Results of KEK-PS E325 experiment

F. Sakuma, RIKEN

• Introduction
• E325 Experiment
• Results of data analysis
  • $\rho/\omega \rightarrow e^+e^-$ spectra
  • $\phi \rightarrow e^+e^-$ spectra
  • $\phi \rightarrow K^+K^-$ spectra
  • Nuclear mass-number dependences of $\phi \rightarrow e^+e^-$ & $\phi \rightarrow K^+K^-$
• Summary
**Quark Mass**

**bare mass**
- $m_u \approx m_d \approx 5\text{MeV/c}^2$
- $m_s \approx 150\text{MeV/c}^2$

**effective mass in QCD vacuum**
- $m_u \approx m_d \approx 300\text{MeV/c}^2$
- $m_s \approx 500\text{MeV/c}^2$

**chiral symmetry breaking**

**chiral symmetry restoration**

**How we can detect such a quark mass change?**

- **at very high temperature or density**, the chiral symmetry is expected to restore
- **even at normal nuclear density**, the chiral symmetry is expected to restore partially

_W. Weise_
_NPA553,59 (1993)
**Vector Meson Modification**

**dropping mass**
- Brown & Rho ('91)
  $$m^*/m = 0.8 \ (\rho = \rho_0)$$
- Hatsuda & Lee ('92)
  $$m^*/m = 1 - 0.16 \rho / \rho_0 \text{ for } \rho / \omega$$
  $$m^*/m = 1 - 0.03 \rho / \rho_0 \text{ for } \phi$$
- Muroya, Nakamura & Nonaka ('03)
  Lattice Calc.

**width broadening**
- Klingl, Kaiser & Weise ('97&98)
  $$1 \text{GeV} > \text{ for } \rho, \ 45 \text{MeV} \text{ for } \phi \ (\rho = \rho_0)$$
- Oset & Ramos ('01)
  $$22 \text{MeV} \text{ for } \phi \ (\rho = \rho_0)$$
- Cabrera & Vicente ('03)
  $$33 \text{MeV} \text{ for } \phi \ (\rho = \rho_0)$$
Vector Meson, $\rho/\omega/\phi$

$\rho/\omega$ meson
- Mass decreases: $16\% \rightarrow 130\text{MeV}/c^2$
- Large production cross-section
- Cannot distinguish $\rho$ & $\omega$

$\phi$ meson
- Mass decreases: $2\sim4\% \rightarrow 20-40\text{MeV}/c^2$
- Small production cross-section
- Narrow decay width ($\Gamma=4.3\text{MeV}/c^2$), no other resonance nearby
  \Rightarrow \text{sensitive to the mass spectrum change}

Expected Modified Mass Spectra in $e^+e^-$

- Small FSI in $e^+e^-$ decay channel
- Double peak (or tail-like) structure

- Second peak is caused by inside-nucleus decay
- Depends on the nuclear size & meson velocity
- Enhanced for larger nuclei & slower meson

$m^*/m = 1 - 0.16 \rho/\rho_0$ in vacuum modified

- $\rho + \omega$
- $\beta \gamma_{lab} \sim 1$, $y = 0.12$

Graphs showing spectra for different elements (Be, Cu, Pb) with modified and unmodified mass distributions.
Experimental Results on the In-medium Mass and Width of the $\rho$, $\omega$ and $\phi$ meson


<table>
<thead>
<tr>
<th>Invariant mass</th>
<th>Attenuation</th>
</tr>
</thead>
<tbody>
<tr>
<td>KEK-PS E325</td>
<td>Jlab CLAS g7</td>
</tr>
<tr>
<td></td>
<td>Jlab CLAS g7</td>
</tr>
<tr>
<td>Reaction</td>
<td>2.6</td>
</tr>
<tr>
<td>Momentum</td>
<td>2.2</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>$\rho$</th>
<th>$\Delta m(\rho_0)/m = -9%$</th>
<th>broadening</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\omega$</td>
<td>no broadening</td>
<td></td>
</tr>
<tr>
<td>$\phi$</td>
<td>$\Delta m(\rho_0)/m = -3.4%$</td>
<td>70mb</td>
</tr>
<tr>
<td></td>
<td>$\Gamma_\phi(\rho_0)/\Gamma \sim 15\text{MeV}/c^2$</td>
<td></td>
</tr>
<tr>
<td></td>
<td>$\sigma_\phi N \sim 20\text{mb}$</td>
<td>$\sigma_\phi N \sim 35\text{mb}$</td>
</tr>
<tr>
<td></td>
<td>$\rightarrow \Gamma_\phi(\rho_0) \sim 45\text{MeV}/c^2$</td>
<td>$\rightarrow \Gamma_\phi(\rho_0) \sim 80\text{MeV}/c^2$</td>
</tr>
</tbody>
</table>

The majority of experiments does not find evidence for a mass shift. [CBELSA/TAPS, arXiv:1005.5694]

Our report is minority report!?

Confirmation @ J-PARC E16
KEK-PS E325 Experiment
**KEK-PS E325 Experiment**

**Measurements**

Invariant Mass of $e^+e^-$, $K^+K^-$ in 12GeV $p+A \rightarrow \rho,\omega,\phi+X$ reactions

- Slowly moving vector mesons ($p_{\text{lab}} \sim 2\text{GeV/c}$)
- Large probability to decay inside a nucleus

**Beam**

Primary proton beam

($\sim 10^9$/spill/1.8s)

**Target**

Very thin targets

($X/\lambda = 0.2/0.05\%$, $X/X_0 = 0.4/0.5\%$ for C/Cu)

---

**History of E325**

- ’93 proposed
- ’96 construction start
  - $\checkmark$ NIM, A457 581(’01).
  - $\checkmark$ NIM, A516 390(’04).
- ’97 first $K^+K^-$ data
- ’98 first $e^+e^-$ data
  - $\checkmark$ $\rho/\omega$: PRL, 86 5019(’01).
- ’99~’02
  - $x100$ statistics in $e^+e^-$
    - $\checkmark$ $\rho/\omega$: PRL, 96 092301(’06).
    - $\checkmark$ $\phi \rightarrow ee$: PRL, 98 042501(’07).
    - $\checkmark$ $\alpha$: PR, C75 025201(’06).
  - $x6$ statistics in $K^+K^-$
    - $\checkmark$ $\phi \rightarrow KK$: PRL, 98 152302(’07).
- ’02 completed
Spectrometer Performance

\[ K^0_s \rightarrow \pi^+\pi^- \]

- Data
- MC

\[ \Lambda \rightarrow p\pi^- \]

- Data
- MC

\[ M = 496.8 \pm 0.2 \text{ (MC 496.9) MeV/c}^2 \]
\[ \sigma = 3.9 \pm 0.4 \text{ (MC 3.5) MeV/c}^2 \]

\[ M = 1115.71 \pm 0.02 \text{ (MC 1115.52) MeV/c}^2 \]
\[ \sigma = 1.73 \pm 0.04 \text{ (MC 1.63) MeV/c}^2 \]

mass resolution for \( \phi \)-meson decays

\[ \phi \rightarrow e^+e^- : 10.7 \text{ MeV/c}^2 \]
\[ \phi \rightarrow K^+K^- : 2.1 \text{ MeV/c}^2 \]
Observed Invariant Mass Spectra

$C$  $\phi(1020)$  $\omega(783)$

$Cu$  $\omega(783)$  $\phi(1020)$

$e^+e^-$  $K^+K^-$

$K^+K^-$ threshold
Result of $\rho/\omega \rightarrow e^+e^-$

\( e^+e^- \) Invariant Mass Spectra

- from 2002 run data (~70% of total data)
- C & Cu targets
- acceptance uncorrected
- \( M < 0.2 \text{GeV/c}^2 \) is suppressed by the detector acceptance

\( \rightarrow \) fit the spectra with known sources
Fitting with known sources

- **resonance**
  - $\rho/\omega/\phi \rightarrow e^+e^-$, $\omega \rightarrow \pi^0 e^+e^-$, $\eta \rightarrow \gamma e^+e^-$
  - relativistic Breit-Wigner shape (with internal radiative corrections)
  - nuclear cascade code JAM gives momentum distributions
  - experimental effects are estimated through the Geant4 simulation (multiple scattering, energy loss, external bremsstrahlung, chamber resolution, detector acceptance, etc.)

- **background**
  - combinatorial background obtained by the event mixing method

- **fit parameter**
  - relative abundance of these components is determined by the fitting

*estimated spectrum using GEANT4*
the excess over the known hadronic sources on the low mass side of $\omega$ peak has been observed. The region $0.60-0.76\text{GeV}/c^2$ is excluded from the fit, because the fit including this region results in failure at 99.9% C.L.
\( \rho/\omega \) ratios are consistent with zero!

\[
\rho/\omega = 0.0 \pm 0.03 \text{(stat.)} \pm 0.09 \text{(sys.)}
\]

\[
\rho/\omega = 0.0 \pm 0.04 \text{(stat.)} \pm 0.21 \text{(sys.)}
\]

\( \rho/\omega = 1.0 \pm 0.2 \) in former experiment (p+p, 1974)

\( \Rightarrow \) the origin of the excess is modified \( \rho \) mesons
Simple Model Calculation

- pole mass: \( m^*/m = 1-k\rho/\rho_0 \) (Hatsuda-Lee formula)
- generated at surface of incident hemisphere of target nucleus
  - \( \alpha_\omega \sim 2/3 \) [PR, C75 025201 (2006).]
  - decay inside a nucleus:

<table>
<thead>
<tr>
<th></th>
<th>C</th>
<th>Cu</th>
</tr>
</thead>
<tbody>
<tr>
<td>( \rho )</td>
<td>52%</td>
<td>66%</td>
</tr>
<tr>
<td>( \omega )</td>
<td>5%</td>
<td>10%</td>
</tr>
</tbody>
</table>

- nuclear density distribution: Woods-Saxon
- mass spectrum: relativistic Breit-Wigner Shape
- no width modification
the excesses for C and Cu are well reproduced by the model including the mass modification.
Contours for $\rho/\omega$ and $k$

- C and Cu data are simultaneously fitted.
- Free parameters
  - Production ratio $\rho/\omega$
  - Shift parameter $k$
- Best-Fit values are
  - $k = 0.092 \pm 0.002$
  - $\rho/\omega = 0.7 \pm 0.1$ (C)
  - $0.9 \pm 0.2$ (Cu)

Mass of $\rho/\omega$ meson decreases by 9% at normal nuclear density.
Result of $\phi \rightarrow e^+e^-$

R. Muto et al., PRL, 98 042501 (2007).
\( \phi \rightarrow e^+e^- \) Invariant Mass Spectra

- from 2001 & 2002 run data
- C & Cu targets
- acceptance uncorrected
- fit with
  - simulated mass shape of \( \phi \) (evaluated as same as \( \rho/\omega \))
  - polynomial curve background

\( \rightarrow \) examine the mass shape as a function of \( \beta \gamma (=p/m) \)
(anomaly could be enhanced for slowly moving mesons)
Fitting Results

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

Large Nucleus

Cu

$\chi^2/\text{ndf} = 83/50$

Small Nucleus

Cu

$\chi^2/\text{ndf} = 46/50$

Rejected at 99% confidence level
A significant enhancement is seen in the Cu data, in $\beta \gamma < 1.25$

→ the excess is attributed to the $\phi$ mesons which decay inside a nucleus and are modified

To evaluate the amount the excess $N_{\text{excess}}$, fit again excluding the excess region (0.95~1.01GeV/c$^2$) and integrate the excess area.
Simple Model Calculation

Simple model like $\rho/\omega$ case, except for

- Pole mass: $m^*/m = 1 - k_1 \rho/\rho_0$ (Hatsuda-Lee formula)
- Width broadening: $\Gamma^*/\Gamma = 1 + k_2 \rho/\rho_0$ (no theoretical basis)
  - $e^+e^-$ branching ratio is not changed
    $$\Gamma^*_{e^+e^-}/\Gamma^*_{tot} = \Gamma_{e^+e^-}/\Gamma_{tot}$$
- Uniformly generated in target nucleus
  - $\alpha_\phi \sim 1$ [PR, C75 025201 (2006).]
  - Decay inside a nucleus (for $\beta_\gamma < 1.25$):

<table>
<thead>
<tr>
<th></th>
<th>C</th>
<th>Cu</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\phi$</td>
<td>3%</td>
<td>6%</td>
</tr>
</tbody>
</table>
Fitting Results by the Simple Model

\[ \frac{m^*}{m} = 1 - 0.034 \quad \rho/\rho_0, \quad \frac{\Gamma^*}{\Gamma} = 1 + 2.6 \quad \rho/\rho_0 \]

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

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

well reproduce the data, even slow/Cu
Pole Mass Shift
\[ \frac{M^*}{M} = 1 - k_1 \rho / \rho_0 \]

Width Broadening
\[ \frac{\Gamma^*}{\Gamma} = 1 + k_2 \rho / \rho_0 \]

- C and Cu data are simultaneously fitted.
- free parameters
  - parameter \( k_1 \) & \( k_2 \)

Best-Fit values are
\[ k_1 = 0.034^{+0.006}_{-0.007} \]
\[ k_2^{\text{tot}} = 2.6^{+1.8}_{-1.2} \]

- mass of \( \phi \) meson decreases by 3.4% 
- width of \( \phi \) meson increases by a factor of 3.6 at normal nuclear density.
Result of $\phi \rightarrow K^+K^-$

F. Sakuma et al., PRL, 98 152302 (2007).
\( \phi \rightarrow K^+ K^- \) Invariant Mass Spectra

- from 2001 run data
- C & Cu targets
- acceptance uncorrected
- fit with
  - simulated mass shape of \( \phi \)
    (evaluated as same as \( \rho/\omega \))
  - combinatorial background obtained
    by the event mixing method
- examine the mass shape as a function of \( \beta \gamma \)
Fitting Results

$\beta_\gamma < 1.7$ (Slow)  

$1.7 < \beta_\gamma < 2.2$  

$2.2 < \beta_\gamma$ (Fast)

Mass-spectrum changes are NOT statistically significant.

However, impossible to compare $\phi \rightarrow e^+e^-$ with $\phi \rightarrow K^+K^-$, directly.
Kinematical Distributions of observed $\phi$

- The detector acceptance is different between $e^+e^-$ and $K^+K^-$.
- Very limited statistics for $\phi \rightarrow K^+K^-$ in $\beta\gamma < 1.25$ where the modification is observed in $\phi \rightarrow e^+e^-$.

The histograms for $\phi \rightarrow K^+K^-$ are scaled by a factor $\sim 3$. 

\[
\begin{align*}
\beta\gamma &= 1.25 \\
\text{events} &\quad \text{events} \\
\end{align*}
\]
Summary of shape analysis
### Summary of Shape Analysis

\[ \frac{m^*/m}{m(0)} = 1 - k_1 \frac{\rho}{\rho_0}, \quad \frac{\Gamma^*/\Gamma}{\Gamma} = 1 + k_2 \frac{\rho}{\rho_0} \]

#### Best Fit Values

<table>
<thead>
<tr>
<th></th>
<th>( \rho, \omega )</th>
<th>( \phi )</th>
</tr>
</thead>
<tbody>
<tr>
<td>( k_1 )</td>
<td>9.2 ( \pm 0.2% )</td>
<td>3.4(^{+0.6}_{-0.7}% )</td>
</tr>
<tr>
<td>( k_2 )</td>
<td>0 (fixed)</td>
<td>2.6(^{+1.8}_{-1.2})</td>
</tr>
<tr>
<td>( \rho/\omega )</td>
<td>0.7 ( \pm 0.1 ) (C)</td>
<td>-</td>
</tr>
<tr>
<td></td>
<td>0.9 ( \pm 0.2 ) (Cu)</td>
<td></td>
</tr>
</tbody>
</table>

Syst. error is not included
Result of nuclear mass-number dependences of $\phi \rightarrow e^+e^-$ & $\phi \rightarrow K^+K^-$

Vector Meson, $\phi$

- **mass decreases**
  
  $2\sim 4\% \rightarrow 20\sim 40\text{MeV}/c^2$

- **narrow decay width** ($\Gamma = 4.3\text{MeV}/c^2$)
  
  $\Rightarrow$ sensitive to the mass spectrum change

- **small decay Q value**
  
  $(Q_{K^+K^-} = 32\text{MeV}/c^2)$
  
  $\Rightarrow$ the branching ratio is sensitive to $\phi$ or $K$ modification

**simple example**

- $\phi$ mass decreases
  
  $\rightarrow \Gamma_{\phi \rightarrow K^+K^-}$ becomes small

- $K$ mass decreases
  
  $\rightarrow \Gamma_{\phi \rightarrow K^+K^-}$ becomes large

---

$r_0$: normal nuclear density


and Nuclear Mass-Number Dependence $\alpha$

- $\Gamma_{\phi \rightarrow K^+K^-}/\Gamma_{\phi \rightarrow e^+e^-}$ changes in a nucleus
  $\Rightarrow N_{\phi \rightarrow K^+K^-}/N_{\phi \rightarrow e^+e^-}$ changes also
- The larger modification is expected in the larger nucleus

$$\sigma(A) = \sigma(A = 1) \times A^\alpha$$

$$\Delta \alpha = \alpha_{\phi \rightarrow K^+K^-} - \alpha_{\phi \rightarrow e^+e^-}\quad (A_1 \neq A_2)$$

- Difference between $\alpha_{\phi \rightarrow K^+K^-}$ and $\alpha_{\phi \rightarrow e^+e^-}$ could be found
- Difference of $\alpha$ is expected to be enhanced in slowly moving $\phi$ mesons
Results of Nuclear Mass-Number Dependence $\alpha$

$\Delta \alpha = \alpha_{e^+e^-} - \alpha_{K^+K^-}$

K$^+K^-$ and $e^+e^-$ are consistent with corrected for the $K^+K^-$ acceptance

possible modification of the decay widths is discussed

$\alpha_{\phi \to K^+K^-}$ and $\alpha_{\phi \to e^+e^-}$ are consistent
We attempt to obtain the upper limit of the $\Gamma_{\phi \rightarrow K^+K^-}$ and $\Gamma_{\phi \rightarrow e^+e^-}$ modification.

① The measured $\Delta \alpha$ provides constraints on the $\Gamma_{\phi \rightarrow K^+K^-}$ and $\Gamma_{\phi \rightarrow e^+e^-}$ modification by comparing with the values of expected $\Delta \alpha$ obtained from the MC.

② The constraint on the $\Gamma_{\phi \rightarrow K^+K^-}$ modification is obtained from the $K^+K^-$ spectra by comparing with the MC calculation.

*Theoretical predictions*

Width broadening is expected to be up to $\sim x10$ (Klingl, Kaiser & Weise, etc.)
Discussion on $\Gamma_{\phi \rightarrow K^+K^-}$ and $\Gamma_{\phi \rightarrow e^+e^-}$

\[
\frac{\Gamma_{\phi}^*}{\Gamma_{\phi}^0} = 1 + k_{\text{tot}} \left( \rho/\rho_0 \right),
\]
\[
\frac{\Gamma_{\phi \rightarrow K^+K^-}^*}{\Gamma_{\phi \rightarrow K^+K^-}^0} = 1 + k_K \left( \rho/\rho_0 \right),
\]
\[
\frac{\Gamma_{\phi \rightarrow e^+e^-}^*}{\Gamma_{\phi \rightarrow e^+e^-}^0} = 1 + k_e \left( \rho/\rho_0 \right)
\]

We expect $k_{\text{tot}} = k_K$ since the $\phi$ meson mainly decays into $KK$ as long as such decays are kinematically allowed.

the first experimental limits assigned to the in-medium broadening of the partial decay widths
Summary


- The significant excesses at the low-mass side of $\omega \rightarrow e^+e^-$ and $\phi \rightarrow e^+e^-$ peak have been observed.
  - These excesses are well reproduced by the simple model calculations which take Hatsuda-Lee prediction into account.

- Mass spectrum changes are not statistically significant in the $K^+K^-$ invariant mass distributions.
  - Our statistics in the $K^+K^-$ decay mode are very limited in the $\beta\gamma$ region in which we see the excess in the $e^+e^-$ mode.

- The observed nuclear mass-number dependences of $\phi \rightarrow e^+e^-$ and $\phi \rightarrow K^+K^-$ are consistent.
  - We have obtained limits on the in-medium decay width broadenings for both the $\phi \rightarrow e^+e^-$ and $\phi \rightarrow K^+K^-$ decay channels.
RIKEN Nishina Center
H. Enyo(*), F. Sakuma, T. Tabaru, S. Yokkaichi

KEK

Kyoto-Univ.

CNS, Univ. of Tokyo
H. Hamagaki

Univ. of Tokyo
K. Ozawa

(*) spokesperson