Experiment on meson-mass modifications at J-PARC

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- physics motivation: hadron mass generation mechanism in QCD
- vector meson measurements
- J-PARC E16: invariant mass spectroscopy
  - experimental method
  - expected mass spectra
- Related experiment at J-PARC
Origin of Mass (Higgs)

- Origin of lepton and quark mass: Higgs
• Origin of lepton and quark mass: Higgs

• Origin of quark and hadron mass: spontaneous breaking of chiral symmetry, originally proposed by Nambu
  
  - Hadron mass could be modified in hot/dense matter, because of the chiral symmetry restoration is expected in such matter
Vector meson measurements in the world

- **HELIOS/3** (ee, μμ) 450GeV p+Be / 200GeV A+A
- **DLS** (ee) 1 GeV A+A
- **CERES** (ee) 450GeV p+Be/Au / 40-200GeV A+A
- **E325** (ee,KK) 12GeV p+C/Cu
- **NA60** (μμ) 400GeV p+A/158GeV In+In
- **PHENIX** (ee,KK) p+p/Au+Au
- **STAR** (ππ, KK, ee) p+p/Au+Au
- **HADES (*)** (ee) 1-4 GeV p+A/ 1-2GeV A+A
- **CLAS-G7 (*)** (ee) 1~2 GeV γ+A
- **J-PARC E16** (ee) 30/50GeV p+A
- **HADES/FAIR** (ee) 2~8GeV A+A
- **CBM/FAIR** (ee) 20~30GeV A+A
- **TAGX** (ππ) ~1 GeV γ+A
- **LEPS** (KK) 1.5~2.4 GeV γ+A
- **CBELSA/TAPS(*)** (π^0γ) 0.64-2.53 GeV γ + p/Nb
- **ANKA** (KK) 2.83 GeV p+A

Published/ 'modified'
Published/ 'unmodified'
Running/in analysis
Future plan
As of 2012/Sep
Dilepton spectrum measurements in the world

- CERES/NA60
- PHENIX/STAR
- E325/E16
- TAPS/CLAS
- HADES/CBM
- DLS/HADES
Dilepton spectrum measurements in the world

NA60: $\rho$ width broadening
PHENIX: enhancement (cannot be explained yet)

*Chiral restoration at High-T is not confirmed yet*

**NA60**

- $\rho$ width broadening

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**E325**

- $\rho/\omega$ mass dropping
- $\phi$ mass dropping and broadening

**CLAS-g7**

- $\rho$ broadening

**HADES**

- Low-mass enhancement
- Partial chiral restoration at $\rho_0$ is measured with the deeply bound pionic atom

**Mass and chiral symmetry in nuclear matter**

**BKG subtracted**
High-p-WS@KEK 2013Jan17 S.Yokkaichi

Dilepton spectrum measurements in the world

- CERES/NA60
- PHENIX/STAR
- E325/E16
- DLS/HADES
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D C

BKG subtracted

Fe+Ti
Dilepton spectrum measurements in the world

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Partial chiral restoration at $\rho_0$ is measured w/ the deeply bound pionic atom
**KEK-PS E325**

- 12GeV p+A (C/Cu) $\rightarrow \rho$, $\omega$, $\phi$ in the $e^+e^-$ channel
- below the $\omega$ and $\phi$ peaks, statistically significant excesses over the known hadronic sources including experimental effects
- interpreted: mass dropping 9.2% ($\rho$, $\omega$), 3.4% ($\phi$)

![Graph](image-url)
Dilepton spectrum measurements in the world

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PHENIX/STAR
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E325:
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HADES: low-mass enhancement

TAPS/CLAS

E325/E16

DLS/HADES

HADES/CBM

Open question:
Observed hadron modifications are signature of the chiral restoration / evidence of the QCD mass generation?
Experimental methods: pros and cons

- leptonic decay VS hadronic decay
  - small FSI in the matter, but small branching ratio
- proton/photon induced VS heavy-ion collision
  - cold VS hot
  - static environment VS time evolution
  - S/N is better, production cross section is smaller
- $\phi$ VS $\rho/\omega$
  - isolated and narrow, but production CS is smaller
- Why only KEK-PS E325 can observe the $\phi$ modification?
  - proton induced: better S/N than the HI collisions
  - large stat. using a high intensity beam: cope with the small CS
  - good spectrometer keeps the good mass resolution and works under the higher interaction rate
J-PARC E16 experiment
Systematic study of the modification of vector meson spectra in nuclei to approach the chiral symmetry restoration

J-PARC E16 Collaboration
KEK  K. Ozawa, M. Naruki, R. Muto, S. Sawada, M. Sekimoto
CNS, U-Tokyo  H. Hamagaki
Hiroshima-U  K. Shigaki
JASRI  A. Kiyomichi
J-PARC E16 experiment

- Measure the vector-meson mass modification in nuclei systematically with the $e^+e^-$ invariant mass spectrum
- A 30 GeV primary proton beam ($10^{10}$/spill) / 5 weeks of physics run to collect $\sim 10^5 \phi \rightarrow e^+e^-$ for each target
- confirm the E325 results, and provide new information as the matter size/momentum dependence of modification

Proposed exp. E16

- $\phi$-mass is modified in large nuclei for slowly moving mesons... consistent with the prediction based on the QCD sum rule

Precedent exp. (KEK-PS E325)

Nuclear matter size dependence of mass modification are measured

Expected

Momentum dependence

$\Delta M \sim 35\text{MeV}$

Measured by E325

Cu, Pb, H
To collect high statistics

- For the statistics 100 times as large as E325, a new spectrometer and a primary beam in the High-p line are required.
  - To cover larger acceptance: $x \sim 5$
  - Higher energy beam (12 → 30/50 GeV): $x \sim 2$ of production
  - Higher intensity beam (10⁹ → 10¹⁰ /spill (1sec)): $x \times 10$ ($\rightarrow$ 10MHz interaction on targets)
  - to cope with the high rate, new detectors (GEM Tracker & HBD) are required.

Proposed Spectrometer

Plan View

Prototype Module

26 detector modules
High-p line in the Hadron hall

- 3 years plan of the construction: budget requested by KEK to MEXT
High-p line in the Hadron hall

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E16 Schedule

• 2007: stage1 approval
• 2008-2010: development of prototype detectors w/ Grant-in-Aid(2007-8, 2009-13)
• JFY 2011-12: additional parts of the spectrometer magnet, R/O circuit development
  – 1st module of production type (GT and HBD)
  – 1st test type preamp for GT
    • tests @ J-PARC K1.1BR
• JFY 2013: start the production of the detectors/circuits
• JFY 2013/4Q-2014/1Q: magnet reconstruction
  – start the detector install
2014/4Q: ready for the first beam
  – staged goal of the spectrometer construction (w/ 8 detector modules)
J-PARC E16 experiment

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  $\sim 10^5 \phi \rightarrow e^+e^-$ for each target

- Confirm the E325 results, and provide new information as the matter size/momentum dependence of modification

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Momentum dependence
ee spectra of $\phi$ meson (divided by $\beta\gamma$)

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

only slow/Cu is not reproduced in 99% C.L.
Expected Invariant mass spectra in $e^+e^-$:

- smaller FSI in $e^+e^-$ decay channel
- double peak (or tail-like) structure:
  - second peak is made by inside-nucleus decay (modified meson): amount depend on the nuclear size and meson velocity
  - could be enhanced for slower mesons & larger nuclei

longer-life meson ($\omega$ & $\phi$) cases: Schematic picture

outside decay (natural) + inside decay (modified) =

expected to be observed
Discussion: modification parameters

- MC type model analysis to include the nuclear size/meson velocity effects
  - generation point: uniform for \( \phi \) meson
    - from the measured A-dependence
  - measured momentum distribution
  - Woods-Saxon density distribution
  - decay in-flight: linearly dependent on the density of the decay point
    - dropping mass: \( M(\rho)/M(0) = 1 - k_1 (\rho/\rho_0) \)
    - width broadening: \( \Gamma(\rho)/\Gamma(0) = 1 + k_2 (\rho/\rho_0) \)
  - consistent result with the predictions by Hatsuda & Lee (\( k_1 \)), Oset & Lamos (\( \Gamma \))

\[
\begin{align*}
k_1 &= 0.034^{+0.006}_{-0.007} \\
k_2^{\text{tot}} &= 2.6^{+1.8}_{-1.2}
\end{align*}
\]

For \( \phi \), 3.4\% mass reduction (35MeV) 3.6 times width broadening (15MeV) at \( \rho_0 \)
E16 : mass resolution requirement

- mass resolution should be kept less than \( \sim 10\text{MeV} \)
- Very ideal case: very slow mesons w/ best mass resolution:

\[
\phi (1020) \\
\text{Cu} \\
\beta\gamma < 1.25
\]

\( \beta\gamma < 0.5, \sigma = 5 \text{ MeV} \)

(E325 data)

(model calc.)
**φ-mass modification at ρ₀**

- (vacuum value: m(0)=1019.456MeV, \(\Gamma(0)=4.26\text{MeV}\))
  
  \[
  m(\rho)/m(0) = 1 - k_1 (\rho/\rho_0), \quad \Gamma(\rho)/\Gamma(0) = 1 + k_2 (\rho/\rho_0)
  \]

- determined by E325 (PRL98(2007)042581)
  
  \[
  \Delta m : -35\ (28\sim41) \text{MeV}, \quad \Gamma : 15\ (10\sim23) \text{MeV}
  \]

- Hatsuda, Lee [PRC46(1992)34] *QCD sum rule*
  
  \[
  \Delta m : -12\sim44 \text{MeV} \quad (k=(0.15\pm0.05)y, \ y=0.12\sim0.22), \quad \Gamma: \text{not estimated}
  \]

  
  - taking account of K-mass modification
  
  \[
  \Delta m : < -10 \text{ MeV}, \quad \Gamma : \sim45 \text{ MeV}
  \]

- Oset, Ramos [NPA 679 (2001) 616] *hadronic*
  
  - different approach for K-mass
  
  \[
  \Delta m : < -10 \text{ MeV}, \quad \Gamma : \sim22 \text{ MeV for } m=1020\text{MeV}, \sim16\text{MeV for } m=985 \text{MeV}
  \]

- Cabrera and Vacas [PRC 67(2003)045203] OR01+ *hadronic*
  
  \[
  \Delta m : -8 \text{ MeV}, \quad \Gamma : \sim30 \text{ MeV for } m=1020\text{MeV}
  \]

- \[
  k_1 = 0.034^{+0.006}_{-0.007}
  \]

- \[
  k_2^{\text{tot}} = 2.6^{+1.8}_{-1.2}
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**expected shape w/ various parameters**

<table>
<thead>
<tr>
<th>E325</th>
<th>OR-01</th>
<th>KWW-98</th>
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<tbody>
<tr>
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</tr>
<tr>
<td>Cu</td>
<td>Pb</td>
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</tr>
<tr>
<td>βγ&lt;0.5</td>
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<td></td>
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</tr>
<tr>
<td>Pb</td>
<td></td>
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- Δm = -35 or -10 MeV
  Γ = 15 or 50 MeV

OR-01
Δm: -10 MeV
Γ : 15 MeV

KWW-98
Δm: -35 MeV
Γ : 50 MeV

can distinguish
Δm = -35 or -10 MeV
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expected shape w/ various parameters

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- blue: decays inside the half-density radius of nuclei in the MC

$\Delta m : -35\ MeV$
$\Gamma : 15\ MeV$

$\Delta m : -10\ MeV$
$\Gamma : 15\ MeV$

$\Delta m : -35\ MeV$
$\Gamma : 50\ MeV$
<s\bar{s}> & \phi\text{-meson mass}

- $<\bar{s}s>(\rho)$ (\bar{s}s condensate in medium whose density is $\rho$) is relevant the $\phi$ mass in nuclear matter under the QCD sum rule analysis by Hatsuda & Lee (PRC46(92)R34 : HL92)
  - linear approx. : $<\bar{s}s>(\rho)=<\bar{s}s>$ (vacuum) + $<N|\bar{s}s|N> \times \rho$

- Recently $<N|\bar{s}s|N>$ (so called “strangeness content in nucleon”) is calculated with Lattice QCD
  - found to be smaller than the assumed value in HL92, however, agree within the error: predicted value '2-4%' is not so affected

\[ f_{Ts} = \frac{m_s}{m_N} <N|\bar{s}s|N> \]
\[ m_s = 80\text{MeV} \]

arXiv:1208.4185
velocity and nuclear size dependence

- velocity dependence of excesses ('modified' component)
- E325 only one data point for $\phi$ (slow/Cu) has significant excess
velocity and nuclear size dependence

- velocity dependence of excesses ('modified' component)
- E325 only one data point for \( \phi \) (slow/Cu) has significant excess
- systematic study: all the data should be explained the interpretation model

- establish the modification
  - by

\[
\begin{align*}
N_{\text{excess}} / (N_{\text{excess}} + N_0) & \quad \text{Cu Model Calc. } k=0.04 \\
& \quad \text{Cu Model Calc. } k=0.02 \\
& \quad \text{C Model Calc. } k=0.04 \\
& \quad \text{C Model Calc. } k=0.02
\end{align*}
\]

x 100 stat.

\[
\begin{align*}
N_{\text{excess}} / (N_{\text{excess}} + N_0) & \quad \text{Pb}
\end{align*}
\]

\[
\begin{align*}
N_{\text{excess}} / (N_{\text{excess}} + N_0) & \quad \text{proton}
\end{align*}
\]
velocity and nuclear size dependence

- velocity dependence of excesses ('modified' component)
- E325 only one data point for $\phi$ (slow/Cu) has significant excess
- systematic study: all the data should be explained the interpretation model

- establish the modification
- check the interpretation model with shape analysis for each histogram
dispersion relation (mass VS momentum)

- prediction for $\phi$ by S.H.Lee($p<1\text{GeV/c}$)
- current E325 analysis neglects the dispersion (limited by the statistics)
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![Graph showing dispersion relation](image)
dispersion relation (mass VS momentum)

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momentum dependence

- From the view point of experimentalists
  - many predictions are for the mesons at rest (p=0)
    - extrapolation to p=0 if it is a simple dependence
- From the view point of theorists
  - dispersion relation of quasi particles are characteristic
  - other effects

- Weldon (PRD40(89)2410)
- Harada & Sasaki (PRC80(09)054912)
- Kondratyuk et al. (PRC58(98)1078)
Impact of E16

• hadron modification are observed in several experiments but interpretation is not converged: “mass dropping or broadening?”
  - theoretically the question is oversimplified: T-dependence, momentum dependence
  - analysis difficulties in $\rho/\omega$ in the dilepton decay channel
  - small statistics and small data sets
• pin down the phenomena for the vector meson in nuclei ($\rho=\rho_0, T=0$) using $\phi$ meson
  - confirm the E325 observation with improved resolution (x2) and statistics (x100)
  - matter-size dependence and momentum dependence will be examined systematically
    • first measurement of the dispersion relation of hadrons in nuclear matter
• establish a low energy phenomenon which can be predicted by means of QCD
  - mass generation due to the chiral symmetry breaking
• Further Step (future experiment)
  - slow $\phi$ at HIHR beam line with $10^9 \pi$ beam, $\mu\mu$ pair measurement, etc.
  - higher density state using medium-energy HI collisions
    • chiral phase transition in the high-density region
Related experiments at J-PARC

- $\omega$ bound state/invariant mass (E26) : K1.8 or High-\(p\)
- $\phi$ bound state (E29) : K1.1 or K10
- $\eta$ bound state and N(1535) (LoI) : K1.8BR or HIHR
- magnetic moment of $\Lambda$ at finite density
- dilepton decay of slow $\phi$ using $10^9 \pi$ beam at HIHR
meson bound state in nuclei : $E26$ ($\omega$)

- $\omega$ bound state (J-PARC E26 / K. Ozawa)
  - missing mass spectroscopy in $\pi^- + A$ reaction – select the bound state
    - elementary: $\sim 2$ GeV/c $\pi^- + p \rightarrow \omega + n$
    - and measure the $\omega$ decay to $\pi^0\gamma$
  - $P_\omega$ is low, and decay in nuclear matter

![Diagram of detector setup]

- $\gamma$ detector around the target
- Neutron counter at the forward direction

Theoretical predictions of missing mass and invariant mass

Expected modified $\omega$ spectrum

High $p$-WS@KEK 2013Jan17 S.Yokkaichi
meson bound state in nuclei: E29 ($\phi$)

- $\phi$ bound state: (J-PARC E29 / H. Ohnishi)
  - missing mass spectroscopy in pbar + A / $\pi^-$ + A reaction
    - elementary: $\sim$1.3 GeV/c pbar + p $\rightarrow$ $\phi$ + $\phi$
    - (or $\sim$2 GeV/c $\pi^-$ + p $\rightarrow$ $\phi$ + n)
    - measurements of the dilepton decay of $\phi$ is difficult

![Diagram of meson interactions]
Summary

- Investigation of the hadron spectral modification in nuclear matter is a study of the nature of QCD vacuum
  
  • A major origin of hadron mass is the spontaneous breaking of chiral symmetry and the spectral modification could be a signal of the chiral restoration
  
  • Spectral modification of hadrons is observed in hot (HI collisions) and dense (nuclei) matter in the dilepton invariant mass spectra
  
  • but discussion is not converged: chiral restoration or not

- J-PARC E16 will measure the vector meson modification in nuclei with the ee decay channel, using 30GeV primary proton beam at the High-p line.
  
  • confirm the observation by KEK-PS E325 and provide more precise information of the mass modification

- E26, E29, etc. will be performed at new beam lines in the Hadron hall, to explore the chiral symmetry at finite density