Chiral symmetry in nuclear matter
--from KEK-PS E325 to J-PARC E16--

Satoshi Yokkaichi
(RIKEN Nishina Center)

1) Introduction
   • How can we observe the chiral symmetry restoration?
   • Expected spectral modification of vector mesons in nuclear matter

2) Experiment E325 at KEK-PS
   • Observed vector meson modification in nuclei

3) Future experiment E16 at J-PARC
   • Systematic study of the modification of vector meson spectra
• Origin of hadron mass: spontaneous breaking of chiral symmetry
• In hot/dense matter, chiral symmetry is expected to be restored
  - hadron modification is also expected
  - many theoretical predictions...

Mass and chiral symmetry in nuclear matter

W. Weise, NPA553(93)59
Vector meson mass spectra in dense matter

Effective Lagrangian (chiral SU(3)+VMD)
Klinge, Kaiser, Weise,
NPA624(97)527

QCD sum rule
Hatsuda and Lee,
PRC46(92)R34, PRC52(95)3364

Linear dependence on density
\[ m^*/m_0 = 1 - k \rho/\rho_0 \]
Mass 'dropping'
- \( 16(\pm 6)\% \) for \( \rho/\omega \)
- \( 0.15(\pm 0.05)\times y \)
  = 2\text{~}4\% \) for \( \phi \)
  (for \( y=0.22 \))

at the normal nuclear density

New hadrons WS 08Dec07 S.Yokkaichi
dispersion (mass VS momentum) in dense matter

- S.H.Lee (PRC57(98)927) \( m^*/m_0 = 1 - k \rho/\rho_0 \)
  - \( \rho/\omega \) : \( k=0.16 \pm 0.06 + (0.023 \pm 0.007)(p/0.5)^2 \)
  - \( \phi \) : \( k=0.15(\pm0.05)\ast y + (0.0005 \pm 0.0002)(p/0.5)^2 \)
  - for \( p<1\text{GeV/c} \)

- Post & Mosel (NPA699(02)169) : \( \rho \) meson

- Kondratyuk et al. (PRC58(98)1078) : \( \rho \) meson
# Vector meson measurements in hot/dense matter

<table>
<thead>
<tr>
<th>Experiment</th>
<th>Process</th>
<th>Energy (GeV)</th>
<th>System</th>
</tr>
</thead>
<tbody>
<tr>
<td>HELIOS/3</td>
<td>(ee, μμ)</td>
<td>450 p+Be / 200 A+A</td>
<td></td>
</tr>
<tr>
<td>DLS</td>
<td>(ee)</td>
<td>1 A+A</td>
<td></td>
</tr>
<tr>
<td>CERES</td>
<td>(ee)</td>
<td>450 p+Be/Au / 40-200 A+A</td>
<td></td>
</tr>
<tr>
<td>E325</td>
<td>(ee,KK)</td>
<td>12 p+C/Cu</td>
<td></td>
</tr>
<tr>
<td>NA60</td>
<td>(μμ)</td>
<td>400 p+A/158 In+In</td>
<td></td>
</tr>
<tr>
<td>PHENIX</td>
<td>(ee,KK)</td>
<td>p+p/Au+Au</td>
<td></td>
</tr>
<tr>
<td>HADES</td>
<td>(ee)</td>
<td>4.5 p+A/1-2 A+A</td>
<td></td>
</tr>
<tr>
<td>CLAS-G7</td>
<td>(ee)</td>
<td>1-2 γ+A</td>
<td></td>
</tr>
<tr>
<td>J-PARC E16</td>
<td>(ee)</td>
<td>30/50 p+A / ~20 A+A</td>
<td></td>
</tr>
<tr>
<td>CBM/FAIR</td>
<td>(ee)</td>
<td>20-30 A+A</td>
<td></td>
</tr>
<tr>
<td>TAGX</td>
<td>(ππ)</td>
<td>~1 γ+A</td>
<td></td>
</tr>
<tr>
<td>STAR</td>
<td>(ππ,KK)</td>
<td>p+p/Au+Au</td>
<td></td>
</tr>
<tr>
<td>LEPS</td>
<td>(KK)</td>
<td>1.5-2.4 γ+A</td>
<td></td>
</tr>
<tr>
<td>CBELSA/TAPS</td>
<td>(π⁰γ)</td>
<td>0.64-2.53 γ+p/Nb</td>
<td></td>
</tr>
</tbody>
</table>

Published/ 'modified' published/ 'unmodified' running/in analysis future plan as of 2008/Jul
Vector meson measurements in HIC

- CERES : $e^+e^-$ (EPJC 41('05)475)
  - anomaly at the lower region of $\rho/\omega$
    - in A+A, not in p+A
    - relative abundance is determined by their statistical model

- NA60 : (PRL96(06)162302)
  - $\rho \rightarrow \mu^+\mu^-$:
    - width broadening
    - 'BR scaling is ruled out'

- Discussion is continuing
  - mass dropping or broadening?
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. 10^9 ppp → 10^6Hz interaction)
  - Large acceptance spectrometer to detect slowly moving mesons, which have larger probability decaying inside nuclei (1<βγ<3)

Collaboration

E325 spectrometer located at KEK-PS EP1-B primary beam line
History of E325

- 1993 proposed
- 1994 R&D start
- 1996 construction start
- '97 data taking start
- '98 first ee data
  - PRL86(01)5019 $\rho/\omega (ee)$
  - 99,00,01,02....
    - x100 statistics
    - PRL96(06)092301 $\rho/\omega (ee)$
    - PRC74(06)025201 $\alpha (ee)$
    - PRL98(07)042501 $\phi (ee)$
    - PRL98(07)152302 $\phi (KK),\alpha$
- '02 completed
- spectrometer paper
  - NIM A457(01)581
  - 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
• Typical $e^+e^-$ Event
  - **blue**: electron
  - **red**: other
  - invariant mass and momentum of mother particle can be calculated
E325 Results

e^+e^- invariant mass spectra

M. Naruki et al.,
PRL 96 (2006) 092301
R.Muto et al.,
PRL 98 (2007) 042501
measured kinematic distribution of $\omega/\phi \rightarrow e^+e^-$

- $0 < P_T < 1$, $0.5 < y < 2$ ($y_{CM}=1.66$)

- $1 < \beta \gamma \ (=p/m) < 3$ ($0.8<p<2.4\text{GeV/c for }\omega$, $1<p<3\text{ GeV/c for }\phi$)
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
**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

shorter-life meson (\(\rho\)) case
- outside decay (natural)
- inside decay (modified)

expected to be observed

\[\text{Schematic picture}\]
E325 observed the meson modifications

- in the $e^+e^-$ channel
- below the $\omega$ and $\phi$, statistically significant excesses over the known hadronic sources including experimental effects
**Analysis : Fitting with known sources**

- Hadronic sources of $e^+e^-$:
  - $\rho/\omega/\phi \rightarrow e^+e^-$, $\omega \rightarrow \pi^0e^+e^-$, $\eta \rightarrow \gamma e^+e^-$
  - 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
\( \phi \rightarrow e^+e^- \) invariant mass spectra

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

- from 2001/02 run data
- C & Cu target
- acceptance uncorrected
- mass resolution : 10.7 MeV
- fit with
  - simulated mass shape of \( \phi \)
  - polynomial curve background
- examine the 'excess' is significant or not
  - check 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) \hspace{2cm} 1.25 < $\beta\gamma$ < 1.75 \hspace{2cm} 1.75 < $\beta\gamma$ (Fast)
$e^+e^-$ spectra of $\phi$ meson (divided by $\beta\gamma$)

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

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.
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.
**Discussion : modification parameters**

- MC type model analysis to include the nuclear size/meson velocity effects
  - generation point: uniform for φ 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 with the predictions

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

3.4% mass reduction (35MeV)  
3.6 times width broadening (16MeV)  
at \( \rho_0 \)
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 with the predictions

$$k_1 = 0.034^{+0.006}_{-0.007}$$
$$k_2^{\text{tot}} = 2.6^{+1.8}_{-1.2}$$

3.4% mass reduction (35MeV)
3.6 times width broadening (16MeV) at $\rho_0$
Summary (1)

- 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, $T=0$.

- 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 $\rho$ (and $\omega$) meson.
  - Simple model calculation including predicted modification of $\rho$ & $\omega$ reproduces the observed spectra. (~9% of mass reduction)

- $\phi \rightarrow e^+e^-$ also have excess, for the larger target, slowly moving component: the first result in the world for the $\phi$-meson spectral modification
  - model calc. including mass shift and width broadening in nuclei also reproduces the data. (~3.4% of mass reduction & ~3.6-times broadening )

- Deduced modification parameters are almost consistent with the theoretical prediction using in-medium QCD sum rule.
From “mass modification” to physics

- Mass shape modification of vector mesons in medium looks to be established by many experimental results (E325/CLAS-G7/TAPS at the lower energy, NA60/CERES in HI collision)
  - statements contradict each other
    - mass dropping and/or width broadening
    - depending on the interpretation models to include the matter size effect
  - physics
    - only hadronic effects? or chiral restoration?
- Next step in the invariant-mass approach
  - put an emphasis on $\phi \rightarrow e^+e^-$: less ambiguous than $\rho/\omega$ case
    - $\rho$'s broad and complicated shape, $\rho-\omega$ interference, $\rho/\omega$ ratio, etc.
  - systematic study of the shape modification
    - nuclear matter size dependence: larger/smaller nuclei, collision geometry
    - momentum dependence: predicted, but not measured yet
J-PARC E16 experiment

Future experiment:
Systematic study of the modification of vector meson spectra in nuclei
to approach the chiral symmetry restoration
**J-PARC E16 experiment**

- **Status**: 2007/3: stage1 (physics) approval / Detector R&D is on going

- **Main goal**: collect $\sim 1 - 2 \times 10^5 \phi \rightarrow e^+e^-$ for each target in 5 weeks using 30 (or 50) GeV $p + A$ (C/CH$_2$/Cu/Pb) reactions
  - statistics: $\sim 100$ times as large as E325
  - **systematic study of the modification**
    - velocity & nuclear size (0~10 fm) dependence
      - proton/Pb targets / collision geometry (impact parameter)
    - momentum dependence (dispersion relation)
      - mass resolution: $< 10$ MeV (E325: 10.7 MeV for $\phi$)

**Collaboration**

RIKEN  
S.Yokkaichi, H. En'yo, F. Sakuma, K. Aoki  
Hiroshima-U  
K. Shigaki

U-Tokyo  
K. Ozawa, K. Utsunomiya, Y. Watanabe  
CNS, U-Tokyo  
H. Hamagaki

KEK  
A.Kiyomichi, M. Naruki, R.Muto, S. Sawada, M. Sekimoto

**Proposal**  
To collect high statistics

- For the statistics 100 times as large as E325, a **new spectrometer** is required.
  - To cover larger acceptance: \( x \sim 5 \)
  - Higher energy beam \( (12 \rightarrow 30/50 \text{ GeV}) \): \( x \sim 2 \) of production
  - Higher intensity beam \( (10^9 \rightarrow 10^{10} / \text{spill (1sec)}) \): \( x \times 10 \) \( \rightarrow 10\text{MHz} \) interaction on

### Geometrical (horizontal & vertical) coverage of the spectrometer

<table>
<thead>
<tr>
<th>Angle (degree)</th>
</tr>
</thead>
<tbody>
<tr>
<td>+135 (left)</td>
</tr>
<tr>
<td>+45</td>
</tr>
<tr>
<td>0</td>
</tr>
<tr>
<td>-135 (right)</td>
</tr>
<tr>
<td>-45</td>
</tr>
</tbody>
</table>

### Target configuration

<table>
<thead>
<tr>
<th>Nuclei</th>
<th>Interaction Length (%)</th>
<th>Radiation Length (%)</th>
<th>Thickness [( \mu \text{m} )]</th>
</tr>
</thead>
<tbody>
<tr>
<td>C</td>
<td>0.05</td>
<td>0.1</td>
<td>200</td>
</tr>
<tr>
<td>CH(_2)</td>
<td>0.05</td>
<td>0.1</td>
<td>400</td>
</tr>
<tr>
<td>Cu</td>
<td>0.05</td>
<td>0.1</td>
<td>80</td>
</tr>
<tr>
<td>Pb</td>
<td>0.01</td>
<td>0.3</td>
<td>20</td>
</tr>
</tbody>
</table>

New hadrons WS 08Dec07 S.Yokkaichi
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

\[ \frac{N_{\text{excess}}}{N_{\text{excess}} + N_p} \]

- establish the modification

\[ \times 100 \text{ stat.} \]

- Pb
- proton
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 ($p<1\text{GeV}$)
- current E325 analysis neglects the dispersion (limited by the statistics)
dispersion relation (mass VS momentum)

- prediction for $\phi$ by S.H.Lee ($p<1\text{GeV}$)
- current E325 analysis neglects the dispersion (limited by the statistics)
- fit with common shift parameter $k_1(p)$, to all nuclear targets in each momentum bin
**mass resolution requirement**

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

\[ \beta \gamma < 0.5, \quad \sigma = 5 \text{ MeV} \]
Summary (2)

- Spectral modification of vector mesons are observed in nuclei (and also in heavy ion collisions).
  - under discussion about the physics behind such phenomena
- Next step at J-PARC: E16 exp.
  - systematic measurements of matter size (0~10 fm) and momentum dependences of the modification of $\phi$ meson
- Possible further steps:
  - measurements of meson decays from mesic nuclei
    - $\omega (\phi)$ bound state in nuclei using $\pi (\bar{p})$ beam at J-PARC
  - density dependence using heavy-ion collisions
    - GSI, J-PARC
Backup slides...
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 results ($\rho/\omega$)

- **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)

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

- However, \( \rho/\omega = 1.0 \pm 0.2 \) in former experiment (p+p, 1974)
- ...suggests that the origin of excess is modified \( \rho \) mesons.
**Discussion (ρ/ω)**

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

- Spectrometer Magnet: reuse E325's
  - remodeling the pole / repairing the coil
  - stronger field for compact detector size
- GEM (Gas electron multiplier) Tracker
  - 0.7mm pitch strip readout
- Two-stage Electron ID ($10^{-4} \pi$ rejection)
  - Hadron Blind Detector (Gas Cherenkov)
    - GEM+CsI photocathode
    - hexagonal pad readout (~30mm φ)
  - Leadglass EMC: reuse of TOPAZ
- ~70K Readout Channels (in 26 segments)
  - cf. E325: 3.6K, PHENIX:~300K (w/o VTX)
- Cost: ~$5M (including ~$2M electronics)
  - cf. E325: $2M not including electronics
High momentum Beamline

30/50GeV proton beam (upto $10^{12}$/sec)
## Discussion: fit with modification

- Assumptions to include the nuclear size effect in the fitting shape
  - dropping mass: $M(\rho)/M(0) = 1 - k_1 (\rho/\rho_0)$
    (Hatsuda & Lee, $k=0.16 \pm 0.06$)
  - width broadening: $\Gamma(\rho)/\Gamma(0) = 1 + k_2 (\rho/\rho_0)$
    (~ Oset & Ramos)
    (momentum dependence of modification is not taken into account this time)

<table>
<thead>
<tr>
<th>$m^*/m$</th>
<th>$\rho$, $\omega$</th>
<th>$\phi$</th>
</tr>
</thead>
<tbody>
<tr>
<td>$1 - k_1 \rho/\omega \rho/\rho_0$</td>
<td>$1 - k_1 \phi \rho/\rho_0$</td>
<td></td>
</tr>
<tr>
<td>$\Gamma^*/\Gamma$</td>
<td>1</td>
<td>$1 + k_2 \rho/\rho_0$</td>
</tr>
<tr>
<td>generation point</td>
<td>surface</td>
<td>uniform</td>
</tr>
<tr>
<td>$\alpha (\sigma(A) \propto A^\alpha)$</td>
<td>$0.710 \pm 0.021$</td>
<td>$0.937 \pm 0.049$</td>
</tr>
<tr>
<td>[PRC74(06)025201]</td>
<td></td>
<td></td>
</tr>
<tr>
<td>momentum dist.</td>
<td>measured</td>
<td></td>
</tr>
<tr>
<td>density distribution</td>
<td>Woods-Saxon, $R = C:2.3\text{fm}/Cu:4.1\text{fm}$</td>
<td></td>
</tr>
</tbody>
</table>
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)
experimental effects on the BW shape (E325)

- E325 Detector Sim.
  - target material is negligible for ~0.5% radiation length \( (X_0) \)
  - detectors: up to 4.5% \( X_0 \) in the tracking region

![Graphs showing E325 Detector Sim. effects]
**experimental effects on the BW shape (E325)**

- E325 Detector Sim.
  - target material is negligible for ~0.5% radiation length ($X_0$)
  - detectors: up to 4.5% $X_0$ in the tracking region

- In the case of the thick targets: 1g/cm$^2$
  - bremsstrahlung in target is so large for the Cu case
E325 Results (2)

KK invariant mass spectra

F. Sakuma et al., PRL98(2007)152302

Production Cross sections

T.Tabaru et al., PRC74(2006)025201
$K^+K^-$ spectra of $\phi$ meson

- slow ($\beta\gamma < 1.7$)
- (1.7 < $\beta\gamma < 2.2$)
- fast ($2.2 < \beta\gamma$)

- mass modification is NOT statistically significant (very low statistics in $\beta\gamma < 1.25$ where modification is observed in $\phi \rightarrow e^+e^-$)
measured kinematic distribution of $\phi \rightarrow K^+K^-$ & $\phi \rightarrow e^+e^-$

- $0.5 < y < 1.5$
- $1 < \beta\gamma < 3$
- $0.5 < P_T < 1.5$
- overlayed
  - $\phi \rightarrow K^+K^-$
  - $\phi \rightarrow e^+e^-$
**mass modification and φ branching ratio**

- small decay Q value (= 32MeV) for $\phi \rightarrow K^+K^-$
  - branching ratio is sensitive to $\phi$ and $K$ mass modification
    - when $\phi$ mass decrease: $\Gamma_{K^+K^-}$ decrease
    - when $K$ mass decrease: $\Gamma_{K^+K^-}$ increase
- change of the ratio: $\Gamma_{K^+K^-}/\Gamma_{e^+e^-}$ can be studied by measurement of parameter: the nuclear dependence of production cross section
  - measure both $\phi \rightarrow K^+K^-$ & $\phi \rightarrow e^+e^-$ simultaneously
  
  => NEXT
nuclear dependence $\alpha$ of the prod. CS of $\phi$ in $K^+K^-$ & $e^+e^-$ channel

• nuclear dependence $\alpha$:
  
  $\sigma(A) = \sigma_0 \times A^{\alpha}$

• $\alpha$ and $\Gamma$ : for example
  
  - $\Gamma_{K^+K^-}/\Gamma_{e^+e^-}$ increases in nuclei, $N_{K^+K^-}/N_{e^+e^-}$ becomes larger
  - larger modification expected in larger nuclei
  - then, $\alpha_{K^+K^-} > \alpha_{e^+e^-}$, especially for slowly moving mesons

• ...looks such tendency but consistent within the errors
nuclear dependence $\alpha$ of the prod. CS of $\phi$ in $K^+K^-$ & $e^+e^-$ channel

- nuclear dependence $\alpha$:
  - $\sigma(A) = \sigma_0 A^\alpha$

- $\alpha$ and $\Gamma$ : for example
  - $\Gamma_{K^+K^-}/\Gamma_{e^+e^-}$ increases in nuclei, $N_{K^+K^-}/N_{e^+e^-}$ becomes larger
  - larger modification expected in larger nuclei
  - then, $\alpha_{K^+K^-} > \alpha_{e^+e^-}$, especially for slowly moving mesons

- looks such tendency but consistent within the errors: $\alpha_{K^+K^-} - \alpha_{e^+e^-} = 0.14 \pm 0.12$
Limit to the $\phi$ width broadening

- limitation from the $\Delta \alpha$:
  - $k_K$ and $k_e$
- limitation from the KK spectra
  - $k_K < 6.0$ (90%CL)

\[
\frac{\Gamma^\ast}{\Gamma^0} = 1 + k_{\text{tot}} \left( \frac{\rho}{\rho_0} \right),
\]
\[
\frac{\Gamma^\ast}{\Gamma^0} = 1 + k_K \left( \frac{\rho}{\rho_0} \right),
\]
\[
\frac{\Gamma^\ast}{\Gamma^0} = 1 + k_e \left( \frac{\rho}{\rho_0} \right)
\]
measured production CS by E325

- values for the CM backward
- consistent w/ the former measurement for $\rho$ meson by Blobel (PLB48(1974)73)

PRC 74(2006)025201
## Experimental setup - targets

<table>
<thead>
<tr>
<th>material</th>
<th>beam intensity (p/spill)</th>
<th>Interaction length(%)</th>
<th>radiation length(%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>C</td>
<td>~1x10^9</td>
<td>0.2%</td>
<td>0.4%</td>
</tr>
<tr>
<td>Cu X 4</td>
<td>~1x10^9</td>
<td>0.05%X4</td>
<td>0.6%X4</td>
</tr>
</tbody>
</table>

### targets in 2002

- **e⁺e⁻ sample in ’02**
- **Beam**
- **Cu**
- **23mm**

---

New hadrons WS 08Dec07 S.Yokkaichi
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
\[ \phi \rightarrow e^+e^- : 10.7 \text{ MeV/c}^2 \]
\[ \phi \rightarrow K^+K^- : 2.1 \text{ MeV/c}^2 \]
**Vector meson measurements in HIC**

- **CERES :** $\mathrm{e^+e^-}$ (EPJC 41('05)475)
  - anomaly at the lower region of $\rho/\omega$
  - in $\mathrm{A+A}$, not in $\mathrm{p+A}$
  - relative abundance is determined by their statistical model

- **NA60 :** (PRL96(06)162302)
  - $\rho \to \mu^+\mu^-$:
    - width broadening
    - 'BR scaling is ruled out'
Vector meson measurements in HIC

- CERES: (arXiv: 0611022v3)
  - “broadening by hadronic effect“ is favored

![Graphs](attachment:graph.png)
Vector meson measurements in HIC

- PHENIX : (arXiv:0706.3034v1)
  - 200GeV /u Au+Au → e⁺e⁻
  - enhancement below ω
CBELSA/TAPS \textbf{(PRL94(05)192303)}

- $\omega \rightarrow \pi^0 \gamma$ (→ $\gamma \gamma \gamma$)
- anomaly in $\gamma + \text{Nb}$, not in $\gamma + p$
  - shift param. $k \sim 0.13$
**CLAS-G7** (PRC78(2008)015201)

- $\gamma + A \rightarrow V \rightarrow e^+e^-$
- no anomaly for $p > 0.8\text{GeV/c}$

BKG subtracted
mass resolution requirement

- mass resolution should be kept less than ~10MeV

Fast

\[ \sigma = 11\text{MeV} \]
\[ \sigma = 5\text{MeV} \]
\[ \sigma = 2.0\text{MeV} \]

Slow

\[ \beta y > 3 \]
\[ \beta y < 1.5 \]

(model calc. for the Cu target)
New nuclear targets with larger statistics

- Smaller nuclear target:
  - proton as reference ($\text{CH}_2 - \text{C}$ subtraction)
  - LH target cannot be used because of the materials

- Larger nuclear target as Pb
  - larger nuclear matter
  - collision geometry ("impact parameter") study using multiplicity (PRC60 024902 (18GeV p+A))
    - can be divided to at least two regions
    - another type of the matter size effect
  - larger radiation length for heavier target
    → more thinner foil target to keep S/N
  - high statistics capability is required.
$\phi \rightarrow e^+e^-$ invariant mass spectra

- from 2001/02 run data
- C & Cu target
- acceptance uncorrected
- mass resolution :10.7MeV
- fit with
  - simulated mass shape of $\phi$
  - polynomial curve background
$\phi \rightarrow e^+e^-$ 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 $\rho$ & $\omega$)
  - polynomial curve background
- examine the 'excess' is significant or not.
  - see the $\beta\gamma$ dependence: excess could be enhanced for slowly moving mesons
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.
Amount of excess

- To evaluate the amount of excess \( N_{\text{excess}} \), fit again excluding the excess region (0.95~1.01 GeV) and integrate the excess area.
MC type calc. : mesons are generated, fitted and modified
- observed momentum dist.
- 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:
  \( \Gamma_{\text{tot}}^*/\Gamma_{\text{tot}}^0 = 1 + k_2 \rho/\rho_0 \)
- e⁺e⁻ branching ratio is not changed
  - \( \Gamma_{e^+e^-}^*/\Gamma_{\text{tot}}^* = \Gamma_{e^+e^-}^0/\Gamma_{\text{tot}}^0 \)
- fits were done with many combinations of \( (k_1, k_2) \)
Fit using modified mass shapes

- MC-type calc. mesons are generated, filled and modified
  - observed momentum dist.
  - 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:
      $$\Gamma_{\text{tot}}^*/\Gamma_{\text{tot}}^0 = 1 + k_2 \rho/\rho_0$$
  - $e^+e^-$ branching ratio is not changed
    - $\Gamma_{e^+e^-}^*/\Gamma_{\text{tot}}^0 = \Gamma_{e^+e^-}^0/\Gamma_{\text{tot}}^0$
    - fits were done with many combinations of ($k_1$, $k_2$)
Model fitting: parameter \( k_1 \) and \( k_2 \)

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

- 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...
  - $m^*/m_0 = 1 - k_1 \rho/\rho_0$
  - $\Gamma_{\text{tot}}^*/\Gamma_{\text{tot}}^0 = 1 + k_2 \rho/\rho_0$

- 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 for each $(k_1, k_2)$ combination on the grid and make the $\chi^2$ contour

Best Fit Value:

$$k_1 = 0.034^{+0.006}_{-0.007} \quad m^* = 985 \text{MeV}$$
$$k_2^{\text{tot}} = 2.6^{+1.8}_{-1.2} \quad \Gamma_{\text{tot}}^* = 16 \text{MeV}$$

(3.6 times width broadening at $\rho_0$)