η' meson under partial restoration of chiral symmetry in nuclear medium

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Reference
Nuclear bound state of eta'(958) and partial restoration of chiral symmetry in the eta' mass.
Daisuke Jido, Hideko Nagahiro, Satoru Hirenzaki.

S. Sakai, D. Jido, in preparation

See also poster of Sakai
Partial restoration of chiral symmetry

effective reduction of quark condensate \( \frac{\langle \bar{q}q \rangle^*}{\langle \bar{q}q \rangle} < 1 \)

**low density theorem**

**model-independent theoretical relation**

\[
\langle \bar{q}q \rangle^* = \left(1 - \frac{\sigma_{\pi N}}{m_\pi^2 f_\pi^2 \rho}\right) \langle \bar{q}q \rangle + \mathcal{O}(\rho^{n>1})
\]

\( \sigma_{\pi N} : \pi N \) sigma term, \( \mathcal{O}(m_q) \), obtained from \( T_{\pi N} \) at soft limit

**quark condensate does decrease at nuclear matter**

phenomenological proof by exp. and analyses of pionic atom and low ene. pi-A scattering

30-40 % reduction at saturation density, if believe linear extrapolation

since QCD is fundamental theory of strong interaction

all hadron quantities have their substantial quark-gluon description

once one knows in-medium change of fundamental quantities, such as quark condensate, one can expect modification of hadron quantities

"quark-hadron duality"

hadronic quantities \( \leftrightarrow \) quark-gluon description (substantial)

K. Suzuki et al. PRL92, 072302, (04);
Friedman et al., PRL93, 122302 (04);
DJ, Hatsuda, Kunihiro, PLB 670, 109 (08).
Contents

1. introduction
   partial restoration of chiral symmetry in nuclear medium
   effective reduction of quark condensate $\langle \bar{q}q \rangle^*/\langle \bar{q}q \rangle < 1$
   accordingly hadronic quantities are modified

2. $\eta'$ mass and chiral symmetry
   $U_A(1)$ anomaly
   significant role of chiral symmetry breaking
   $\eta'$ mass is reduced under PRχS

3. $\eta'$-N interaction
   estimate $\eta'$-N interaction
   strong attraction in scalar channel
   linear $\sigma$ model as a model of chiral restoration

4. summary
U_A(1) anomaly and \( \eta' \) mass

There is no \( U_A(1) \) symmetry in Quantum ChromoDynamics. \( U_A(1) \) symmetry is broken by quantum anomaly.

**Divergence of axial current** (symmetry property of QCD)

- **Flavor octet** (small) PCAC

\[
\partial^\mu A^{(8)}_\mu = \frac{i}{\sqrt{3}} (m_u \bar{u} \gamma_5 u + m_d \bar{d} \gamma_5 d - 2m_s \bar{s} \gamma_5 s)
\]

- **Flavor singlet**

\[
\partial^\mu A^{(0)}_\mu = 2i (m_u \bar{u} \gamma_5 u + m_d \bar{d} \gamma_5 d + m_s \bar{s} \gamma_5 s) + \frac{3\alpha_s}{8\pi} F^a_{\mu\nu} \tilde{F}^{a\mu\nu}
\]

(small) PCAC anomaly

**Octet axial currents are conserved at chiral limit**

\[
SU(3)_L \otimes SU(3)_R \rightarrow SU(3)_V
\]

The octet mesons are massless (8 Nambu-Goldstone bosons)

**Singlet axial current is NOT conserved due to quantum anomaly**

- \( U_A(1) \) symmetry is always broken by anomaly explicitly

- \( \eta' \) is not a NG boson, nor necessarily massless, when chiral symmetry is spontaneously broken

What happens on \( \eta' \) mass, when chiral symmetry is restored??

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Tuesday, 2 October 2012
\( \eta' \) meson in chiral representation

in fact, \( \pi, \eta \) and \( \eta' \) are in the same multiplet of \( SU_L(3) \otimes SU_R(3) \)

all the particle belonging to the same multiplet should get degenerate, when chiral symmetry is restored.

Scalar and Pseudoscalar mesons

\[
\begin{align*}
(3, 3) \oplus (3, \bar{3}) & \quad q_i^L q_j^R \quad \bar{q}_i^L q_j^R \\
both \text{octet and singlet contain} & \quad \pi, K, \eta_8, \eta_0 \quad \sigma, a_0, \kappa, f_0 \\
parity \text{ eigenstate} & \quad \bar{q}_i \gamma^5 q_j, \bar{q}_i q_j \\
1+8 \text{ scalar and } 1+8 \text{ pseudoscalar} & \quad SU_L(3) \otimes SU_R(3)
\end{align*}
\]

vector transformation can not mix singlet and octet representations

axial trans. \[
\begin{align*}
[Q_A^a, \phi_5^B] & = \bar{q} \left\{ \frac{\lambda^a}{2}, \frac{\lambda^B}{2} \right\} q = d^{aBC} \phi^C \\
mixes \text{octet} & \quad \eta_0 \rightarrow S^a, \quad S^a \rightarrow \eta_0 \quad \text{and} \quad P^a \\
and \text{singlet} & \quad since the axial transformation is not a generator of SU(3)_v, it can mix octet and singlet.
\end{align*}
\]

both singlet and octet belong to the same chiral multiplet without \( U_A(1) \)

if chiral symmetry is manifest or restored, \( \eta_8 \) and \( \eta_0 \) should degenerate even though anomaly is there

dynamical argument is given by Lee and Hatsuda

\( \eta' \) meson in chiral restoration

Mass spectrum of pseudoscalar mesons in breaking patterns of SU(3) chiral symmetry

In order that \( U_A(1) \) anomaly affects the \( \eta' \) mass, chiral symmetry is necessarily broken spontaneously and/or explicitly.

- \( \pi, K, \eta_8, \eta_0 \)
  - \( m_q = m_s = 0 \)
  - \( \langle \bar{q}q \rangle = 0 \)
  - ChS manifest

- \( \pi, K, \eta_8 \)
  - \( m_q = m_s = 0 \)
  - \( \langle \bar{q}q \rangle \neq 0 \)
  - ChS broken dynamically

- \( \eta_0 \)
  - \( m_q = m_s = 0 \)
  - \( \langle \bar{q}q \rangle = 0 \)
  - ChS broken dynamically and explicitly

- \( \eta' \)
  - \( m_q \neq m_s \neq 0 \)
  - \( \langle \bar{q}q \rangle \neq 0 \)

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**η' meson in nuclear matter**

**a simple estimation**

linear dependence of quark condensate on η'-η mass difference (400 MeV)

partial restoration of ChS takes place with 35% at $\rho_0$

we expect strong η' mass reduction

$$\Delta m_{\eta'} \sim 150 \text{ MeV} \quad @ \quad \rho = \rho_0$$
η’ meson in nuclear matter

a simple estimation

linear dependence of quark condensate on η’-η mass difference (400 MeV)

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‘t Hooft - Kobayashi - Maskawa interaction

$$U_A(1) \text{ anomaly contributes } \eta' \text{ mass through ChSB}$$

NJL model

$\eta'$ mass difference (400 MeV)

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$\eta'$-N interaction and SU(3) linear $\sigma$ model

mass reduction $\leftrightarrow$ scalar potential $\leftrightarrow$ nuclear many-body effect $\rightarrow$ $\eta'$-N interaction as an elementary interaction
SU(3) linear sigma model

**Lagrangian**

\[
M = \Sigma + i\Pi
\]

\[
\mathcal{L} = \frac{1}{2} \text{Tr}[\partial_\mu M \partial^\mu M^\dagger] - \frac{\mu^2}{2} \text{Tr}[M M^\dagger] - \frac{\lambda}{4} \text{Tr}[(M M^\dagger)^2] - \frac{\lambda'}{4} (\text{Tr}[M M^\dagger])^2 - A \text{Tr}[\chi M^\dagger + \chi^\dagger M] + \sqrt{3} B (\text{det } M + \text{det } M^\dagger)
\]

- explicit ChS breaking
- flavor symmetry breaking
- anomaly term
- breaks \(U_A(1)\) symmetry
- nuclear mean field

**vacuum condition**

effective potential \(V(\sigma_0, \sigma_8)\)

\[
\left. \frac{\delta V}{\delta \sigma_0} \right|_{\sigma_i = \langle \sigma_i \rangle} = 0 \quad \left. \frac{\delta V}{\delta \sigma_8} \right|_{\sigma_i = \langle \sigma_i \rangle} = 0
\]

determine values of condensates

\[
\langle \sigma_0 \rangle, \quad \langle \sigma_8 \rangle
\]

**meson mass**

massless PS boson obtained with the vacuum condition

\[
m^2_{\eta_0} - m^2_{\eta_8} = 6 B \langle \sigma_0 \rangle
\]

at chiral limit

parameters are fixed by in-vacuum meson properties

- sigma meson mass : 700 MeV, insensitive to the results
- \(g\) parameter is fixed so as to reproduce 35% reduction of chiral condensate in nuclear density

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Schechter, Ueda, PRD3, 2874 (71)
Papazoglou et al., PRC57, 2576 (98)

\[\text{Tuesday, 2 October 2012}\]
$\eta'$-N interaction

\[ m^*^2 = m^2(\langle\sigma_0\rangle^*, \langle\sigma_8\rangle^*) + \Sigma_{ph} \]

**medium effect on $\eta'$ mass**

**$\eta'$-nucleon interaction in L$\sigma$M**

if mass reduction associated with partial restoration of ChS, there should be strong attraction in $\eta'$-nucleon channel with scalar-isoscalar exchange

\[ V_{\eta'N} = 6B \cdot \frac{g/\sqrt{3}}{-m_{\sigma_0}^2} \approx -0.053 \text{ [MeV}^\cdot\text{I]} \]

**two-body bound state**

\[ \sim 6 \text{ MeV} \]

\[ \text{calculated in the same way as } \Lambda(1405) \text{ of } K^{\bar{\text{N}}} \text{ bound state} \]

**interaction strength**

\[ V_{\eta'N} \]

\[ \text{cf. -0.086 MeV}^\cdot\text{I} \quad \text{WT term of } K^{\bar{\text{N}}} (I=0) \]

\[ \rightarrow 10-15 \text{ MeV binding of } K^{\bar{\text{N}}} \]

\[ \text{calculation in the same way as } \Lambda(1405) \text{ of } K^{\bar{\text{N}}} \text{ bound state} \]
Conclusion

Quark condensate decreases at finite density
accordingly hadronic quantities also change

\( \eta' \) mass: interplay of chiral symmetry breaking and \( U_A(1) \) anomaly

\( U_A(1) \) anomaly can affect \( \eta' \) mass only through chiral symmetry breaking
reduction of \( \eta' \) mass due to partial restoration of chiral symmetry
in order of 100-150 MeV at saturation density

Strong attraction of \( \eta' \)-N interaction in scalar channel
same mechanism as NN attraction in isoscalar-scalar channel
strength is comparable with \( K^{\text{bar}}N \) Weinberg-Tomozawa interaction
enough strength to form \( \eta' \)-N bound state

If no bound state, we need repulsive interaction in other channels
no Weinberg-Tomozawa (vector exchange) interaction

For the details, see poster of Sakai
small absorption into nuclei

**CB-ELSA/TAPS**

Transparency ratio

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

Normalized to \(^{12}\text{C}\)

\[ \Gamma(\rho_0, \langle p_{\eta'} \rangle) \approx 1 \text{ GeV/c} \approx 15-25 \text{ MeV} \]

Nanova et al. (CBELSA/TAPS), PLB710(2012)600.

small or large mass reduction ??

**RHIC: phenix/star** (low energy pion)

Indirect measurement: \(\eta'\) mass reduction of at least 200 MeV

**COSY**

Three-body final state interaction \(\text{pp} \rightarrow \eta'\text{pp}\)

\(\text{p}\eta'\) scattering length \(\approx 0.1-0.8\) fm (\(\Delta m\approx\) a few - tens MeV)

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\(\text{Hyp2012}\)