η’-nucleon interaction in chiral dynamics and η' meson in nuclear medium

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collaboration with
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References

see also

Related contributions to η' physics in this conference
Sakai, Nagahiro, Fujioka, Tanaka, Metag, Moskal, Bass, ...
η'-nucleon system

keywords in this talk

1. exotic hadron
2. chiral symmetry
Introduction

1. exotic hadrons  hadrons which do not fit quark model systematics
hadrons have been classified based on quark model
various excitation modes are possible, but only quark excitation in quark model

quark excitation
conventional picture

hadronic excitation
hadron composite state

strong interaction is as complicated as we expect

dual nature of strong force

colorful "constituent" force and colorless "interaction" force
inside confinement range  
~ 0.5 fm 
larger than hadron size  
> 1.0 fm

we show that
η'-nucleon system has attraction in isoscalar-scalar channel and it forms a bound state N* with several MeV binding energy and a small width

Thursday, 18 September 14
Introduction

2. chiral symmetry

- chiral symmetry, ChS, is a fundamental symmetry in QCD
- ChS is spontaneously broken by physical states
- ChSB is a phase transition phenomenon and provides vacuum property
- most of light hadron properties is determined by ChSB light pion mass, mass generation etc.

we show that, also for the $\eta'$ meson mass

chiral symmetry plays an important role on the $\eta'$ mass

partial (incomplete) restoration of ChS in nuclear medium

quark condensate does decrease in nuclear medium
- phenomenological proof by analysis of pionic atom and low energy pi-A scattering
- 30-40 % reduction at saturation density, if believe linear extrapolation

combining the role of ChS in the $\eta'$ mass and PRChS in nuclear medium, we discuss the $\eta'$ mass in nuclear medium
Contents

1. introduction
   exotic hadron
   chiral symmetry
   partial restoration of chiral symmetry in nuclear medium

2. η’ meson and chiral symmetry
   $U_A(1)$ anomaly
   significant role of chiral symmetry breaking
   η’ mass is reduced under PRχS

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

4. summary
$\eta'$ meson
and
chiral symmetry

References

η' meson and chiral symmetry

η' is a PS meson having 1 GeV mass.

1 GeV is a typical mass scale of hadrons

looks nothing special

special mesons are π, K, η

light mass because they are Nambu-Goldstone bosons associated with ChSB

\[ \eta'(958) \]

\[ I^G(J^{PC}) = 0^+(0^-+) \]

Mass \( m = 957.78 \pm 0.06 \text{ MeV} \)

Full width \( \Gamma = 0.198 \pm 0.009 \text{ MeV} \)
η' meson and chiral symmetry

η' is a PS meson having 1 GeV mass.

1 GeV is a **typical mass scale** of hadrons

looks **nothing special**

**special mesons are** π, K, η

light mass because they are Nambu-Goldstone bosons associated with ChSB

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**chiral symmetry in QCD**

octet axial currents are (almost) conserved

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

(small) PCAC

octet chiral symmetry is spontaneously broken

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

---

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

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

(small) PCAC

**anomaly**

singlet chiral symmetry is **always broken by anomaly explicitly**

η' cannot be a NG boson, nor necessarily massless, when ChSB takes place
η' meson in chiral symmetry

Chiral symmetry plays an important role in η' mass as well as anomaly. In fact, π, η and η' are in the same multiplet of $SU_L(3) \otimes SU_R(3)$

No matter how $U_A(1)$ symmetry is broken by quantum anomaly, because all the particle belonging to the same multiplet should get degenerate, when the system has the symmetry,

π, η and η' get degenerate when chiral symmetry is restored.
The $\eta'$ meson in chiral symmetry

Chiral symmetry plays an important role in $\eta'$ mass as well as anomaly.

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

no matter how $U_A(1)$ symmetry is broken by quantum anomaly.

Because all the particle belonging to the same multiplet should get degenerate when the system has the symmetry,

$\pi$, $\eta$ and $\eta'$ get degenerate when chiral symmetry is restored.

**- Symmetry property of $SU_L(3) \otimes SU_R(3)$ without $U_A(1)$ symmetry**

Scalar and Pseudoscalar mesons in $SU_L(3) \otimes SU_R(3)$

$$\begin{pmatrix} 3, 3 \end{pmatrix} \oplus \begin{pmatrix} 3, \bar{3} \end{pmatrix}$$

contains both octet and singlet

8+1 scalar and 8+1 pseudoscalar

$$q_i^L q_j^R \pm q_i^R q_j^L$$

these 18 mesons including $\eta$ and $\eta'$ get degenerate if chiral symmetry is not broken.

$U_A(1)$ is broken so that singlet axial current is not conserved, but $\pi$, $\eta$, $\eta'$... do get degenerate in case of no chiral symmetry breaking.

Dynamical argument is given by Lee and Hatsuda.
in order that $U_A(1)$ anomaly affects the $\eta'$ mass, **chiral symmetry is necessarily broken spontaneously and/or explicitly.**

**nonchiral gluon field cannot couple to chiral pseudoscalar states without chiral symmetry breaking.**
in order that $U_A(1)$ anomaly affects the $\eta'$ mass, **chiral symmetry is necessarily broken spontaneously and/or explicitly.**

The mass gap of $\eta'$ and $\eta$ is generated by chiral symmetry breaking through $U_A(1)$ anomaly.
the mass gap of $\eta'$ and $\eta$ is generated by chiral symmetry breaking

**a simple order estimation**

- linear dependence of quark condensate on $\eta'$-$\eta$ mass difference (400 MeV)
- partial restoration of ChS takes place with 35% at $\rho_0$
- we expect strong $\eta'$ mass reduction $\Delta m_{\eta'} \sim 100$ MeV @ $\rho = \rho_0$

assume linear dependence of quark condensate on $\eta'$-$\eta$ mass difference

$$m_{\eta'}^2 - m_{\eta}^2 = B(2\langle \bar{q}q \rangle + \langle \bar{s}s \rangle)$$

consistent with linear $\sigma$ model

assume no change of $\eta$ mass and $\langle s\bar{s} \rangle$ in nuclear medium

$$m_{\eta'}^2 - m_{\eta}^2 = 2B(\langle \bar{q}q \rangle - \langle \bar{q}q \rangle^*)$$

using low density theorem

$$\Delta m_{\eta'} = \frac{2}{3} \frac{m_{\eta'}^2 - m_{\eta}^2}{2m_{\eta'}} \frac{\sigma_{\pi N}}{m_{\pi}^2 f_{\pi}^2 \rho}$$

low density theorem

$$\langle \bar{q}q \rangle^* = \left(1 - \frac{\sigma_{\pi N}}{m_{\pi}^2 f_{\pi}^2 \rho}\right) \langle \bar{q}q \rangle$$

$$B = \frac{m_{\eta'}^2 - m_\eta^2}{3\langle \bar{q}q \rangle} \quad @ \text{SU}(3)$$

we expect strong $\eta'$ mass reduction

$$\Delta m_{\eta'} \sim 80 - 100$$ MeV @ $\rho = \rho_0$ for $\sigma_{\pi N} = 45$–60 MeV
**η’ meson in nuclear matter**

the mass gap of η' and η is generated by chiral symmetry breaking

**a simple order estimation**

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

partial restoration of ChS takes place with 35% at ρ₀

we expect strong η’ mass reduction \[ Δm_{η'} \sim 100 \text{ MeV} @ ρ = ρ₀ \]

we assume that η’ is purely flavor singlet

\[ m_{η'}^2 - m_η^2 = B(2⟨\bar{q}q⟩ + ⟨\bar{s}s⟩) \]

strange component of η' can be different

here we discuss the mass gap of η' and η and assume no change of η mass

the η mass can be changed in nuclear matter, see S. Bass's talk

here we consider only the scalar part of the η' self-energy in nuclear matter

the (Lorentz) vector part of the self-energy could be repulsive

**energy dependence** of self-energy is also important

\[ \sim -40 \text{ MeV} \text{ [CBELSA/TAPS]} \]

from η' production
η′ meson in nuclear matter

the mass gap of η' and η is generated by chiral symmetry breaking

a simple order estimation
linear dependence of quark condensate on η′-η mass difference
partial restoration of ChS takes place with 35% at ρ₀
we expect strong η’ mass reduction \( Δm_{\eta'} \sim 100 \text{ MeV} \)

‘t Hooft - Kobayashi - Maskawa interaction

\( U_A(I) \) anomaly contributes η’ mass through ChSB

\( \Delta m_{\eta'} \sim 150 \text{ MeV} \) @ \( ρ = ρ₀ \)

\[ \begin{align*}
\langle \bar{q}q \rangle^* & \quad \eta' \quad V_D \\
\eta' & \quad \eta' \\
\end{align*} \]

Nagahiro, Takizawa, Hirenzaki
PRC85 (12) 032201(R)

See also, P. Costa, M. C. Ruivo, and Y. L. Kalinovsky,
η’-N interaction in SU(3) linear σ model

References


see the talk (Wed.) by S. Sakai for the details
SU(3) linear sigma model

has mechanism of spontaneous chiral symmetry breaking

**Lagrangian**

\[
\mathcal{L} = \frac{1}{2} \text{Tr}[\partial_\mu M \partial^\mu M^\dagger] - \frac{\mu^2}{2} \text{Tr}[MM^\dagger] - \frac{\lambda}{4} \text{Tr}[(MM^\dagger)^2] - \frac{\lambda'}{4} (\text{Tr}[MM^\dagger])^2
\]

- $M = \Sigma + i\Pi$
- $\chi = \text{diag}(m_q, m_q, m_s)$

explicit ChS breaking

flavor symmetry breaking

anomaly term

breaks $U_A(1)$ symmetry

vacuum is determined so as to realize spontaneous breaking of ChS

finite sigma condensates $\langle \sigma_0 \rangle$, $\langle \sigma_8 \rangle$

massless PS boson obtained with the vacuum condition

$\eta'$ meson mass

at chiral limit

\[
m_{\eta_0}^2 - m_{\eta_8}^2 = 6B\langle \sigma_0 \rangle
\]
SU(3) linear sigma model

has mechanism of spontaneous chiral symmetry breaking

Lagrangian

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

quark mass \( \chi = \text{diag}(m_q, m_q, m_s) \)

\[
\mathcal{L} = \frac{1}{2} \text{Tr}[\partial_\mu M \partial^\mu M^\dagger] - \frac{\mu^2}{2} \text{Tr}[MM^\dagger] - \frac{\lambda}{4} \text{Tr}[(MM^\dagger)^2] - \frac{\lambda'}{4} (\text{Tr}[MM^\dagger])^2
\]

explicit ChS breaking

flavor symmetry breaking

anomaly term

breaks \( U_A(1) \) symmetry

\[
\mathcal{L}_N = \bar{\psi}(i\slashed{D} - m_N)\psi - g\bar{\psi} \left( \frac{1}{\sqrt{3}} \tilde{\sigma}_0 + \frac{1}{\sqrt{6}} \tilde{\sigma}_8 \right) \psi
\]

\( \sigma N \) interaction

\[
- g\bar{\psi}i\gamma_5 \left( \frac{1}{\sqrt{2}} \vec{\pi} \cdot \vec{\tau} + \frac{1}{\sqrt{3}} \eta_0 + \frac{1}{\sqrt{6}} \eta_8 \right) \psi
\]

Yukawa coupling

meson and baryon fields transform linearly under the SU(3)xSU(3) chiral symmetry

partial restoration of chiral symmetry in nuclear medium

parameter \( g \) is determined so as to restore chiral symmetry in order of 35% in mean field approximation
in-medium condensates

determine values of in-medium condensates from effective potential $V(\sigma_0, \sigma_8, \rho)$

$$\frac{\delta V}{\delta \sigma_0} \bigg|_{\sigma_i = \langle \sigma_i \rangle^*} = 0, \quad \frac{\delta V}{\delta \sigma_8} \bigg|_{\sigma_i = \langle \sigma_i \rangle^*} = 0,$$

in-medium condensates $\langle \sigma_0 \rangle^*$, $\langle \sigma_8 \rangle^*$

quark condensate

$$\langle \bar{q}q \rangle^* = A(2\langle \sigma_0 \rangle^* + \sqrt{2}\langle \sigma_8 \rangle^*) \quad \langle \bar{s}s \rangle^* = 2A(\langle \sigma_0 \rangle^* - \sqrt{2} \langle \sigma_8 \rangle^*)$$

![Graph showing the behavior of quark condensates with density.](image)

not change so much

input: 35% reduction at $\rho_0$
in-medium masses

**meson mass**

- **in vacuum** \( m^2 = m^2(\langle \sigma_0 \rangle, \langle \sigma_8 \rangle) \)
- **in medium** \( m^*^2 = m^2(\langle \sigma_0 \rangle^*, \langle \sigma_8 \rangle^*) + \Sigma_{ph} \)

**medium effect on \( \eta' \) mass**

This model reproduces \( \eta' \) mass reduction associated with PRChS

In-medium \( \eta \) mass is a consequence of cancellation of several terms. For qualitative discussion, we have to fix model parameters more precisely.
η’-N interaction

η’-nucleon interaction in $\Sigma M$

![Diagram](image)

B term: anomaly effect cancel each other at chiral limit thanks to ChS

interaction strength (symmetric limit)

$$V_{\eta'N} = 6B \cdot \frac{g/\sqrt{3}}{-m_{\sigma_0}^2} \approx -0.053 [\text{MeV}^{-1}]$$

two-body bound state

~ 6 MeV

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

coupled channel effect ($\eta'N$, $\eta N$)

BE = 12 - 3i [MeV]

scattering length = -1.9 + 0.2i [fm]

the details numbers are sensitive to the parameters of symmetry breaking
**η’-N interaction**

**η’-nucleon interaction in LσM**

B term: anomaly effect **cancel each other** at chiral limit thanks to ChS

attraction in scalar channel is related to mass generation mechanism

a part of η' mass (400 MeV) is generated by spontaneous breaking of ChS

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

→ presence of strong coupling \(\sigma\eta'\eta'\)

nucleon mass is generated also by spontaneous breaking of ChS

\[ m_N = g\langle\sigma_0\rangle \]

→ presence of strong coupling \(\sigma\eta\eta\)

strong attraction in η’-nucleon channel with scalar-isoscalar exchange

**this mechanism is same as scalar attraction in NN interaction**

η'N interaction mediated by \(\frac{\alpha_s}{4\pi} F_{\mu\nu} \tilde{F}^{\mu\nu}\) was studied by S. Bass

Sakai, Dj, PRC88 (13) 064906; in preparation
Narrow width ??

**inelastic channel** \( \eta' \ N \to \eta \ N \)

attraction coming from sigma exchange with anomaly

\[ \sigma_0, \sigma_8 \]
\[ \lambda, \lambda' \]

anomaly effect selectively affects \( \eta' \) channel

large **elastic channel** \( \eta' \ N \to \eta' \ N \)

small **inelastic channel** \( \eta' \ N \to \eta \ N \quad \eta' \ N \to \pi \ N \)

two-body absorption ?? \( \eta' \ NN \to NN \)

\[ \eta' \]
\[ \eta' \]
\[ \eta' \]
\[ \eta' \]

depending on size of Yukawa coup. of \( \eta'NN \)

calculation result coming soon.
Conclusion

η’ mass : interplay of chiral symmetry breaking and $U_A(1)$ anomaly

$U_A(1)$ anomaly can affect η’ mass only through chiral symmetry breaking
reduction of η’ mass due to partial restoration of chiral symmetry
in order of 100 MeV at saturation density

strong attraction of η’-N interaction in scalar channel

same mechanism as NN attraction in isoscalar-scalar channel
mass generation by sigma condensate and sigma exchange
strength is comparable with $K^{\bar{b}ar}N$ Weinberg-Tomozawa interaction
enough strength to form η’-N bound state

if no bound state, we need repulsive interaction in other channels
no Weinberg-Tomozawa (vector exchange) interaction
Partial restoration of chiral symmetry

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

**low density theorem**

**model-independent theoretical relation**

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

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

**quark condensate does decrease in nuclear medium**

phenomenological proof by analysis of pionic atom and low energy 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

this does NOT contradict conventional nuclear physics

"quark-hadron duality"

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