Medium modification of vector mesons in 12 GeV p+A reactions at KEK-PS

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- Physics
- Expected experimental signature
- Performed experiment KEK-PS E325
- E325 Results
  - 1) $\rho/\omega \rightarrow e^+e^-$ spectra
  - 2) $\phi \rightarrow e^+e^-$ spectra
  - 3) $\phi \rightarrow K^+K^-$ spectra
- Future experiment at J-PARC
Chiral symmetry restoration in dense matter

- In hot/dense matter, chiral symmetry is expected to restore
  - hadron modification is expected in such matter
- quark-antiquark condensate (order parameter): \( \sim 2/3 \) even at the normal nuclear density, \( T=0 \)
  - Achievable at KEK-PS in use of nuclear medium of target nuclei themselves.
- Many theoretical predictions of vector meson (mass/width) modification in dense medium, related (or not related) with CS
  - Brown & Rho ('91): \( m^*(\rho)/m_0 \sim f^*_\pi/f_\pi \sim 0.8 \) at \( \rho=\rho_0 \)
  - Hatsuda &Lee ('92), Klingle, Kaiser &Weise ('97), Muroya, Nakamura & Nonaka('03), etc.
Hatsuda and Lee, PRC46(92)R34, PRC52(95)3364
linear dependence on density
\[ \frac{m^*}{m_0} = 1 - k \frac{\rho}{\rho_0} \]

mass decreasing
- 16(±6)% for \( \rho/\omega \)
- 0.15(±0.05)*y
  \[ = 2 \sim 4\% \text{ for } \phi \]
  (for \( y = 0.22 \))
at the normal nuclear density

Klinge, Kaiser, Weise, NPA624(97)527

Muroya, Nakamura, Nonaka, PLB 551 (03) 305

\begin{align*}
\text{mass} & \quad \mu \alpha \\
\text{\pi} & \quad \text{\rho}
\end{align*}
Expected signal in p+A reaction in our energy region
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 \textit{inside-nucleus} decay (modified meson): amount depend on the nuclear size and meson velocity
  - could be enhanced for slower mesons & larger nuclei

\textit{longer-life meson}(\omega & \phi) cases: Schematic picture

outside decay
(natural) + inside decay
(modified) = expected to be observed
Expected Invariant mass spectra in $e^+e^-$

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shorter-life meson($\rho$) cases: Schematic picture
outside decay (natural) + inside decay (modified) = expected to be observed

1) decay inside nuclei
2) decay outside nuclei
(Expected $e^+e^-$ spectra)

- $\rho$ (770) & $\omega$ (783):
  - larger production cross section
  - larger decay prob. inside nuclei
  - $\rho$: $\Gamma=150\text{MeV} \sim 1.3\text{fm}$
  - $\omega$: $\Gamma=8.4\text{MeV} \sim 24\text{ fm}$
  - cannot distinguish $\rho$ & $\omega$ in $e^+e^-$

(toy model calc.)

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    - $\omega : \Gamma = 8.4 \text{MeV} \sim 24 \text{ fm}$
  - cannot distinguish $\rho$ & $\omega$ in $e^+e^-$
- $\phi$ (1020): narrow width
  - smaller decay prob. inside nuclei
    - $\phi : \Gamma = 4.3 \text{MeV} \sim 46 \text{ fm}$
  - smaller production cross section
- $L = \beta \gamma c \tau = p/m * h/2\pi c/\Gamma$
**Experiment KEK-PS E325**

- 12GeV p+A → ρ/ω/φ +X (ρ/ω/φ → e⁺e⁻, φ → K⁺K⁻)

- Experimental key issues:
  - Very thin target to suppress the conversion electron background (typ. 0.1% interaction/0.2% radiation length of C)
  - To compensate the thin target, high intensity proton beam to collect high statistics (typ. 10⁹ ppp → 10⁶Hz interaction)
  - Large acceptance spectrometer to detect slowly moving mesons, which have larger probability decaying inside nuclei (1<βγ<3)

**Collaboration**

History of E325

- 1993 proposed
- 1996 const. start
- '97 data taking start
- '98 first ee data
  - PRL86(01)5019
- 99,00,01,02....
  - x100 statistics
    - PRL96(06)092301
    - nucl-ex/0511019
- '02 completed
- spectrometer paper
  - NIM A516(04)390
Experimental setup

- Spectrometer Magnet
  - 0.71T at the center
  - 0.81Tm in integral
- Targets
  - at the center of the Magnet
  - C & Cu are used typically
  - very thin: ~0.1% interaction length
- Primary proton beam
  - 12.9 GeV/c
  - ~1x10^9 in 2sec duration, 4sec cycle
Experimental setup - Detectors

Electron ID counters
Gas Cherenkov & Lead Glass EMC
total $3 \times 10^{-4}$ $\pi$ rejection with 78% efficiency in two-stage operation

Tracker
Three Drift Chambers

Kaon ID counters
Aerogel Cherenkov & TOF
• Typical $e^+e^-$ Event
  - blue: electron
  - red: other
  - invariant mass and momentum of mother particle can be calculated
Result (1)

ee invariant mass spectra
M. Naruki et al.,
PRL 96 (2006) 092301
(nucl-ex/050416)
Observed $e^+e^-$ invariant mass spectra

- from 2002 run data (~70% of total data)
- C & Cu target
- clear resonance peaks
- $m<0.2$ GeV is suppressed by detector acceptance
- acceptance uncorrected

→ fit the spectra with known sources
Fitting with known sources

- Hadronic sources of $e^+e^-$:
  - $\rho/\omega/\phi \rightarrow e^+e^-, \ \omega \rightarrow \pi^0 e^+e^-, \ \eta \rightarrow \gamma e^+e^-$
  - relativistic Breit-Wigner shape (without any modifications, but internal radiative corrections are included)
  - Geant4 detector simulation
    - multiple scattering and energy loss of $e^+/e^-$ in the detector and the target materials
    - chamber resolutions
    - detector acceptance, etc.
- Combinatorial background: event mixing method
- Relative abundance of these components are determined by the fitting
Fitting results

- 1) excess at the low-mass side of $\omega$
  
  - To reproduce the data by the fitting, we have to exclude the excess region: 0.60–0.76 GeV

- 2) $\rho$–meson component seems to be vanished!
Fitting results (BKG subtracted)

\[ \frac{\rho}{\omega} < 0.06 + 0.09\text{(syst.)} , \quad < 0.08 + 0.21\text{(syst.)} \quad (95\%\text{CL}) \]

However, \( \frac{\rho}{\omega} = 1.0 \pm 0.2 \) in former experiment (p+p, 1974) ...suggests that the origin of excess is modified \( \rho \) mesons.
Toy model M.C. including modification

- Assumptions to include the nuclear size effect in the fitting shape
  - mesons fly through the nucleus, decay with modified mass if the decay point is inside nucleus
    - meson production point: incident surface of nucleus
      - measured $\alpha \sim 2/3$ for $\omega$ [nucl-ex/0603013]
    - meson momentum:
      - measured distribution in our experiment
        - $\sim 0.8 \text{ GeV} < p < \sim 2.4 \text{ GeV}$ for $\omega$
    - nuclear density distribution: Woods-Saxon type

- $\rho$ & $\omega$ meson modification form:
  
  
  \[
  m^*/m_0 = 1 - k \frac{\rho}{\rho_0}
  \]

  \[ (k=0.16\pm0.06 \text{ in Hatsuda & Lee, '92,'96}) \]

- (width modification & momentum dependence of modification are not taken into account this time)
Fitting results by the toy model

Free param.: - scales of background and hadron components for each C & Cu
- modification parameter k for \( \rho \) and \( \omega \) is common for C & Cu

From the fit: \( k = 0.092 \pm 0.002 \): ~ 9% reduced at normal nuclear density

\( \rho/\omega \) ratio: 0.7±0.1 (C), 0.9±0.2 (Cu): ... \( \rho \) meson returns.
Remark on the model fitting

- constraint at right side of peak
  - Introducing the width broadening (x2 & x3) are rejected by this constraint.
  - prediction of 'ρ mass increasing' is also not allowed.

- ρ (ω) decay inside nucleus: 46%(5%) for C, 61%(10%) for Cu
  - used spectrum is the sum of the modified and not-modified components.

- momentum dependence of mass shift is not included. (But typical ρ =1.5GeV/c)
Result (2)

\(ee\) invariant mass spectra of \(\phi\)

(R. Muto et al., nucl-ex/0511019)
$\phi \rightarrow e^+e^-$ invariant mass spectra

- from 2001/02 run data
- C & Cu target
- acceptance uncorrected
- mass resolution : 10.7 MeV
- fit with
  - simulated mass shape of $\phi$
    - (evaluated as same as $\rho$&$\omega$)
  - polinomial curve background
$\phi \rightarrow e^+e^-$ invariant mass spectra

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- mass resolution : 10.7 MeV
- fit with
  - simulated mass shape of $\phi$
    - (evaluated as same as $\rho$ & $\omega$)
  - polinomial curve background
- examine the 'excess' is significant or not.
  - see the $\beta\gamma$ dependence : excess could be enhanced for slowly moving mesons
$e^+e^-$ spectra of $\phi$ meson (divided by $\beta\gamma$)

- $\beta\gamma < 1.25$ (Slow)
- $1.25 < \beta\gamma < 1.75$
- $1.75 < \beta\gamma$ (Fast)
e\(^{+}\)e\(^{-}\) spectra of \(\phi\) meson (divided by \(\beta\gamma\))

\(\beta\gamma<1.25\) (Slow) \hspace{1cm} 1.25<\(\beta\gamma<1.75\) \hspace{1cm} 1.75<\(\beta\gamma\) (Fast)

only slow/Cu is not reproduced in 99% C.L.
**Amount of excess**

- To evaluate the amount of excess ($N_{\text{excess}}$), fit again excluding the excess region (0.95~1.01GeV) and integrate the excess area.
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- Model calculation reproduces the tendency of $N_{\text{excess}} / (N_{\text{excess}} + N_{\phi})$
Toy model again for $\phi$ meson

- Toy model like $\rho/\omega$ case, except for
  - uniformly made in nuclei
    - measured $\alpha$ of $\phi$ production $\sim 1$
  - $m*/m_0 = 1 - k_1 \rho/\rho_0$
    
    ($k_1 = 0.04$, Hatsuda & Lee, '92,'96)
  - To reproduce such amount of excess, linear-dependent width broadening is adopted:
    $\Gamma_{tot}^*/\Gamma^0_{tot} = 1 + k_2 \rho/\rho_0$
    
    - $e^+e^-$ branching ratio is not changed
    - $\Gamma_{e^+e^-}^*/\Gamma_{tot}^* = \Gamma_{e^+e^-}^0/\Gamma_{tot}^0$
  - $k_1$ & $k_2$ is not free param., but fixed.
  - Fits were done with many combinations of $(k_1, k_2)$ and data were well reproduced
**Toy model again for φ meson**

- Toy model like ρ/ω case, except for
  - uniformly made in nuclei
    - measured α of φ production ~ 1
  - $m^*/m_0 = 1 - k_1 \rho/\rho_0$
    - ($k_1 = 0.04$, Hatsuda & Lee, '92,'96)
  - To reproduce such amount of excess, linear-dependent width broadening is adopted:
    $$\Gamma_{tot}^*/\Gamma_{tot}^0 = 1 + k_2 \rho/\rho_0$$
    - $e^+e^-$ branching ratio is not changed
      $$\frac{\Gamma_{e^+e^-}}{\Gamma_{tot}} = \frac{\Gamma_{e^+e^-}^0}{\Gamma_{tot}^0}$$
  - $k_1$ & $k_2$ is not free param., but fixed.
    - fits were done with many combinations of $(k_1, k_2)$ and data were well reproduced

\[\beta\gamma < 1.25 \text{ (Slow) } k_1 = 0.04, k_2 = 2\]
Model fitting: parameter $k_1$ and $k_2$

- To determine the shift parameters...
  
  \[ \frac{m^*}{m_0} = 1 - k_1 \rho/\rho_0 \]
  \[ \frac{\Gamma^*}{\Gamma^0} = 1 + k_2 \rho/\rho_0 \]

- We fit the observed 6 mass spectra (C/Cu, slow/mid/fast) with modified MC shapes and calculate the $\chi^2$ as the sum of 6 spectra

\[(k_1 = 0.04, k_2 = 2, \chi^2 = 316)\]
Model fitting: parameter \( k_1 \) and \( k_2 \)

- To determine the shift parameters...
  - \( m^*/m_0 = 1 - k_1 \rho/\rho_0 \)
  - \( \Gamma^*/\Gamma^0_{tot} = 1 + k_2 \rho/\rho_0 \)

- We fit the observed 6 mass spectra (C/Cu, slow/mid/fast) with modified MC shapes and calculate the \( \chi^2 \) as the sum of 6 spectra for each \((k_1, k_2)\) combination on the grid and make the \( \chi^2 \) contour

**Best Fit Value:**

\( k_1 = 0.042 +/- 0.008 \)

(4.2% mass decreasing at \( \rho_0 \))

\( k_2 = 2.6 +/- 1.9 \)

(3.6 times width broadening at \( \rho_0 \))
Result (3)

(KK invariant mass spectra by F. Sakuma)
Mass modification is NOT statistically significant (very low statistics in $\beta\gamma < 1.25$ where modification is observed in $\phi \rightarrow e^+e^-$).
Proposed Experiment at J-PARC
What is J-PARC?
(Japan Proton Accelerator Reserch Complex)

- KEK/JAERI joint project
- 50 GeV proton synchrotron is under construction at Tokai, Japan
  - first beam is planned in 2008
- Proposed experiments
  - hypernuclei
  - deeply bound K-nuclei and tribaryon
  - Pentaquark search
  - dimuon production measurements
  - Neutrino physics
  - .... etc.
- And our project: electron pair spectrometer
Next generation experiment at J-PARC

- Same concept as E325
  - thin target / primary beam \((10^9 \sim 10^{10} \text{ ppp})/\) slowly moving mesons
- **Main goal**: collect \(\sim 1 \times 10^5 \phi \rightarrow ee\) for each target in 5 weeks
  - \(~100\) times as large as E325
    - velocity dependence of 'modified' component
    - new nuclear targets: proton (\(\text{CH}_2\) -C subtraction), Pb
    - collision geometry for larger nucleus target
- narrow width -> sensitive to modification
- \(\rho, \omega\) and \(J/\psi\) can be collected at the same time
  - higher statistics of \(\rho\) and \(\omega\) than E325 with different nuclear targets
  - 100-1000 \(J/\psi\) are expected in 50GeV operation
- **Normal nuclear density (\(p+A\)**
  - but also high matter density \((A+A, \sim 20\text{GeV/u})\)
To collect high statistics

- To cover larger acceptance : x5
- Higher energy beam (12 → 30/50 GeV) : x2
- Higher intensity beam (10^9 → 10^{10} Hz) : x10

Geometrical (horizontal & vertical) coverage of the spectrometer
**Proposed spectrometer**

- **Tracking Device**
  - GEM (Gas electron multiplier)
    - 0.7mm pitch strip readout
- **Two-stage Electron ID**
  - Gas Cherenkov
    - GEM+CsI photocathode
      - pad readout
  - Leadglass EMC
- **~70K Readout Channels (in 27 units)**
  - E325: 3.6K, PHENIX:~300K
- **Cost**: ~$5M (including $2M electronics)
  - 2 times of E325
high statistics

- **Main goal**: collect $\sim 1 \times 10^5 \, \phi \rightarrow ee$ for each target in 5 weeks
  - 100 times as large as E325
    - velocity dependence of 'modified' component
**high statistics**

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  - 100 times as large as E325
    - velocity dependence of 'modified' component

![](image)

- Error bars are shrunk and \( \beta \gamma \) bin can be divided

**x 100 stat.**
**high statistics**

- **Main goal**: collect \(~1 \times 10^5\ \phi \rightarrow ee\) for each target in 5 weeks
  - 100 times as large as E325
    - velocity dependence of 'modified' component

We can compare the data with theoretical predictions more precisely, and we could approach the puzzle that the modification is due to the chiral symmetry restoration or not.

Advance of the theoretical works is also required to solve the puzzle.
- in finite-size nuclear matter
- possible time evolution of the density
- density/momentum dependence of the mass/width modification, etc.
We detected the mass modification in the invariant mass spectra...

- We may exclude some predictions like upward mass-shift
- Now we ignore:
  - finite-size nuclei $\leftrightarrow$ infinite nuclear matter
  - Possible time evolution of the density of nuclei in the reaction
    - our model is just toy model...
    - transport calculation?
  - momentum dependence of 'mass shift' & 'width broadening'
- We expect the precise prediction to be compared with coming high statistics result.
- How can we connect the results with chiral symmetry restoration?
Summary

- KEK-PS E325 measured the $e^+e^-$ & $K^+K^-$ decay of slowly moving vector mesons in nuclei produced by 12-GeV proton beam, to explore the chiral symmetry restoration at the normal nuclear density.

- Observed $e^+e^-$ invariant mass spectra have excesses below the $\omega$ meson peak, which cannot be explained by known hadronic sources in normal (unmodified) shape. These suggest modification of (at least) $\rho$ meson.
  
  - Simple model calculation including predicted modification of $\rho$ & $\omega$ reproduces the observed spectra.

- $\phi \rightarrow e^+e^-$ also have excess, for the larger target, slowly moving component
  
  - model calc. including mass shift and width broadening in nuclei also reproduces the data.

- In $\phi \rightarrow K^+K^-$ spectra, no modification is observed, however, the data are relatively fast component
**Outlook**

- production cross section of $\omega$ & $\phi$ and their nuclear dependence:
  - nucl-ex/0603013 (to be published in PRC)

- Analysis of nuclear dependence of $\phi \rightarrow K^+K^-$ & $\phi \rightarrow e^+e^-$ is on going to investigate $\Gamma_{K^+K^-}/\Gamma_{e^+e^-}$ changing in nuclei.
  - paper is in preparation

- Analysis of $\beta\gamma$ dependence of $\rho$ & $\omega$ data is also on going.

- ... and next generation experiment at J-PARC has been proposed.
Backup slides...
measured kinematic distribution of $\omega \rightarrow e^+e^-$

- $0.5 < y < 2$
- $1 < \beta\gamma < 3$
  - $(0.8 < p < 2.4\text{GeV/c})$
- $0 < P_T < 1$
measured kinematic distribution of $\phi \rightarrow e^+e^-$

- $0.5 < y < 2$
- $1 < \beta \gamma < 3$
  - $(1 < p < 3 \text{ GeV/c})$
- $0 < P_T < 1$
measured kinematic distribution
of $\phi \rightarrow K^+K^-$ & $\phi \rightarrow e^+e^-$

- $0.5 < y < 1.5$
- $1 < \beta \gamma < 3.5$
- $0.5 < P_T < 1.5$
- overlayed
  - $\phi \rightarrow K^+K^-$
  - $\phi \rightarrow e^+e^-$