target

Proton

$\Lambda(1405)$ in d($K^-,n$)

kaonic nuclei

High momentum

MC

$\phi(1020)$

$\pi^+\Sigma^-$

$\pi^0\Sigma^0$

$\pi^-\Sigma^+$

MC
beam power

3kW  10kW  25kW  270kW

E19: Search for Pentaquark $\Theta^+$
E10: neutron rich $\Lambda$-Hypernuclei
E27: Search for K-pp

E05: $\Xi$-Hypernucleus (priority 1)
E07: Double Strangeness with Emulsion
E03: X rays from $\Xi^-$ Atom

E13: Gamma-ray spectroscopy of light hypernuclei (priority 2)

E17: Kaonic 3He
E15: deeply bound kaonic nucleus
E31: spectral information of $\Lambda(1405)$

K1.8

K1.8BR

now

30 days
at SM1 high-p beam branches off from the primary line

- 30 GeV primary proton ($10^{10}$/s, $10^{12}$/s)
- 8 GeV primary proton for COMET
- secondary particles (~20 GeV/c)
Di-electron spectrometer to investigate medium mass modification of vector meson (J-PARC E16)

$10^7$ interaction ($10 \times E325$)

$10^{10}$ protons/spill with 0.1% interaction length target

→ GEM Tracker

Large Acceptance ($5 \times E325$)

Higher energy beam ($12 \rightarrow 30 \text{GeV}$)

$x \sim 2$ of production CS

100 times as large statistics as $E325$

velocity dependence

nuclear number dependence ($p \rightarrow \text{Pb}$)

centrality dependence

→ systematic study of mass modification
Detector R & D

Particle tracking in a magnetic field and measure momentum.

Gas Electron Multiplier (GEM)
- High Rate Capability (up to 25kHz/mm²)
- Can cover Large acceptance (No wire)
- Good resolution & Low material

3 chambers of GEM Tracker @ r=20, 40, 60 cm

GEM foil (30cm x 30cm)

Beam test @ Tohoku ELPH
- Made in Japan
- Enough position resolution is achieved.
- Ready for mass production.

Electron identification in large acceptance

Hadron Blind Detector (HBD)
- Mirror less gas cherenkov counter
- CsI photocathode (UV sensitive) + Gas Electron Multiplier (GEM)
- Follow PHENIX exp @ BNL

CsI is evaporated on the surface of the top GEM.
Photoelectrons are amplified using GEM (like Track GEM made in Japan
CsI is evaporated by ourselves.

 CSI evaporated GEM foil

Quantum Efficiency
- Enough Q.E. is achieved

- pion rejection factor 100 with e-efficiency 70% achieved.
- Improvement of efficiency is on going.
momentum dependence of mass

Expected Signal

Measured by E325
ΔM~35MeV

βγ<0.5, σ=5 MeV

Cu

Pb

~35MeV
History & Schedule

• 2007 approval
• 2013 Jan.
  o beam line construction budget was approved.
• 2014
  o beam line construction
  o mass production
• 2015
  o spectrometer construction at the hadron hall
• 2016 Jan.
  o high-momentum beam line is completed.
  o first commissioning run
Thank you for your attention!