Meson Properties from Mesic Atoms and Mesic Nuclei

Satoru Hirenzaki

Nara Women’s University,

13th Int. Workshop Meson Production, Properties and Interaction (MESON2014)
Krakow, Poland, May 29 – June 3, 2014
schematic view of the mass of $\pi, K, \eta$ & $\eta'$

\[\begin{array}{c}
\eta_0 \\
\eta \\
K \\
\pi, K, \eta_8 \\
\pi, K, \eta_0
\end{array}\]

$U_A(1)$ anomaly effect

$m_q, m_s = 0$ \quad $m_q, m_s = 0$ \quad $m_q, m_s \neq 0$

\[\begin{array}{c}
\langle \bar{q}q \rangle = 0 \\
\langle \bar{q}q \rangle \neq 0 \\
\langle \bar{q}q \rangle \neq 0
\end{array}\]

ChS manifest

dynamically broken

dyn. & explicitly broken

cf.) NJL model with KMT

$\rho/\rho_0$

\[\begin{array}{c}
\Delta m \sim -150 \text{ MeV} @ \rho_0
\end{array}\]

Jido et al., PRC85(12)032201(R)
Nagahiro et al., PRC (2013)

$U_A(1)$ breaking
(KMT term$^{[1,2]}$)

$\langle \bar{q}q \rangle \rightarrow 0$

PTP44(70)1422
[2] G. 't Hooft,
PRD14(76)3432

Costa et al., PLB560(03)171,
Nagahiro-Takizawa-Hirenzaki, PRC74(06)045203
Meson in Nucleus (related topics)

- Deeply Bound Pionic Atoms
- $\eta'(958)$ anomaly effect @ finite density, Exp. Plan
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- Kaonic Atoms, Kaonic Nuclei
  $\Lambda(1405), K^- pp$, high-precision exp. plan (atom)
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- $\eta$ mesic nucleus couple to $N^*(1535)$, mix with $\eta'$
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- Vector Mesons at finite density $\phi, \omega$
  mass shift, width and up dated QCD sum rule
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- Vector Mesons at finite density $\phi, \omega$
  mass shift, width and up dated QCD sum rule

- Heavy Q mesons in Nucleus
- ........
$\eta'(958)$ mesic nucleus


K. Itahashi, H. Fujioka, H. Geissel, R. S. Hayano, S. Hirenzaki, S. Itoh, D. Jido,

H. Nagahiro, D. Jido, H. Fujioka, K. Itahashi, S. Hirenzaki,
Introduction

- $\eta'(958)$ meson … close connections with $U_A(1)$ anomaly
  - Theoretical works
    - the effects of the $U_A(1)$ anomaly on $\eta'$ properties
    - at finite temperature/density
      - T. Kunihiro, PLB219(89)363
      - R.D. Pisarski, R. Wilczek, PRD29(84)338
      - K. Fukushima, K. Onishi, K. Ohta, PRC63(01)045203
      - P. Costa et al., PLB560(03)171, hep-ph/0408177
      - etc…
    - the possible character changes of $\eta'$ at $\rho \neq 0$
  - Poor experimental information
    - on the $U_A(1)$ anomaly at finite density

- Proposal for the study of the $\eta'$-mesic nuclei
  - $U_A(1)$ anomaly effect in medium from the “mesic nuclei”
  - the $\eta'$ properties at finite density
\( \eta' \) optical potential: state of the art

-150 \quad -100 \quad -50 \quad COSY-11

-20 \quad -10 \quad \text{V}_0 [\text{MeV}]

\text{COSY-11}

exp. \( \eta' A \) int.

exp. \( \eta' N \) int.

theory

Hiroyuki Fujioka (Kyoto Univ.)
Nambu–Jona-Lasinio model

Nagahiro, presentation at “Hadron in Nucleus”

\[ \Delta m \sim -150 \text{ MeV} \text{ at } \rho_0 \]

Nagahiro et al., PRC 76, 045203 (2006)

Hiroyuki Fujioka (Kyoto Univ.)
### Chiral Unitary Model

Oset and Ramos, PLB 704, 334 (2011)
Nagahiro et al., PLB 709, 87 (2012)

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**Re $V_{\eta'}$ and Im $V_{\eta'}$ with various $\alpha$ values**

| $\alpha$ | $|\alpha_{\eta'N}|$ fm | $V_{\eta'}^{1st}(\rho_0)$ | $V_{\eta'}^{2nd}(\rho_0)$ | $V_{\eta'}^{total}(\rho_0)$ |
|----------|-----------------|-----------------|-----------------|-----------------|
| $-0.193$ | 0.1             | $-8.6 - 1.7i$   | $-0.1 - 0.1i$   | $-8.7 - 1.8i$   |
| $-0.834$ | 0.3             | $-26.3 - 2.1i$  | $-0.6 - 0.9i$   | $-26.8 - 3.0i$  |
| $-1.79$  | 0.5             | $-43.8 - 3.0i$  | $-1.3 - 2.5i$   | $-44.1 - 5.5i$  |
| $-9.67$  | 1.0             | $-87.7 - 6.9i$  | $-4.1 - 10.4i$  | $-91.8 - 17.2i$ |

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Hiroyuki Fujioka (Kyoto Univ.)
An important piece of
E. Oset, A. Ramos, PLB704(11)334
H.Nagahiro, S. H., E. Oset, A. Ramos, PLB709(12)87

Coupling of the singlet component of pseudoscalar to baryons

Borasoy , PRD61(00)014011
Kawarabayashi-Ohta, PTP66(81)1789

This interaction
*seems to dominate the eta’-N interaction
*contributes mostly to the elastic channel & barely to the inelastic channel

\[ \mathcal{L}_{\eta_0 B} \propto \eta_0^2 \left( \partial_\mu \bar{B} \gamma^\mu B - \bar{B} \gamma^\mu \partial_\mu B \right) \]

\( \alpha \ldots \text{free parameter} \)
chiral unitary model

Oset and Ramos, PLB 704, 334 (2011)
Nagahiro et al., PLB 709, 87 (2012)

Re $V_\eta$, and Im $V_\eta$, with various $\alpha$ values

| $\alpha$ | $|\alpha'_{\eta N}|$ fm | $V^{1st}_{\eta}(\rho_0)$ | $V^{2nd}_{\eta}(\rho_0)$ | $V^{total}_{\eta}(\rho_0)$ |
|----------|----------------|----------------|----------------|----------------|
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Nagahiro, presentation at “Hadron in Nucleus”

Hiroyuki Fujioka (Kyoto Univ.)
transparency ratio measurement

\[ T_A = \frac{\sigma(\gamma A \rightarrow \eta' X)}{A \cdot \sigma(\gamma N \rightarrow \eta' X)} \]

\( E_\gamma = 1.7 \text{ GeV} \)

\( \rightarrow \Gamma = 15-25 \text{ MeV at } p=p_0 \)

for \( \langle p_{\eta'} \rangle \sim 1.05 \text{ GeV/c} \)

Nanova et al., PLB 710, 600 (2012)

Hiroyuki Fujioka (Kyoto Univ.)
Excitation function and momentum distribution

$V_0 = -(40 \pm 6) \text{ MeV}$

CBELSA/TAPS

$V_0 = -(32 \pm 11) \text{ MeV}$

$V_0 = -(37 \pm 10_{\text{stat}} \pm 10_{\text{syst}}) \text{ MeV}$

Nanova et al., PLB 727, 417 (2013)

Hiroyuki Fujioka (Kyoto Univ.)
elementary process : \( pp \rightarrow pp\eta' \)

Moskal, presentation at “Hadron in Nucleus”

\[ \sigma = \frac{1}{F} \int dV_{ps} |M|^2 \]

\[ |M|^2 \sim |M_0|^2 |M_{FSI}|^2 \]

\[ |M_{FSI}|^2 \sim |M_{pp}|^2 |M_{p1\eta}|^2 |M_{p2\eta}|^2 \]

\[ \gamma p \rightarrow \eta' p \text{ at LEPS2?} \]

\[ |a_{\eta'N}| \sim 0.1 \text{ fm} \]

Moskal et al., PLB 482, 356 (2000)
Determination of the $\eta'$-proton scattering length in free space

E. Czerwiński,1,* P. Moskal,1 M. Silarski,1 S. D. Bass,2 D. Grzonka,3 B. Kamys,1 A. Khoukaz,4 J. Klaja,1 W. Krzemięń,1 W. Oelert,5 J. Ritman,3 T. Sefzick,3 J. Smyrski,1 A. Täschner,4 M. Wolke,6 and M. Zieliński1

1Institute of Physics, Jagiellonian University, PL-30-059 Cracow, Poland
2Stefan Meyer Institute for Subatomic Physics, Austrian Academy of Sciences, Boltzmanngasse 3, A 1090 Vienna, Austria
3Institute for Nuclear Physics and Jülich Center for Hadron Physics, Research Center Jülich, D-52425 Jülich, Germany
4IKP, Westfälische Wilhelms-Universität, D-48149 Münster, Germany
5Johannes Gutenberg-Universität Mainz, 550099 Mainz, Germany
6Department of Physics and Astronomy, Uppsala University, SE-751 20 Uppsala, Sweden

(Dated: April 23, 2014)

Taking advantage of both the high mass resolution of the COSY–11 detector and the high energy resolution of the low-emittance proton-beam of the Cooler Synchrotron COSY we determine the excitation function for the $pp \rightarrow pp\eta'$ reaction close-to-threshold. Combining these data with previous results we extract the scattering length for the $\eta'$-proton potential in free space to be $\text{Re}(a_{p\eta'}) = 0 \pm 0.43 \text{ fm}$ and $\text{Im}(a_{p\eta'}) = 0.37 + 0.40 - 0.16 \text{ fm}$.

$$\text{Re}(a) = 0 \pm 0.43 \text{fm}$$

$$\text{Im}(a) = 0.37 + 0.40 - 0.16 \text{fm}$$

Talk by Dr. Eryk Czerwiński in this conference.
$\eta'$ optical potential: state of the art

$|\text{Re } V| > |\text{Im } V|$

search for $\eta'$ bound states!

NJL

linear $\sigma$

chiral unitary

COSY-11

$V_0$ [MeV]

($=m_{\eta'}(\rho_0)-m_{\eta'}$)

CBELSA/TAPS

exp. ($\eta'$A int.)

QMC

exp. ($\eta'$N int.)

W_0 [MeV]

($=-\Gamma/2$)

theory

Hiroyuki Fujioka (Kyoto Univ.)
Formation by \((p,d)\) reaction

Missing mass spectroscopy

K. Itahashi, H. Fujioka et al., PTP128(12)601

Proton kinetic energy \(T_p = 2.5\) GeV

Target: \(^{12}\text{C}\), \(^{16}\text{O}\), \(^{40}\text{Ca}\)

Forward reaction: \(\theta_d = 0\) deg.

Momentum transfer

Elementary cross section \(pn \to \eta'd\)

No information

J. Klaja et al., PRC81(10)035209 (COSY)

\[
\sigma_{pp\to pp\eta'}
\]

Assumptions

\[
\left(\frac{d\sigma}{d\Omega}\right)_{pn\to \eta'd} = 30\ \mu b/sr
\]

K. Nakayama in private comm

Itahashi et al., PTP128(12)601
Green’s function method


where $\varepsilon_\alpha = E_\alpha - E_i$ is the nucleon separation energy for the state $|\alpha\rangle$, and $G$ is the Green function for the optical potential $U$, satisfying the equation

$$G = G_0 + G_0 U G$$  \hspace{1cm} (10)

with $G_0$ denoting the free Green function for $\Sigma$.

Taking the imaginary part of eq. (10), we obtain the following identity:

$$\text{Im } G = (1 + G^+ U^+) \text{Im } G_0(1 + U G) + G^+ \text{Im } U G.$$  \hspace{1cm} (11)

The first term on the r.h.s. of eq. (11) represents the contribution from the escape of the $\Sigma$ from the nucleus, while the second term is due to the conversion of the $\Sigma$ into $\Lambda$ because the imaginary part of $U$ is due to this conversion effect. Let us define the following quantities:

$$S_{\text{tot}}(E) = -\tilde{f} \text{Im } G f$$

$$= -\sum_\alpha \text{Im } \int d\mathbf{r} \, d\mathbf{r}' \, f^*_\alpha(\mathbf{r}') G(E - \varepsilon_\alpha; \mathbf{r}', \mathbf{r}) f_\alpha(\mathbf{r}),$$  \hspace{1cm} (12)

$$\Rightarrow S_{\text{esc}}(E) = -\tilde{f}(1 + G^+ U^+) \text{Im } G_0(1 + U G) f,$$  \hspace{1cm} (13)

$$\Rightarrow S_{\text{con}}(E) = -\tilde{f} G^+ \text{Im } U G f.$$  \hspace{1cm} (14)
target-nucleus dependence

light nucleus \leftarrow \text{ less (shallow) } \eta' \text{ bound states } \text{ less hole-states } \checkmark \text{ simpler structure }

\rightarrow \text{ heavy nucleus } \text{ many (deeper) } \eta' \text{ bound states } \text{ many hole-states } \checkmark \text{ complex structure }

\eta' \text{ bound states : } (V_0, W_0) = -(100, 10) \text{ MeV case }

<table>
<thead>
<tr>
<th>11C</th>
<th>15O</th>
<th>39Ca</th>
</tr>
</thead>
<tbody>
<tr>
<td>s, p</td>
<td>s, p, d</td>
<td>s, p, d, f, g</td>
</tr>
</tbody>
</table>

one neutron-hole state (excited states of daughter nucleus)

<table>
<thead>
<tr>
<th>hole</th>
<th>$\Delta S_p$</th>
<th>$\Gamma$</th>
<th>hole</th>
<th>$\Delta S_p$</th>
<th>$\Gamma$</th>
<th>hole</th>
<th>$\Delta S_p$</th>
<th>$\Gamma$</th>
</tr>
</thead>
<tbody>
<tr>
<td>0p_{3/2}</td>
<td>-</td>
<td>-</td>
<td>0p_{1/2}</td>
<td>-</td>
<td>-</td>
<td>0d_{3/2}</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>0s_{1/2}</td>
<td>18</td>
<td>12</td>
<td>0p_{3/2}</td>
<td>6.3</td>
<td>0</td>
<td>1s_{1/2}</td>
<td>3.2</td>
<td>7.7</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>0s_{1/2}</td>
<td>29</td>
<td>19</td>
<td>0d_{5/2}</td>
<td>8</td>
<td>3.7</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>0p_{1/2}</td>
<td>25</td>
<td>21.6</td>
<td>0p_{3/2}</td>
<td>25</td>
<td>21.6</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>0s_{1/2}</td>
<td>48</td>
<td>30.5</td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

observed spectrum

merit \text{ to see peaks}
demerit

\text{element}
\begin{align*}
\text{light nucleus} & \leftarrow \\
\text{heavy nucleus} & \rightarrow \\
\eta' \text{ bound states} & \text{: } (V_0, W_0) = -(100, 10) \text{ MeV case} \\
\text{one neutron-hole state} & \text{ (excited states of daughter nucleus)}
\end{align*}
\( ^{12}\text{C}(p,d)^{11}\text{C} \eta' \): **strong attraction** \( (V_0, W_0) = -(100,10) \text{ MeV} \)

- light nucleus \( \leftrightarrow \) heavy nucleus
  - less (shallow) \( \eta' \) bound states
  - less hole-states
  - simpler structure
  - many (deeper) \( \eta' \) bound states
  - many hole-states
  - complex structure

\[
(V_0, W_0) = -(100,10) \text{ MeV}
\]
$^{12}\text{C}(p,d)^{11}\text{C} \eta'$: **shallower case** $(V_0, W_0) = -(50,5) \text{ MeV}$

- **light nucleus** ←
  - less (shallower) $\eta'$ bound states
  - less hole-states
  - ✓ simpler structure

- **heavy nucleus** →
  - many (deeper) $\eta'$ bound states
  - many hole-states
  - ✓ complex structure

---

**Shallower case**: $(V_0, W_0) = -(50,5) \text{ MeV}$

**$^{12}\text{C}$ target**

**$^{40}\text{Ca}$ target**
Numerical Results: $^{12}\text{C}(\gamma,p)^{11}\text{B}_{\eta'}$

$V_0 = 0$
$W_0 = -5 \text{ MeV}$

$V_0 = -100 \text{ MeV}$
$W_0 = -5 \text{ MeV}$

$V_0 = 0$
$W_0 = -20 \text{ MeV}$

$V_0 = -100 \text{ MeV}$
$W_0 = -20 \text{ MeV}$
$\eta'$-mesic nuclei formation spectra: $^{12}$C target: $(\pi^+, p)$ reaction@JPARC

- $p_\pi = 1.8$ GeV/c
- proton angle = 0 deg.

By H. Nagahiro
Experimental plan at GSI

- 1st Step: Inclusive measurement of \((p,d)\) reaction with FRS at GSI

Simulation of spectra
- \(\eta' \times C\) formation and background processes
- 4.5 days DAQ assumed


Decomposition into different final states (based on chiral unitary model)

three final states

(a) $\eta'$ escape

(b) $\eta'N \rightarrow MB$

(c) $\eta'NN \rightarrow NN$

Energetic Nucleon
Uniform Ang. Dist.

$|a_{\eta'N}| = 0.3$ fm

$\eta'NN \rightarrow NN$

$\eta'N \rightarrow MB$

$\eta'$ escape

$E_{ex} - E_0$ [MeV]

$E_{ex} - E_0$ [MeV]

$E_{ex} - E_0$ [MeV]
Proton emission from 2N abs.

**Background** (3712 points)

**Signal** (1.0 × 10^6 points)

<table>
<thead>
<tr>
<th>Inclusive (p, d) ( \frac{d\sigma}{d\Omega_d} ) × 1</th>
<th>proton cut ( \frac{d\sigma}{d\Omega_d} ) × 2</th>
</tr>
</thead>
<tbody>
<tr>
<td>Background</td>
<td>990 [µb/sr]</td>
</tr>
<tr>
<td></td>
<td>( \frac{28}{3712} )</td>
</tr>
<tr>
<td>Signal</td>
<td>1.1 [µb/sr]</td>
</tr>
<tr>
<td></td>
<td>( \frac{2.72 \times 10^5}{1.0 \times 10^6} )</td>
</tr>
<tr>
<td>S/N 比</td>
<td>( 1.1 \times 10^{-3} )</td>
</tr>
</tbody>
</table>

(Results by Y. Higashi)
$\eta'(958)$-meson-nucleus bound system

$U_\Lambda(1)$ anomaly effect at finite density in the viewpoint of mesic-nuclei

- large mass reduction
- without large absorption

$ReV \gg ImV$

special feature of $\eta'$
- attraction from ‘elastic’ interaction
- smaller inelastic channel

possibilities to observe bound state peaks

$\Rightarrow$ Experiment
$\eta'(958)$-meson-nucleus bound system

$U_A(1)$ anomaly effect at finite density in the viewpoint of mesic-nuclei

possible large mass reduction hopefully without large absorption

ReV $\gg$ ImV

special feature of $\eta'$ ?? ✓ attraction from ‘elastic’ interaction
✓ smaller inelastic channel

possibilities to observe bound state peaks

⇒ Experiment
Recent Activities on Pionic Atoms

= GSI → RIBF/RIKEN (Next talk)

N. Ikeno, J. Yamagata-Sekihara, H. Nagahiro and S. Hirenzaki, PTEP(2013) 063D01
N. Ikeno, H. Nagahiro and S. Hirenzaki, EPJA47 (2011) 161
Introduction

**Deeply bound pionic atom**
... Useful system to study pion properties at finite density and partial restoration of chiral symmetry

**Current status**

- (d,\(^3\)He) reaction in \(^{116},^{120},^{124}\)Sn:
  Observation of pionic 1s states

- Pion-Nucleus optical potential

\[
2\mu V_{\text{opt}}^s = -4\pi [\varepsilon_1 b_0 \rho(r) + b_1 \delta \rho(r)] + \varepsilon_2 B_0 \rho^2(r)
\]

- GOR relation + Tomozawa-Weinberg

\[
\frac{\langle \bar{q}q \rangle}{\langle \bar{q}q \rangle_0} \approx \frac{f_{\pi}^2}{f_\pi^2} \approx \frac{b_2^{\text{free}}}{b_1^*(\rho)} = 0.78 \pm 0.05 \quad @ \rho \approx 0.6 \rho_0 \\
\sim 0.67 \quad @ \rho = \rho_0
\]

Theoretical basis
Kolomeitsev, Kaiser, Weise, PRL90(2003)092501

What’s next?

Interests

\( \bar{q}q \) condensate: beyond the linear density approx. (ex.) Goda, Jido

: in asymmetric (n or p rich) Nuclear Matter

⇒ Aspects of symmetry in “various circumstances”

Difficulties for precise studies

= Limited sensitivity of known atomic pion to \( \rho \sim 0.6 \rho_0 \) (Seki-Masutani)

= Uncertainties of Neutron density distribution

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N. Ikeno et al., PTP126(11)483
What’s next?

Interests

- $\bar{q}q$ condensate: beyond the linear density approx. (ex.) Goda, Jido
  - in asymmetric (n or p rich) Nuclear Matter
  $\Rightarrow$ Aspects of symmetry in “various circumstances”

Difficulties for precise studies

- Limited sensitivity of known atomic pion to $\rho \sim 0.6\rho_0$ (Seki-Masutani)
- Uncertainties of Neutron density distribution

How we can..

- Several atomic states data (ex. 1s, 2s, 2p) in each nucleus
  ($\Rightarrow$ possible reduction of systematic errors)

- Systematic ‘precise’ observation for various nucleus including unstable nuclei
  ($\Rightarrow$ observation of various effective $\rho$ and p/n ratio)

- Odd-n nuclear target to avoid residual interaction effects

N. Ikeno et al., PTP126(11)483
Some Numerical Results (by N. Ikeno)

**0 degree**

Even target: $^{122}$Sn ($0^+$)

Odd target: $^{117}$Sn ($1/2^+$)

- Pionic 1s state formation with neutron s-hole state
- Spectrum of $^{117}$Sn(d, $^3$He) is spread over wider energy range.
- Cross section of $^{117}$Sn(d, $^3$He) is smaller.
- Pionic 1s and 2s states can be observed
Some Numerical Results (by N. Ikeno)

Even target: $^{122}\text{Sn} \ (0^+)$

Odd target: $^{117}\text{Sn} \ (1/2^+)$

- Pionic $2p$ state contributions become relatively larger.
Expected effective density seen by pion

Pionic atom 1s state in 112-132Sn

Relatively large variation of $\rho_p/\rho_n$ ratio

Evaluation by N. Ikeno
Summary

- Meson property at finite density,
  Mesic atoms and Mesic nuclei

- $\eta'(958)$: Anomaly effect at finite density

- Pionic atom: for getting deeper insights
  = information at various $\rho$ and $\rho_p/\rho_n$ ratio
  = Pionic atom in various nucleus including unstable nuclei
Summary

- Meson property at finite density, Mesic atoms and Mesic nuclei

- $\eta'(958)$ : Anomaly effect at finite density

- Pionic atom: for getting deeper insights
  = information at various $\rho$ and $\rho_p/\rho_n$ ratio
  = Pionic atom in various nucleus including unstable nuclei
  ➣ Exotic many body with exotic structure?