The η'N 2-body interaction
and
η' optical potential in the nuclear medium

Shuntaro Sakai (Kyoto Univ.), Daisuke Jido (Tokyo Metro. Univ.)

Abstract:

Recently, we have been attracted by many studies focusing on the in-medium properties of the η' meson as a probe of the partial restoration of chiral symmetry. The interaction between η' and nucleon, which is the fundamental quantity of the η' properties in the nuclear medium, is not known well. In this study, we estimate the η'N interaction and transition amplitude of η'N to ηN with linear sigma model as a chiral effective theory. We also evaluate the the η'-optical potential in the nuclear matter and find that its real part is deep while the imaginary part is small.

The purposes

To investigate…

☞the η'N→ηN transition amplitude

☞the possibility to form a bound state of η'N bound state

☞the η' optical potential in nuclear matter

■Introduction

Possible modification of hadron properties in medium

➡ one of the interesting topics of hadron physics [1]

Ex.)dilepton process of vector meson, deeply bound state of pionic atom,…

<u>○Nuclear matter modifies the chiral properties</u>

Quark condensate @low density[2]

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

ρ:nuclear density[fm^{-3}]

$\sigma_{\pi N} = 2m_q \langle N|\bar{q}q|N\rangle$

$\langle \bar{q}q\rangle$:quark condensate in vacuum

$\langle \bar{q}q\rangle^*$:quark condensate in nuclear matter

※***The change of the ⟨$q^{bar}q$⟩ can affect the hadron properties***

Ex.)Gell-Mann-Oakes-Renner relation: $f_\pi^2 m_\pi^2 = -m_q\langle \bar{q}q\rangle$

Medium effect on η' properties through chiral symmetry

: ***<u>degeneracy of η and η' with chiral restoration with 3 favor</u>*** [3]

<u>Brief Explanation:</u>

η and η' are related with twice axial trans. of $SU(3)_L \times SU(3)_R$.

$$[Q_5^a,[Q_5^b,\eta']] = d^{abc}\eta^c$$

Generator of axial trans. / Singlet ps meson / Octet ps meson

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

※<u>No matter how $U_A(1)$ is explicitly broken by the quantum effect</u>

・chiral restoration in the nuclear matter

・small change of η mass in nuclear matter

The possible mass reduction of η' in nuclear matter

$$\Delta m_{\eta'} = m_{\eta'}(\rho) - m_{\eta'}(\rho=0) = \frac{2}{3}\frac{m_{\eta'}^2 - m_\eta^2}{2m_{\eta'}}\frac{\sigma_{\pi N}}{m_\pi^2 f_\pi^2}\rho \quad [4]$$

➡ **The possibility of the η'-mesic nuclei [5]**

(In-medium mass reduction→attractive optical potential)

Information on the η' optical potential in nuclear matter is necessary.

(Important quantity for the discussion of η'-mesic nuclei)

How to obtain the η'-optical potential ? : <u>Conventional many body calculation</u>

Need the additional input : η'N 2-body interaction

➡ Estimate the η'N interaction with **<u>inelastic channel</u>**

(generate the imaginary part of the optical potential)

■2-body interaction of η'N and transition amplitude of η'N→ηN

<u>Analysis with Linear sigma model (LSM)</u>

<u>Merit:</u>
- ■ Possess the global symmetry as QCD (chiral symmetry:$SU(3)_L \times SU(3)_R$, $U_A(1)$ anomaly)
- ■ Introduction of explicit nucleon field
- ■ *<u>Consistent description with chiral restoration in nuclear matter</u>*

→ About 80MeV reduction of the η' mass in nuclear matter [3]

○Lagrangian of LSM[6]

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

Meson part

Finite quark mass effect ($A\mathrm{tr}\chi M^\dagger$), $U_A(1)$ anomaly effect ($\sqrt{3}B\det M$)

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

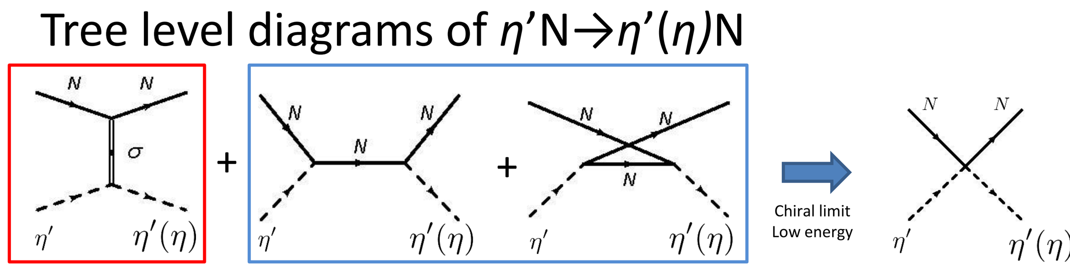
Nucleon part

$M = \sum_{a=0}^{8}\frac{\sigma_a\lambda_a}{\sqrt{2}} + i\sum_{a=0}^{8}\frac{\pi_a\lambda_a}{\sqrt{2}}$ (Meson fields) $N = \begin{pmatrix} p \\ n \end{pmatrix}$ (Nucleon fields) (λ_a:Gell-Mann matrices) $\chi = \begin{pmatrix} m_u & & \\ & m_d & \\ & & m_s \end{pmatrix}$:finite quark mass

※Parameters of the Lagrangian are determined to reproduce…
- ➢ the meson masses and decay constants
- ➢ the 35% restroration of quark condensate at normal nuclear density[7]

<u>η'N interaction with Linear sigma model</u>

- Tree level diagrams of η'N→η'(η)N



$$V_{\eta' N} = -\frac{6gB}{\sqrt{3}m_{\sigma_0}^2}$$

$$V_{\eta' N\to\eta N} = \frac{\sqrt{2}g}{3m_N}\frac{m_{\eta'}^2}{m_{\eta'}^2 + m_{\sigma_8}^2}$$

- sigma meson exchange
- $U_A(1)$ anomaly

are essential to these processes

- B:coefficient of determinant interaction (breaking $U_A(1)$ symmetry explicitly)
- Born terms are cancelled out and sigma exchange term only remains.

※ The ηN interaction is zero in the chiral limit.

■η'N bound state with ηN channel

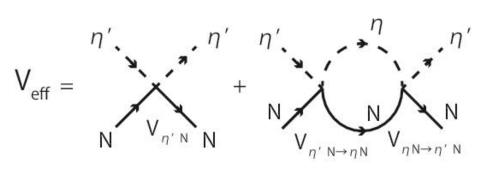
Scattering equation : $T_{\alpha\beta} = V_{\alpha\beta} + V_{\alpha\gamma}G_\gamma T_{\gamma\beta}$ (α,β,γ:ηN and η'N channel)

(The method of the inclusion of channel coupling is discussed in Ref.[8])

$$T_{\rm eff} = V_{\rm eff} + V_{\rm eff}G_{\eta' N}T_{\rm eff}$$

$$V_{\rm eff} = V_{\eta' N} + V_{\eta' N\to\eta N}G_{\eta N}V_{\eta N\to\eta' N} + V_{\eta' N\to\eta N}G_{\eta N}T_{\eta N}G_{\eta N}V_{\eta N\to\eta' N}$$

$$T_{\eta N} = \frac{1}{V_{\eta N}^{-1} - G_{\eta N}}$$



(containing the ηN intermediate state)

From the sub-threshold pole of the obtained T matrix T_{eff},

Binding energy of η'N [MeV]	η'N scattering length [fm]	η'N effective range [fm]
10.4-5.2i	-2.0+0.5i	-0.24+0.005i

(The η'N scattering length is repulsive sign due to the η'N bound state)

※With the analysis of the pp→ppη' data, $|\mathrm{Re}\, a_{\eta' N}| < 0.8\mathrm{fm}$, $|a_{\eta' N}| \sim 0.1\mathrm{fm}$ [9]

■η' optical potential in nuclear medium

- Klein-Gordon eq. in nuclear matter

$$\left(-\nabla^2 + m_{\eta'}^2 + \Sigma(\rho)\right)\Psi = E^2\Psi$$

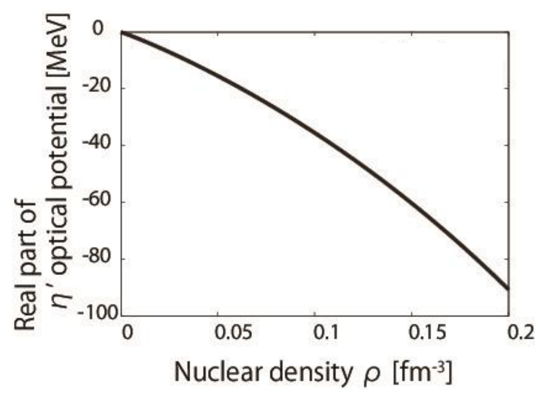
$\Sigma(\rho)$: meson optical potential in nuclear matter=In-medium meson self energy

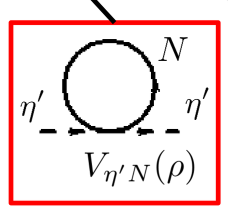
➡ Investigate the in-medium self energy of the η' meson

<u>Real part :</u> $V_{\eta'}(\rho) = \frac{\rho}{2m_{\eta'}}V_{\eta' N}(\rho)$

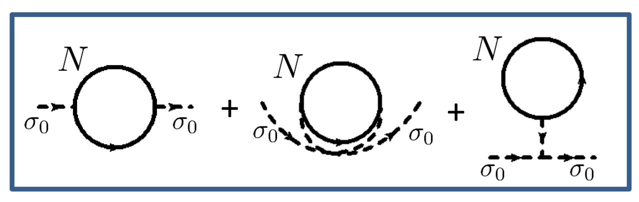
$$V_{\eta' N}(\rho) = -\frac{2\sqrt{3}gB}{m_{\sigma_0}^2(\rho)}$$

$$m_{\sigma_0}^2(\rho) = m_{\sigma_0}^2 - \frac{g\rho}{\sqrt{3}m_{\sigma_0}^2}(\lambda\langle\sigma_0\rangle + 3\lambda'\langle\sigma_0\rangle - 2B) - \frac{g^2\rho}{3m_N}$$





(Including the effect of the σ mass reduction)



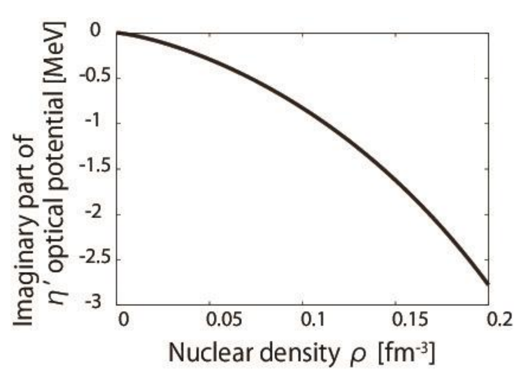
<u>In-medium self-energy of sigma meson</u>

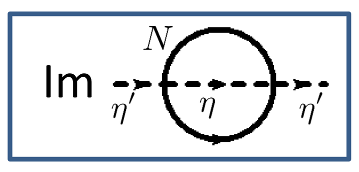
(change of the sigma meson properties in nuclear matter is important[])

<u>Imaginary part :</u> $\mathrm{Im}V_{\eta'} = -\frac{1}{2m_{\eta'}}\cdot 8\int_0^{k_f}\frac{d^3p}{(2\pi)^3}\gamma_{\eta N}(\mu_1, k_f)$

$$\gamma_{\eta' N} \equiv \int d\Phi_{\eta N}|\chi^\dagger T_{\eta' N\to\eta N}\chi|(2\pi)^4\delta^{(4)}(p_{\eta'} + p_1 - p_\eta - p_Y)$$

$T_{\eta' N\to\eta N}$: η'N→ηN transition amplitude





In-medium self-energy of sigma meson (with Cutkoski rule[10])

➡ ***<u>V(ρ=ρ$_0$)=-70-2.0i [MeV]</u>*** with the LSM analysis.

※With the analysis of the experimental data the η' photoproduction (E_γ=1.2-1.6GeV),…
- ➢ depth : -37±10(stat)±10(syst) [MeV] [11]
- ➢ width : 15-25 [MeV] [12]

✓ Comparison with these experimental data should be done carefully,

because ・the energy region focusing on ・the method to extract the values from the experimental data,…

■Conclusion & Future works

We have studied the η' meson in a view of chiral symmetry, taking account of the fact that the η' meson should degenerate with the η meson when any SU(3) chiral symmetry is restored. Using the linear sigma model, we have calculated the η'N interaction and the η'N transition amplitude. With these amplitudes, we have evaluated the η'N scattering amplitude in coupled channels of η'N and ηN. We have found that the interaction between η'N is enough strong to form a bound state with the 10.4 MeV binding energy and the 10.4 width. We have also estimated the strength of the η'-optical potential in nuclear medium, which has a large real part while a small imaginary part. With this strongly attractive optical potential, one may have η' bound state in nuclei. Further investigation is going on.

References

[1] T. Hatsuda, R. Hayano, Rev. Mod. Phys. 82, 2942 (2010); R. Rapp, J. Wambach, H. van Hees, arXiv:0901.3289.
[2] E.G. Durkarev, E.M. Levin, Nucl. Phys. A511, 679 (1990).
[3] T.D. Cohen, Phys. Rev. D54, 1867(1996); S.H. Lee, T. Hatsuda, Phys. Rev. D54, 1871 (1996); D. Jido, H. Nagahiro, S. Hirenzaki, Phys. Rev. C85, 032201 (2012).
[4] S. Sakai, D. Jido, Phys. Rev. C88, 064906 (2013).
[5] K. Saito, et al. Prog. Part. Nucl. Phys. 58, 1 (2007); H.Nagahiro,S.Hirenzaki, Phys. Rev. Lett. 94, 232503 (2005).
[6] J. Schechter, Y. Ueda, Phys. Rev. D3, 168 (1971); J.T. Renaghan, et al., Phys. Rev. D62, 085008 (2000).
[7] K. Suzuki, et al., Phys. Rev. Lett. 92, 72302 (2004); Friedman, et al., Phys. Rev. Lett. 93, 122302 (2004).
[8] T. Hyodo, W. Weise, Phys. Rev. C77, 035204 (2008).
[9] P. Moskal, et al., Phys. Lett. B474, 416 (2000); P. Moskal, et al., Phys. Lett. B482, 356 (2000).
[10] T. Sekihara, et al., Phys. Rev. C86, 065205 (2012).
[11] M. Nanova, et al., Phys. Lett. B710, 600 (2012).
[12] M. Nanova, et al., Phys. Lett. B727, 417 (2013).