The η'N 2body system and the η'-optical potential in nuclear medium based on the η'N interaction from a chiral effective model

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- Introduction to the η' properties
- The analysis of η' with linear sigma model
  - The η'N 2body system
  - The η'-optical potential in nuclear medium
- Summary and future prospects

Introduction

$U_A(1)$ anomaly and η' mass

(considering 3flavor case)

<u>QCD: micro. theory of hadrons</u>

The global symmetry of QCD Lagrangian
$\sim U(3)_L \times U(3)_R$ (in chiral limit)

No parity doubling
→spontaneous break down of chiral symmetry
$(U(3)_L \times U(3)_R \rightarrow U(3)_V)$

9 Nambu-Goldstone (NG) bosons?

The pseudoscalar meson mass

- π:135MeV
- K:497MeV
- η:548MeV

Large difference

- η':958MeV

NG boson of $U(3)_L \times U(3)_R \rightarrow U(3)_V$?

$U_A(1)$ anomaly : Non-zero divergence of the $U_A(1)$ current: $\partial_\mu J_5^\mu = -\frac{g^2}{4\pi^2} F_{\mu\nu}\tilde{F}^{\mu\nu}$

No necessity of the $U_A(1)$ NG boson (The relatively large mass of η' is permitted.)

(e.g. Fujikawa, Suzuki, Path Integrals and Quantum Anomalies (2004))

$U_A(1)$ anomaly: One of the origin of the η' mass

The $U_A(1)$ anomaly effect on the meson mass spectrum may change in medium.
(The change of the instanton effect in medium)

Shuryak (1982)

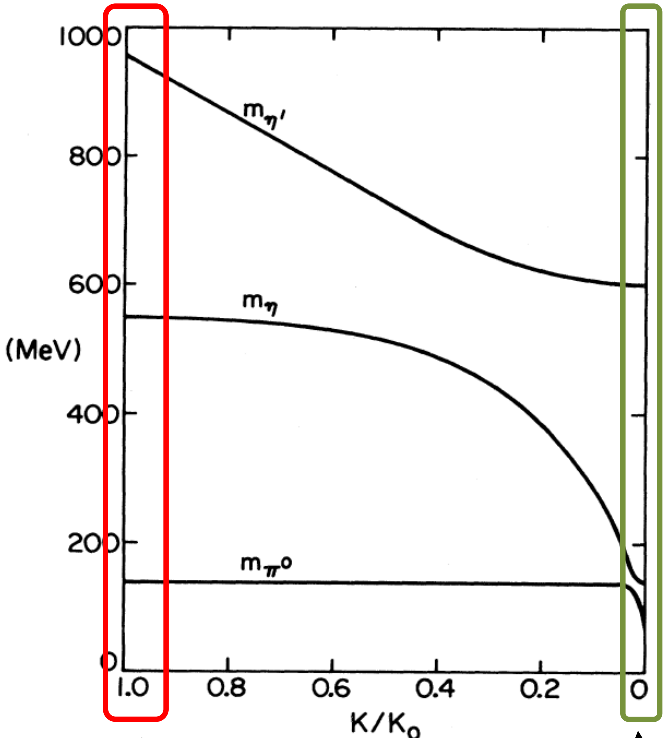
The η' properties is discussed from the "effective $U_A(1)$ restoration".

Witten (1979), Veneziano (1979), Pisarski, Wilczec (1984), Kiuchi,et al.(1988), Kapsta,et al.,(1996),….

η' mass in medium

Ex.) Analysis with linear σ model

R.D. Pisarski and F. Wilczek ,PRD29(1984)338.



η' mass reduces with the $U_A(1)$ restoration

※Mixing property is different

Free space

$$\eta' \sim \bar{u}u + \bar{d}d + \bar{s}s$$
$$\eta \sim \bar{u}u + \bar{d}d - 2\bar{s}s$$
$$\pi^0 \sim \bar{u}u - \bar{d}d$$

(mass eigen state ~$SU(3)_V$ eigen state; small mixing angle)

K=0

$$\eta' \sim \bar{s}s$$
$$\eta \sim \bar{d}d$$
$$\pi^0 \sim \bar{u}u$$

(mass eigen state ~flavor eigen state; large mixing angle)

Observed masses

Masses in $U_A(1)$ restored phase

(K: strength of the $U_A(1)$ breaking)

The effect of chiral symmetry breaking on the η' mass

The degeneracy of the pseudoscalar-singlet (η') and octet mesons (η) in chiral SU(3) symmetric phase(@high T or ρ)

Cohen (1996), Lee and Hatsuda (1996), Jido, Nagahiro, and Hirenzaki (2012)

η and η' are contained in the same multiplet of $SU(3)_L \times SU(3)_R$.

Singlet-pseudoscalar meson

$$\eta' \sim \bar{q} i \gamma_5 q \xrightarrow{\text{Axial trans.}} [Q_5^a, \eta'] = -\bar{q} i \frac{\lambda^a}{\sqrt{6}} q$$

$$\xrightarrow{\text{Axial trans.}} [Q_5^a, [Q_5^b, \eta']] = d^{abc} \bar{q} i \gamma_5 \frac{\lambda^c}{\sqrt{6}} q \sim d^{abc} \boxed{\eta^c}$$

Octet-pseudoscalar mesons

(Q_5^a:axial charge (generator of axial trans. of $SU(3)_L \times SU(3)_R$))

⇒ η and η' degenerate when chiral symmetry is restored.

※1. We used only the axial transformation of $SU(3)_L \times SU(3)_R$ (no necessity of the $U_A(1)$ restoration).
※2. We cannot transform the singlet to the octet ps-meson in the 2-flavor case.

⇒ ***Chiral symmetry breaking is also responsible for the generation of the η' mass.***

The degeneracy of *η* and *η'* in chiral SU(3) symmetric phase

- Partial restoration of chiral symmetry

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

Experimental suggestion from πN system
(Suzuki, et al.(2004), Friedman, et al.(2004))

- Small change of the *η* mass in nuclear medium

<u>The possibility of the η' mass reduction in the nuclear medium</u>

<u>through the partial restoration of chiral symmetry</u>

Related works: The *η'* properties in medium with chiral model
- NJL, Linear sigma model, Quark Meson Coupling model,…

Bernard, et al.(1988), Hatsuda and Kunihiro(1994), Costa, et al.(2003), Renaghan, et al.(2000), Bass and Thomas(2006), Nagahiro, et al.(2006), S.S and Jido(2013)…

<u>The existence of the *η'*-mesic nuclei</u>

Saito, Tsushima, and Thomas(2007), Nagahiro and HIrenzaki(2005)

(mass reduction in nuclear medium↔attractive optical potential)

$$\left(-\nabla^2 + m_{\eta'}^2 + \boxed{\Sigma_{\eta'}(\rho)}\right)\Phi = E^2\Phi$$

The in-medium *η'* self energy

※ Some experiments are progressing.

The purpose

Investigate the η'-optical potential from a <u>microscopic viewpoint</u>

based on the $\eta^{(\prime)}$N 2-body system

- Inclusion of the ηN channel

generate the imaginary part of the η'-optical potential

(Important quantity for the discussion of the possibility of the η'-nucleus bound state)

- Study of the η'N system
  - Further information or constraints on the η' properties

The important effects in η':

- Symmetries of QCD ($SU(3)_L \times SU(3)_R$, $U(1)_A$ anomaly)
- Modeling partial restoration of chiral symmetry
- Nucleon degree of freedom

Analysis with the linear sigma model

Study of η' with linear σ model

Lagrangian of linear sigma model

Schechter and Ueda (1971), Renaghan, et al. (2000)

$$\mathcal{L} = \frac{1}{2}\mathrm{tr}(\partial_\mu M \partial^\mu M^\dagger) - \frac{\mu^2}{2}\mathrm{tr}(MM^\dagger) - \frac{\lambda}{4}\mathrm{tr}\left[(MM^\dagger)^2\right]$$
$$-\frac{\lambda'}{4}\left[\mathrm{tr}(MM^\dagger)\right]^2 + A\mathrm{tr}\chi M^\dagger + \sqrt{3}B\det M + \mathrm{h.c.}$$

The effect from the current quark mass

$U_A(1)$ anomaly effect

$$+\bar{N}i\partial\!\!\!/ N - g\bar{N}\left(\frac{1}{\sqrt{3}}\sigma_0 + \frac{1}{\sqrt{6}}\sigma_8 + i\gamma_5\frac{\vec{\tau}\cdot\vec{\pi}}{\sqrt{2}} + i\gamma_5\frac{1}{\sqrt{3}}\eta_0 + i\gamma_5\frac{1}{\sqrt{6}}\eta_8\right)N$$

Contribution from nucleon

$$M = \sum_{a=0}^{8}\frac{\sigma_a\lambda_a}{\sqrt{2}} + i\sum_{a=0}^{8}\frac{\pi_a\lambda_a}{\sqrt{2}} \quad N = \begin{pmatrix} p \\ n \end{pmatrix} \quad \chi = \sqrt{3}\begin{pmatrix} m_u & & \\ & m_d & \\ & & m_s \end{pmatrix} = \begin{pmatrix} m_q & & \\ & m_q & \\ & & m_s \end{pmatrix}$$

(λ_a: Gell-Mann matrix, τ_i: Pauli matrix)

※1.) 6 free parameters are fixed to reproduce in-vacuum meson properties and 35% reduction of quark condensate @normal nuclear density.

π atom: Suzuki (2004)., π-nucleus elastic scattering: Friedman, et al. (2004).

※2.) $\langle\sigma_0\rangle \neq 0$ when chiral symmetry is broken (spontaneously and explicitly).

※3.) $\langle\sigma_8\rangle \neq 0$ when flavor symmetry is broken ($m_q \neq m_s$).

η' in linear sigma model

S.S and D.Jido,PRC89(2013)041901.

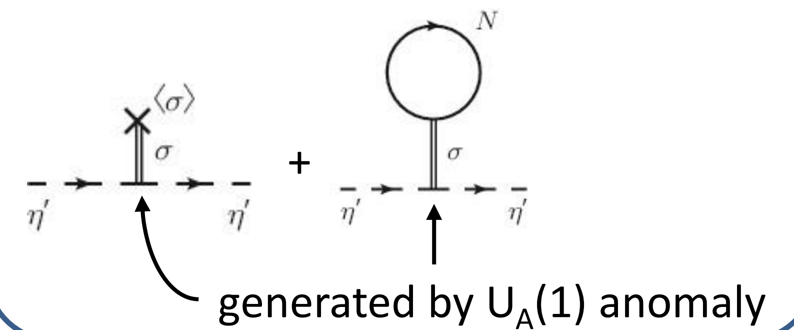
■The η' mass in nuclear medium

✓ Chiral limit

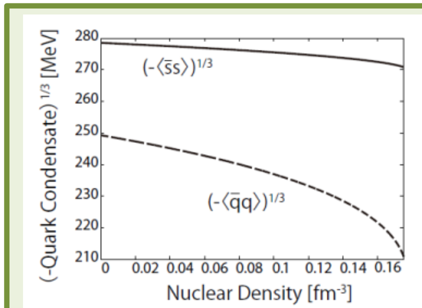
$$m_{\eta'}^2(\rho) = \underline{m_{\eta'}^2(\rho=0)} \times \frac{\langle \bar{q}q \rangle (\rho)}{\langle \bar{q}q \rangle (\rho=0)}$$

≠0 even in chiral lim.

※$m_\pi \to 0$ ($m_q \to 0$)



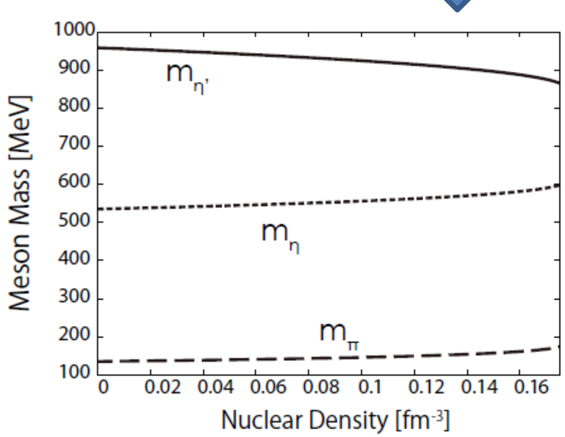
→ Necessity both of the $U_A(1)$ anomaly and chiral symmetry breaking for the generation of the η' mass in linear σ model



The 35% reduction of ⟨$q^{bar}q$⟩ @$\rho=\rho_0$ is input.

π atom:K.Suzuki, et al.(2004).
π-nucleus elastic scattering:E.Friedman, et al.(2004).

✓ Off-chiral limit



- ~80MeV reduction of the η' mass
- ~50MeV enhancement of the η mass @$\rho=\rho_0$

<u>η and η' tend to degenerate with chiral restoration</u>

and

<u>Mass reduction of η' in nuclear medium</u>

η' in linear sigma model

In the linear σ model,

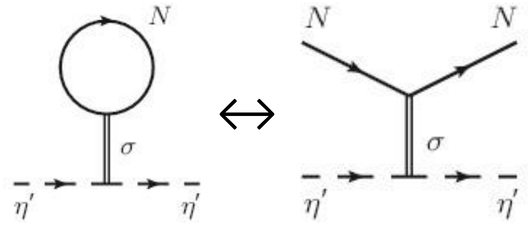
The large mass reduction ⇐ **Strong coupling with nucleon through σ exchange**

Within the mean-field approximation,

Large mass reduction of η' in nuclear medium

= Strong attraction of the η'N 2body system

In the linear σ model,



⇒ Importance of the complemental study of the η'N system

Study of the η'N 2body system

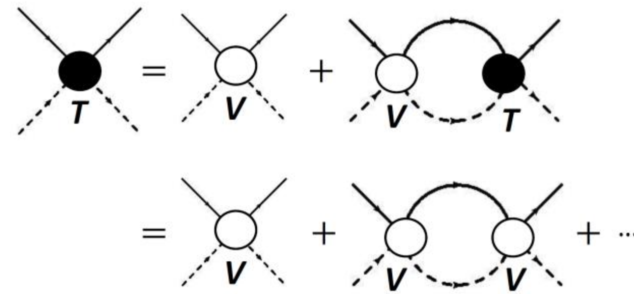
η'N 2-body system

■<u>Scattering equation</u>

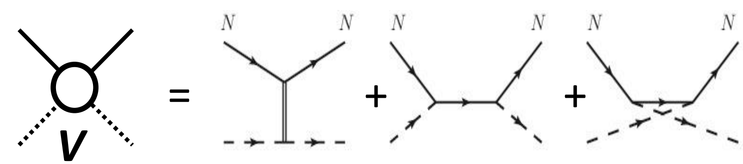
$$T_{\alpha\beta} = V_{\alpha\beta} + V_{\alpha\gamma} G_{\gamma} T_{\gamma\beta}$$

from LSM calculation

T : T matrix
V : interaction kernel
G : 2body Green function
α, β, γ : η'N, ηN, πN



In linear σ model at tree level,



Analysis of η'N with the similar way to the K^{bar}N system

✓ Use of Natural renormalization scheme

T.Hyodo,D.Jido,A.Hosaka,PRC78025203(2008).

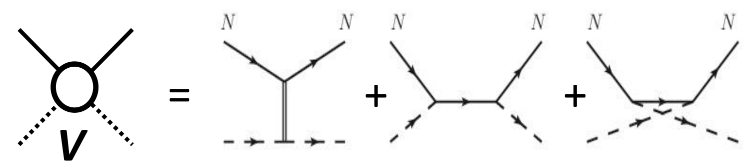
→ <u>Analysis focusing on the hadronic state</u>

η'N 2body interaction

✓ <u>Chiral limit</u>

$$V_{\eta_0 N} = -\frac{6gB}{\sqrt{3}m_{\sigma_0}^2} \qquad V_{\eta_0 N\to\eta_8 N} = \frac{6gB}{\sqrt{6}m_{\sigma_8}^2}$$

In linear σ model at tree level,



<u>The properties of $V_{\eta' N}$</u>

- ☐ Non-vanishing vertex even in the chiral limit
- ☐ Interaction induced by scalar meson exchange
- ☐ Crucial role of the $U_A(1)$ anomaly

■NG bosons (η,π)

$$V_{\pi N} = -\frac{g^2 m_\pi}{8m_N^2}\left[\lambda_a, \lambda_b\right]$$ (q^2~0, p, p'~$m_{N,}$ k, k'~m_π)

✓ <u>Off-chiral limit</u> (Focus on the zero-momentum)

$$V_{\eta_0 N} = -\frac{g}{\sqrt{3}}\frac{\frac{2}{3}\lambda\langle\sigma_0\rangle + 2\lambda'\langle\sigma_0\rangle + 4B}{m_{\sigma_0}^2} - \frac{g}{\sqrt{6}}\frac{\frac{2}{3}\lambda\langle\sigma_8\rangle + 2\lambda'\langle\sigma_8\rangle}{m_{\sigma_8}^2} + \frac{g^2}{3m_N}$$

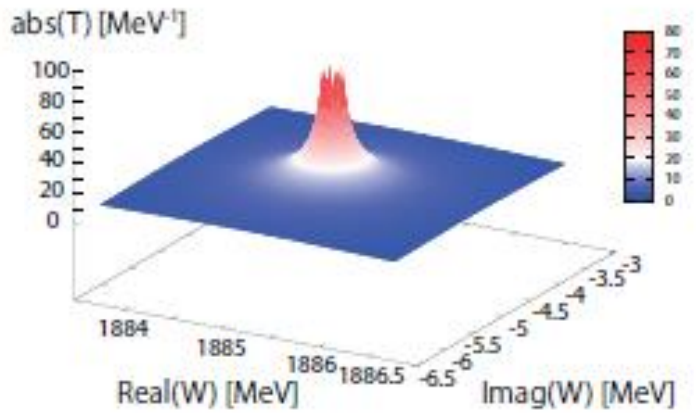
Comparable attractive potential to the K^{bar}N system

※ $M_{\mathrm{ps}} = \begin{pmatrix} \eta_0/\sqrt{3}+\eta_8/\sqrt{6} & & \\ & \eta_0/\sqrt{3}+\eta_8/\sqrt{6} & \\ & & \eta_0/\sqrt{3}-\sqrt{2}\eta_8/\sqrt{3} \end{pmatrix}$

$\eta_{0,8}$: $SU(3)_V$ eigen state
Physical η, η': linear comb. of $\eta_{0,8}$

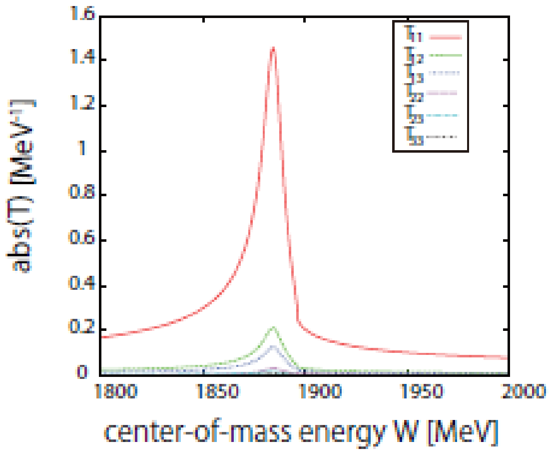
η'N 2body system

T matrix in the complex energy plane



A pole in the complex energy plane
→ A η'N quasi-bound state

Absolute value of η'N T matrix in Real axis



Pole position:

1885-4.5iMeV (η'N thr.=1896.7MeV)

(Binding energy= 11.7MeV
Full width= 9MeV)

meson-nucleon-bound state coupling

$|g_{\eta' NN^*}|=2.59$, $|g_{\eta NN^*}|=0.38$, $|g_{\pi NN^*}|=0.22$

Small couplings compared with the $g_{\eta' NN^*}$

η'N 2body system

Scattering length and effective range

Binding energy [MeV]	η'N scattering length [fm]	η'N effective range [fm]
11.7-4.5i	-1.91+0.33i	0.25-0.009i

※1. The existence of the hadronic bound state (binding energy~1MeV order)

→Scattering length is order 1fm : $a_{\eta' N} = \frac{1}{\sqrt{2\mu E_B}}$

※2. Comparison with experimentally suggested values:

$|\mathrm{Re} a_{\eta' p}| < 0.8\mathrm{fm}$ P. Moskal, et al., PLB482,356(2000).

$$\begin{cases} \mathrm{Re}(a_{\eta' p}) = 0 \pm 0.43(\mathrm{stat})\mathrm{fm} \\ \mathrm{Im}(a_{\eta' p}) = 0.37^{+0.02}_{-0.11}(\mathrm{stat})^{+0.38}_{-0.05}(\mathrm{syst})\mathrm{fm} \end{cases}$$

P. Moskal, et al., PRL,113,062004(2014).

✓ Comparison with these experimental data should be done carefully,
because of ・the difference of the energy region focusing on
・the method to extract the values from the experimental data,…

η'-optical potential

η'-optical potential

Calculation of the η'-optical potential

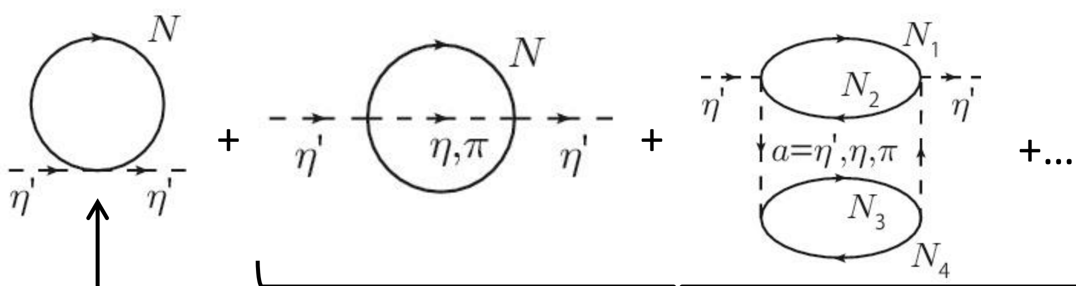
= Calculation of the in-medium η' mass

$$V_{\eta'}(\rho) = \frac{1}{2m_{\eta'}}\Sigma_{\eta'}(\rho)$$

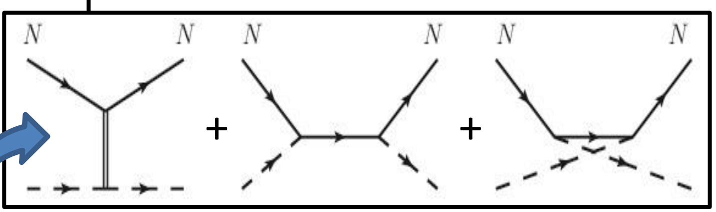
The η' optical potential in nuclear medium

The in-medium η' self energy

Diagrams

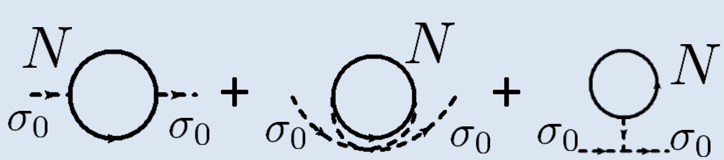


generate the imaginary part of the potential



The nuclear medium effect comes from the nucleon loop.

$$(\not{p}+m)\left\{\underbrace{\frac{i}{p^2-m^2+i\epsilon}}_{\text{Free propagation}} - \underbrace{2\pi\theta(p_0)\delta(p^2-m^2)\theta(k_f-|\vec{p}|)}_{\text{Pauli Blocking}}\right\}$$

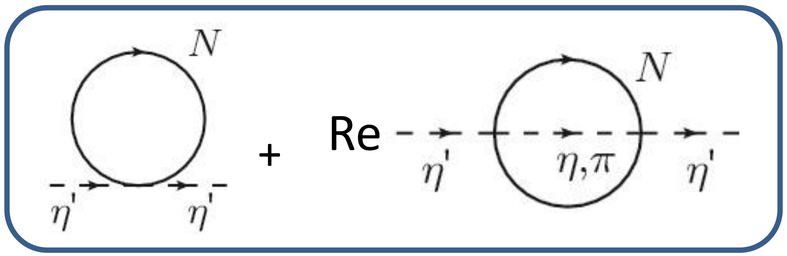


Effect of the σ mass modification in nuclear matter

※Effect of the chiral restoration
through the scalar mass modification
(σ mass~chiral order parameter ⟨σ⟩
→ sensitive to the chiral restoration)

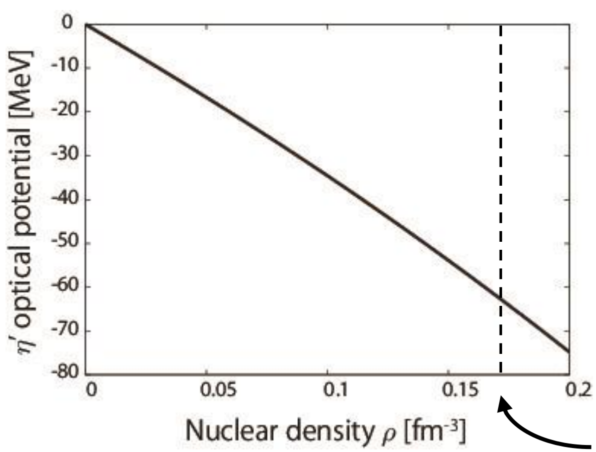
η'-optical potential

- Real part of the η' optical potential



$$\mathrm{Re}V_{\eta'}(\rho) = V_{\eta' N}\rho + \frac{V^2_{\eta' N\to\eta N}}{4\pi^4}k_f^4 + \frac{V^2_{\eta' N\to\pi N}}{4\pi^4}k_f^4 \quad \left(\rho = \frac{2}{3\pi^2}k_f^3\right)$$

✓ Density dependence of η'-optical potential



$V_{\eta'}(\rho=\rho_0)$= -62 [MeV] @$\rho=\rho_0$

Ex.)
- Depth: -37±10(stat) ±10(syst) [MeV]
- Width: 15-25 [MeV]

M.Nanova, et al.PLB727(2013)417.

Normal nuclear density ρ_0=0.17[fm^{-3}]

Summary

- Significant role of $U_A(1)$ anomaly and chiral symmetry breaking for the η' mass and η'N interaction
  - Relevance to the η'N attraction
- The possible η'N bound state
  - Binding energy: 11.7-4.5i[MeV]
- The η'-optical potential
  - Real part: -62[MeV]@$\rho=\rho_0$

Future prospects

- The calculation of the imaginary part with two-body absorption

Thank you for your attention!