Study of finite-density QCD using a primary beam (and related experiments)

Satoshi Yokkaich (RIKEN Nishina Center)

- Contents
  - QCD phase diagram and finite density QCD
  - To explore the structure of QCD vacuum
    - systematic study of mass modification of vector meson in nuclei (E16)
    - proposed mesic-nuclei experiments (P26, P29, Lol)
      - ω, φ, and η –nuclei
    - ...
  - quark structure of hadrons using High-p beam line (P04/P24, ...)
    - spin structure of nucleon / pion polarizability
Origin of Mass (Higgs)

Big Bang 10p[sec]/1P[K]

quark mass

0 MeV 3 MeV

“resistance”

Higgs condensate

schematic diagram of vacuum
Origin of quark and hadron mass: spontaneous breaking of chiral symmetry, originally proposed by Nambu.
Mass and chiral symmetry in nuclear matter

- Origin of quark and 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...

W. Weise, NPA553(93)59

Mass and chiral symmetry in nuclear matter

| vacuum | normal nuclear density |

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

**Bronwn-Rho scaling**

PRL 66(91)2720, etc

\[
m^*_\rho / m_\rho \sim \left( \langle \bar{q}q \rangle^*/\langle \bar{q}q \rangle \right)^{1/2}
\]

**Effective Lagrangian**

(chiral SU(3)+VMD)

Klinge,Kaiser,Weise, NPA 624(97)527

**QCD sum rule**

Hatsuda and Lee, PRC 46(92)R34, PRC 52(95)3364

**Linear dependence on density**

\[ m^*/m_0 = 1 - k \rho/\rho_0 \]

**Mass 'dropping'**

- 16(±6)% for \( \rho/\omega \)
- 0.15(±0.05)*y = 2~4% for \( \phi \)

for \( y = 0.22 \)

at the normal nuclear density
dispersion (mass VS momentum) in dense matter

- S.H.Lee (PRC57(98)927)
  - \( m^*/m_0 = 1 - k \rho/\rho_0 \)
  - \( \rho/\omega : k=0.16 \pm 0.06 + (0.023 \pm 0.007)(p/0.5)^2 \)
  - \( \phi : k=0.15(\pm 0.05)\ast y - (0.0005 \pm 0.0002)(p/0.5)^2 \)
  - for \( p<1 GeV/c \)

- Harada & Sasaki (arXiv:0902.3608v1)

- Post & Mosel (NPA699(02)169)

- Kondratyuk et al. (PRC58(98)1078)
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
- **HADES** (ee) 4.5GeV p+A/ 1-2GeV A+A
- **CLAS-G7** (*) (ee) 1~2 GeV γ+A
- **J-PARC E16** (ee) 30/50GeV p+A / ~20GeV A+A ?
- **CBM/FAIR** (ee) 20~30GeV A+A
- **TAGX** (ππ) ~1 GeV γ+A
- **STAR** (ππ,KK) p+p/Au+Au
- **LEPS** (KK) 1.5~2.4 GeV γ+A
- **CBELSA/TAPS(*)** (π^0γ) 0.64-2.53 GeV γ + p/Nb

Dilepton measurement

*published/ 'modified' published/ 'unmodified' running/in analysis future plan as of 2009/Dec*
Experimental setup of KEK-PS E325

$12\text{GeV} \, p + A \rightarrow \rho / \omega / \phi + X \, \left( \rho / \omega / \phi \rightarrow e^+ e^-, \phi \rightarrow K^+ K^- \right)$

- Typical $e^+ e^-$ Event
  - **blue**: electron
  - **red**: other
  - invariant mass and momentum of mother particle can be calculated

- Experimental condition
  - 1GHz proton beam, 1MHz interaction, 1K $\phi$ mesons, 0.3 $ee$ decays, 9% come into detector, 10% overall efficiency, ...
**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 (ω & φ ) cases: Schematic picture**

1) decay inside nuclei
2) decay outside nuclei

expected to be observed
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
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 ($\Gamma$)

$k_1 = 0.034^{+0.006}_{-0.007}$

$k_2^{\text{tot}} = 2.6^{+1.8}_{-1.2}$

For $\phi$, 3.4% mass reduction (35MeV) 3.6 times width broadening (16MeV) at $\rho_0$
Recent status in the world

- mass modification of vector mesons in nuclear matter exist (E325/CLAS-G7/(TAPS) at the lower energy, NA60/CERES/PHENIX in HI collision)
  - interpretations are not converged
    - mass dropping and/or width broadening?
    - interpretation model dependence?
      - space-time evolution of the (T, ρ) of matter in the real world
  - physics
    - hadronic many-body effect? chiral symmetry restoration?

- Next step in the invariant-mass approach
  - φ → e+e−: less uncertain than the ρ/ω case
    - ρ's broad and complicated shape, ρ–ω interference, ρ/ω ratio, etc.
  - systematic study of the mass modification
    - matter-size dependence: larger/smaller nuclei, impact parameter
    - momentum dependence: never measured
  - check the interpretation models
J-PARC E16 experiment
Systematic study of the modification of vector meson spectra in nuclei
to approach the chiral symmetry restoration

Collaboration
RIKEN S.Yokkaichi, H. En'yo, F. Sakuma, K. Aoki, J. Kanaya
U-Tokyo K. Ozawa, K. Utsunomiya, Y. Watanabe, Y.Komatsu, S.Masumoto
CNS, U-Tokyo H. Hamagaki Hiroshima-U K. Shigaki
KEK A.Kiyomichi, M. Naruki, R. Muto, S. Sawada, M. Sekimoto


Scientific approval : 2007/3
... Detector R&D ...
Ready for beam : 2012/autumn
Location of E16: High-momentum beam line

SM1: branched by 5°
Vertical Bend

3.9°
5.8° x3

Experimental Area

Beam dump and shields are for $10^{10}$ protons/s

by R. Muto
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 ($12 \rightarrow 30/50$ GeV): $x \sim 2$ of production
  - Higher intensity beam ($10^9 \rightarrow 10^{10}$/spill (1sec)): $x \times 10$ ($\rightarrow 10$ MHz interaction on targets)

Proposed Spectrometer
Detector R&D
Beam test results of the Prototype Detector Module

GEM Chamber:
required position resolution (~100µm) is achieved

Hadron Blind Detector:
UV Cherenkov photons from the electron beam are detected by CsI-GEM in CF4
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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**mass resolution requirement**

- mass resolution should be kept less than ~10MeV
- Very ideal case: very slow mesons with best mass resolution:

![Graph](image)

PRL98(07)042501, E325 data

\[ \phi (1020) \]

Cu

\[ \beta \gamma < 1.25 \]

\[ \beta \gamma < 0.5, \sigma = 5 \text{ MeV} \]

(model calc.)
charmonium yield @E16

- charmonium mass is governed by gluon condensate
  - small modification is expected for $J/\psi$
    - even narrow width (no in-medium decays)
      - width broadening ($\sim 10$MeV) for $\chi_c$, $\psi(2s)$ and mass decreasing ($\sim 10$-100MeV)

- very rough estimation w/ the production CS ratio

<table>
<thead>
<tr>
<th></th>
<th>$\phi$ (12GeV)</th>
<th>$J/\psi$ (50GeV)</th>
<th>ratio</th>
<th>$\psi (3686)$</th>
</tr>
</thead>
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<tr>
<td>pp</td>
<td>70ub</td>
<td>0.01ub</td>
<td></td>
<td></td>
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<tr>
<td>pCu</td>
<td>1mb</td>
<td>5mb*1</td>
<td>0.5ub*2</td>
<td>1/10000</td>
</tr>
<tr>
<td>ee branch</td>
<td>0.03%</td>
<td>6%</td>
<td>200</td>
<td>0.7%</td>
</tr>
<tr>
<td>yield</td>
<td>100000</td>
<td>2000</td>
<td>1/50</td>
<td>&lt;200</td>
</tr>
</tbody>
</table>

- *1: JAM & empirical formula, from 12GeV data
- *2: nuclear dependence $\sim A$, from pp
- $10^{10}$ ppp, 0.1% int. target
Summary of E16 experiment

- 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: $\sigma < 10$ MeV (E325: 10.7 MeV for $\phi$)
    - double peak structure can be seen with $\beta \gamma < 0.5$, $\sigma \sim 5-6$ MeV
  - $\rho$, $\omega$, J/$\psi$'s also can be measured at the same time
  - Confirm the modification observed in E325, and provide new information about the mass of hadrons
Meson bound state
Deeply bound pionic atom@GSI

- optical potential $b_1$
  - $\rightarrow$ pion decay const. (TW)
  - $\rightarrow$ chiral condensate (GOR)
  - $\langle \bar{q}q \rangle_{\rho_0} / \langle \bar{q}q \rangle_0$ ~ 0.67

K. Suzuki et al, PRL 92(04)072302
meson bound state in nuclei

- \( \omega \) bound state (P26 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

theoretical predictions of missing mass and invariant mass
meson bound state in nuclei

- $\phi$ bound state : (P29 Ohnishi)
  - missing mass spectroscopy in $\text{pbar} + A / \pi^- + A$ reaction
    - elementary: $\sim 1.3 \text{ GeV/c}$ $\text{pbar} + p \rightarrow \phi + \phi$
    - ($\phi$ or $\sim 2 \text{ GeV/c}$ $\pi^- + p \rightarrow \phi + n$)
    - measurements of the dilepton decay of $\phi$ is difficult

- $\eta$ bound state (Lol Itahashi)
  - missing mass spectroscopy in $\pi^- + A$ reaction
    - elementary: $\sim 1 \text{ GeV/c}$ $\pi^- + p \rightarrow \eta + n$
    - information of the $N^*(1535)$ : chiral partner of nucleon
    - possibly can measure the $\eta$ decay to $\gamma\gamma$
Chiral restoration and degeneration of chiral partners

\[ \pi - \sigma \]

\[ \rho - a_1 \]

\[ N - N^* : \text{mirror representation} \]

- \( \eta N - N^* \) coupling

Jido, Oka, Hosaka (PTP 106(01)873)

Mesons

Baryons

GeV

\( 1^+ \eta (1260) \)
\( 1^+ f_1(1285) \)
\( 0^+ \pi (1300) \)
\( \eta (1295) \)
\( 1^+ K_1(1400) \)
\( 0^+ K_1(1270) \)
\( 1^- N(1535) \)

\( 1^- \rho (770) \)
\( 1^- \omega (780) \)
\( 0^+ a_0 (980) \)
\( f_0 (975) \)
\( 1^- K (890) \)

\( 0^- \pi (139) \)

\( \sigma (600) \)

\( \eta N^* \)

\( N^* \)

	

\[ m_0 = 270 \]

\[ m_+ \]

\[ m_\perp \]

\[ \text{vacuum} \]

Chiral condensate \( \sigma_0 [\text{MeV}] \)

Naive

Mirror
Structure of hadrons
Spin Structure of nucleon

- orbital angular momentum of partons in nucleon
- sivers distribution function
- DY experiment @ High-\(p\) line
  - + polarized proton \(~10^{12} /\text{pulse}\) (P04 Peng, Sawada)

\[
\frac{1}{2} = \frac{1}{2} (\Delta u + \Delta d)
\]

\[
\frac{1}{2} = \frac{1}{2} (\Delta q + \Delta \bar{q}) + \Delta G + L_z
\]

25m

4.9m
Polarizability of hadron

- Electric/Magnetic polarizability
  - Primakoff effect (EM field of target nuclei)
    - using 40 (20) GeV/c $\pi$ beam
      @ High-$p$ line (Nakagawa)

Electric Polarizability
\[ P_E = 4\pi\alpha_E E \]

Magnetic Polarizability
\[ \mu_M = 4\pi\beta_M H \]
Summary

- Study of the nature of QCD vacuum
  - spontaneous breaking of chiral symmetry as a major origin of mass
  - hadrons (as a probe) in finite density
    - hadrons in nuclei: measurements of invariant mass and/or meson bound state
      - chiral condensate, gluon condensate, baryon representation...
    - ...and more dense QCD matter
  - ...and its excitation (i.e. hadrons and constituent quarks)
    - structure of hadrons
Summary

- Study of the nature of QCD vacuum
  - Next frontier of QCD is the dense matter
Backup slides...
density & chiral condensate in HIC

- Friman et.al (EPJA 3(98)165)

where $\langle \bar{q}q \rangle / \langle \bar{q}q \rangle_0$ is smaller than $r$
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!
$e^+e^-$ spectra of $\phi$ meson (divided by $\beta\gamma$)

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

\[ \chi^2/\text{ndf} = 36/50 \]  
\[ \chi^2/\text{ndf} = 63/50 \]  
\[ \chi^2/\text{ndf} = 46/50 \]  
\[ \chi^2/\text{ndf} = 83/50 \]  
\[ \chi^2/\text{ndf} = 43/50 \]  
\[ \chi^2/\text{ndf} = 56/50 \]
$e^+e^-$ 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.
**mass resolution requirement**

- mass resolution should be kept less than ~10MeV

Fast

\[ \sigma = 11\text{MeV} \quad \sigma = 5\text{MeV} \quad \sigma = 20\text{MeV} \]

\[ \beta y > 3 \]

Slow

\[ \beta y < 1.5 \]

(model calc. for the Cu target)
Experiment KEK-PS E325

• $12\text{GeV } p+A \rightarrow \rho/\omega/\phi + X \left( \rho/\omega/\phi \rightarrow e^+e^-, \phi \rightarrow K^+K^- \right)$

• 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 $\rightarrow$ $10^6$Hz interaction)
  - Large acceptance spectrometer to detect slowly moving mesons, which have larger probability decaying inside nuclei ($1<\beta\gamma<3$)

Collaboration

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
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 $\omega/\phi \rightarrow e^+e^-$

- $0 < P_T < 1, \quad 0.5 < y < 2 \quad (y_{CM} = 1.66)$
- $1 < \beta \gamma (=p/m) < 3 \quad (0.8<p<2.4\text{GeV/c for } \omega, \ 1<p<3 \text{ GeV/c for } \phi)$
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

shorter-life meson ($\rho$) case:

outside decay (natural)  +  inside decay (modified)

Schematic picture expected to be observed
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

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- systematic study: all the data should be explained the interpretation model

- establish the modification

**velocity and nuclear size dependence**

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

- establish the modification
- check the interpretation model with shape analysis for each histogram