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

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Abstract

In-medium modification of the η' mass is discussed in the context of partial restoration of chiral symmetry in nuclear medium. We emphasize that the $\mathrm{U}_A(1)$ anomaly effects causes the η'-η mass difference necessarily through the chiral symmetry breaking. As a consequence, the η' mass is expected to be reduced by order of 100 MeV in nuclear matter where about 30% reduction of chiral symmetry takes place. The strong attraction relating to the η' mass generation eventually implies that there should be also a strong attractive interaction in the scalar channel of the η'-N two-body system. We find that the attraction can be strong enough to form a bound state.

Key words: η' meson mass, chiral symmetry restoration, η'-N interaction, linear σ model

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1 Introduction

Recently the properties of the η' meson have been studied intensively in both theoretical and experimental aspects. Particularly its in-medium properties are very interesting in the context of exploring possible bound states of the η' meson in nuclei as suggested in Refs. [1,2]. It is known that the flavor singlet pseudoscalar meson strongly depends on the breaking pattern of chiral symmetry in QCD [3,4]. Especially in the SU(3) chiral symmetry the flavor octet and singlet pseudoscalar masons belong to the same SU(3) chiral multiplet and they should degenerate each other in the chiral symmetric limit together with the scalar partners even though the $U_A(1)$ symmetry is broken. This feature implies that the η' mass is expected to be reduced under partial restoration of chiral symmetry in nuclear medium [5]. In Ref. [6] η'-nucleon scattering is discussed based on a coupled channel approach with chiral dynamics. Using this formulation Ref. [7] has calculated the η' optical potential in nuclei for one and two-body absorptions. Experimentally the observation of the transparency ratio in the η' photoproduction on nuclear targets by the CBELSA/TAPS collaboration [8] is so remarkable that the observed transparency is sufficiently larger than those of the ω and η mesons. This result estimates the in-medium η' width to be 15-25 MeV at the saturation density for an average momentum 1 GeV/c independently of momenta in a certain range. Thus, the absorption of the η' meson in nuclear matter may be small. The elastic $\eta' N$ interaction could be also weak according to the threshold η' production from pp [9]. An experimental observation of η'-nucleus bound states by a (p, d) reaction on a ^{12}C target is planned at GSI [10]. The formation spectrum of the (p, d) reaction is comprehensively investigated with various attraction strengths of the η' meson in nucleus in Ref. [11].

2 η' mass in nuclear medium

It is the well-known fact that the $U_A(1)$ symmetry in QCD is broken explicitly by the quantum anomaly. Consequently the flavor singlet pseudoscalar meson η_0 is not a Nambu-Goldstone boson associated with the spontaneous breaking of chiral symmetry any more. Eventually the η' meson has a larger mass than the other pseudoscalar mesons being the Nambu-Goldstone bosons. In fact the π, η and η' with the strangeness partners belong to the same multiplet of the chiral SU(3) group together with the scalar companies, thus in the SU(3) chiral symmetric limit these particles get degenerated [4,5], as shown in Fig. 1 (left), even though the $U_A(1)$ symmetry is broken owing to the quantum anomaly. This implies that the mass gap between η and η' is generated necessarily by the SU(3) chiral symmetry breaking in the sense of both explicitly and spontaneously under the presence of the $U_A(1)$ breaking as depicted in Fig. 1 (right). Once assuming that the spontaneous SU(3) chiral symmetry breaking predominates over the explicit breaking by the strange quark, one expects that the η' and η mass difference should decrease as the chiral symmetry is being restored. Therefore under partial restoration of chiral symmetry in nuclear matter the η' meson mass gets reduced since the η mass hardly changes in nuclear matter owing to its Nambu-Goldstone boson nature. The magnitude of the mass reduction is estimated as an order of 100 to 150 MeV at the saturation density [5].

The fact that the flavor singlet pseudoscalar η_0 belongs to the same multiplet of the SU(3) chiral group as the octet pseudoscalars can be shown in the following

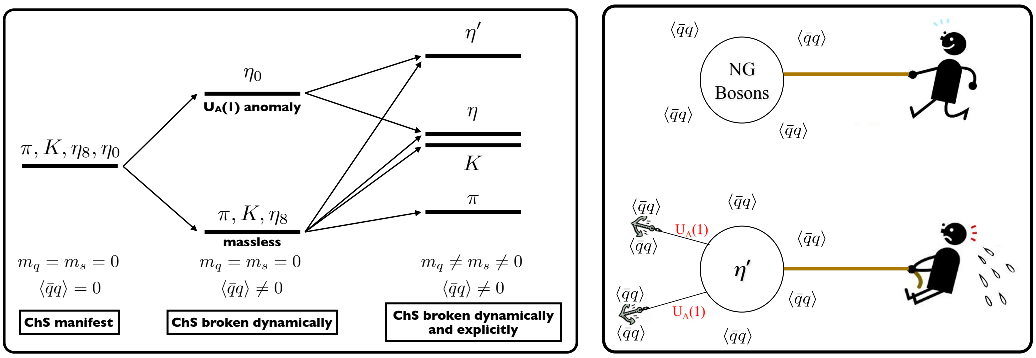

Fig. 1. (Left) Light pseudoscalar meson spectrum in the various patterns of the SU(3) chiral symmetry breaking. In the left, chiral symmetry is manifest without explicit nor dynamical breaking. All the pseudoscalar mesons have a common mass. In the middle, chiral symmetry is dynamically broken in the chiral limit. The octet pseudoscalar mesons are identified as the Nambu-Goldstone bosons associated with the symmetry breaking. In the right, chiral symmetry is broken dynamically and explicitly. The U$_A$(1) symmetry is always broken without assuming its breaking pattern. (Right) Intuitive picture of the role of the U$_A$(1) anomaly and the chiral symmetry breaking for the Nambu-Goldstone bosons and the η' meson. The mass of the Nambu-Goldstone boson is light owing to the spontaneous symmetry breaking, while the η' meson is anchored by the U$_A$(1) anomaly to the vacuum condensate.

argument: The pseudoscalar and scalar meson fields are composed by pairs of $\bar{q}_L q_R$ and $\bar{q}_R q_L$ as $\phi, \phi_5 = \bar{q}_L q_R \pm \bar{q}_R q_L$. Since the left and right quarks are in the fundamental representation of SU(3), $\mathbf{3}$, the combination $\bar{q}_L q_R \oplus \bar{q}_R q_L$ belongs to the $(\bar{\mathbf{3}}, \mathbf{3}) \oplus (\mathbf{3}, \bar{\mathbf{3}})$ multiplet. The member of this multiplet can be classified into the terminology of SU(3)$_V$ which is a subgroup of SU(3)$_L$⊗SU(3)$_R$. Since the vector transformation does not distinguish the left and right rotations, we have the singlet and octet representations of SU(3)$_V$ in the $(\bar{\mathbf{3}}, \mathbf{3}) \oplus (\mathbf{3}, \bar{\mathbf{3}})$ multiplet as obtained by $\bar{\mathbf{3}} \otimes \mathbf{3} = \mathbf{1} \oplus \mathbf{8}$. Therefore, we have η_8 and η_0 in the same multiplet. We also show that these fields can be transformed each other under the axial transformations: Since the axial transformation is an adjoint (octet) operator of SU(3)$_V$ and is not a generator of SU(3)$_V$, it can mix the octet and singlet, for instance $[Q_A^a, \eta_0] = \sqrt{2/3}\phi^a$ meaning that the singlet pseudoscalar is transformed into an octet scalar under the axial transformation Q_A^a. The scalar octet is also transformed into a linear combination of the singlet and octet pseudoscalars as $[Q_A^a, \phi^b] = \delta^{ab}\sqrt{2/3}\eta_0 + d^{abc}\phi_5^c$ with the SU(3) structure constant d^{abc}. In this way, the singlet and octet pseudoscalar fields are transformed each other under twice axial transformations, and thus are in the same multiplet even though the U$_A$(1) symmetry is broken.

3 Linear σ model and η'-N interaction

Let us consider the SU(3) linear σ model [12] as a chiral effective model embodying partial restoration of chiral symmetry.

$$\begin{aligned}\mathcal{L} =& \tfrac{1}{2}\mathrm{tr}\partial_\mu M\partial^\mu M^\dagger - \tfrac{\mu^2}{2}\mathrm{tr}(MM^\dagger) - \tfrac{\lambda}{4}\mathrm{tr}[(MM^\dagger)^2] - \tfrac{\lambda'}{4}[\mathrm{tr}(MM^\dagger)]^2 \\ &-A\,\mathrm{tr}(\chi M^\dagger + \chi^\dagger M) + \sqrt{3}B(\det M + \det M^\dagger)\end{aligned} \qquad (1)$$

where the meson field is given by $M = \sum_{a=0}^{8}(\lambda_a\sigma_a + i\lambda_a\pi_a)/\sqrt{2}$ with the scalar and pseudoscalar mesons, σ_a and π_a, respectively, and the Gell-Mann matrix λ_a. M and χ belong to the $(\bar{\mathbf{3}}, \mathbf{3})$ multiplet transforming $(M,\chi) \to L(M,\chi)R^\dagger$ under the chiral rotation. By fixing $\chi = \mathrm{diag}(m, m, m_s)$ with the u-d and strange quark masses, m and m_s, the chiral and flavor symmetries are explicitly broken. The last term with the parameter B of Eq. (1) represents the axial anomaly effect breaking the $\mathrm{U}_A(1)$ symmetry. For certain parameter sets, chiral symmetry is spontaneously broken with a finite chiral condensate given by a linear combination of $\langle\sigma_0\rangle$ and $\langle\sigma_8\rangle$, and the octet pseudoscalar mesons become the Nambu-Goldstone bosons. The η' mass in the chiral limit is obtained as

$$m_{\eta'}^2 = 6B\langle\sigma_0\rangle \qquad (2)$$

at tree level. This implies that the η' mass is generated by the chiral symmetry breaking as well as the anomaly effect. Consequently, when chiral symmetry is partially restored in nuclear matter, the η' mass should be reduced.

The nuclear medium effect is introduced based on the SU(3) linear sigma model with the baryon field [13,14]. An effective Lagrangian for the meson in linear density [14] is obtained as

$$\mathcal{L}_{\mathrm{MF}} = -\frac{g\rho}{\sqrt{3}}\left(\sigma_0 + \frac{\sigma_8}{\sqrt{2}}\right) - \frac{1}{2}\frac{g^2\rho}{m_N}\left(\frac{1}{6}\eta_8^2 + \frac{1}{3}\eta_0^2 + \sqrt{2}\frac{2}{3}\eta_0\eta_8\right)\,, \qquad (3)$$

with the nuclear density ρ and the coupling constant g for the nucleon meson Yukawa interaction. The second term of Eq. (3) comes from the particle-hole excitation in the meson propagation. We have omitted other interactions irrelevant to the current discussion. The vacuum is changed owing to the first term at finite density. The in-medium modification of the meson masses stems from two contributions, $m^{*2} = m^2(\langle\sigma_0\rangle^*, \langle\sigma_8\rangle^*) + \Sigma_{\mathrm{ph}}$: one is the effect of the shift of the vacuum induced by the first term of Eq. (3), and the other is the particle-hole excitations expressed by the second term of Eq. (3). Determining the value of g such that partial restoration of chiral symmetry takes place

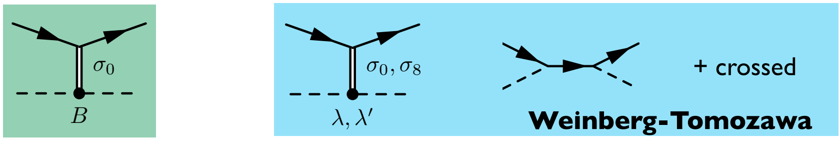

Fig. 2. Diagrammatic representation of the η'-nucleon interaction. The left diagram comes from the σ meson exchange with the anomalous $\eta_0\eta_0\sigma_0$ coupling. The residual terms cancel in low energy, giving the Weinberg-Tomozawa interaction, which is null for the $\eta' N$ channel.

with 35% reduction of the quark condensate at the saturation density, we find the reduction of the η-η' mass difference to be 135 MeV at the saturation density [14].

The η'-N two-body interaction can be extracted from the above linear σ model [14]. At the tree level, there are two types of the contributions, the σ meson exchange and the Born term, as depicted in Fig. 2. It is notable that, thanks to chiral symmetry, athe sum of a part of the σ meson exchange and the Born terms give the Weinberg-Tomozawa interaction in low energy and it is known to be null for the $\eta' N$ channel from the flavor structure. Therefore, the contributions coming from the right three terms of Fig. 2 cancel at low energy in the chiral limit and there remains the σ exchange term with the $\eta_0\eta_0\sigma_0$ coupling coming from the anomaly effect as shown in the left diagram of Fig. 2. The η'-N interaction from the σ exchange is estimated to be $V_{\eta' N} = -6B(g/\sqrt{3})/m_\sigma^2$, which is -0.053 MeV^{-1} in the parameter producing 35% reduction of the quark condensate at the saturation density. This interaction is comparably strong to the $\bar{K}N$ interaction with $I = 0$ obtained by the Weinberg-Tomozawa term as $V_{\bar{K}N} = -0.086$ MeV^{-1} at the threshold, which dynamically generates the $\Lambda(1405)$ as a quasibound state with a 10-15 MeV binding energy. Using the same machinery to $\Lambda(1405)$ in the $\bar{K}N$ channel, we calculate a bound state with the $\eta' N$ interaction obtained here, and find that η' and N form a bound state with a 6 MeV binding energy in s wave. Here we have used the natural renormalization scheme suggested in Ref. [15] in order to exclude other components than η' and N. In this way the $\eta' N$ system has strong attraction in the scalar channel.

It is worth emphasizing again that the mass gap between η and η' stems from the SU(3) chiral symmetry breaking, especially the spontaneous breaking owing to the modest explicit breaking by the strange quark mass. Thus, a good part of the η' mass is generated by the sigma condensate in the view of the linear sigma model. This leads to a large coupling of the $\eta'\eta'\sigma$ vertex as one of the U$_A$(1) anomaly effects. This is the reason that the scalar channel of the $\eta' N$ interaction is strongly attractive. This scenario recalls us of the NN interaction in the scalar-isoscalar channel. In the linear sigma model, the nucleon mass is explained as a consequence of spontaneous breaking of chiral symmetry with a finite sigma condensate and the nucleon has a strong

Yukawa coupling with the sigma meson. Consequently the NN interaction has a strong attraction in the scalar-isoscalar channel induced by the sigma meson exchange. Therefore, the mechanism of the strong attraction of the $\eta' N$ system in the scalar channel is same as the NN attraction, and it would be natural to expect a bound state of η' and N in a similar way to the deuteron as a pn bound state. For the detailed discussion, one should examine the $\eta' N$ interactions in the other channels.

4 Conclusion

We have discussed the η' meson in the context of partial restoration of chiral symmetry in the nuclear medium. Emphasizing the significant role of the chiral symmetry (spontaneous) breaking for the generation of the η'-η mass gap, we find a substantial reduction of the η'-η mass difference in the nuclear medium with an order of 100-150 MeV at the saturation density. We also find that, since the mass generation of the η' mass is a consequence of the spontaneous chiral symmetry breaking with a help of $\mathrm{U}_A(1)$ anomaly, η' has a strong coupling to the σ meson. This suggests that there should be a large attraction between η' and N in the scalar channel with the σ meson exchange as the same mechanism to the attraction of the NN interaction in the isoscalar-scalar channel. Thus, if η'-N and η'-nucleus systems have weak interactions, there should be repulsive interactions in other channels than the scalar channel. Nevertheless, there is no vector interaction for the $\eta' N$ channel induced by the Weinberg-Tomozawa interaction, since it is not allowed by the flavor structure of the $\eta' N$ system. For the detailed discussion, it is certainly necessary to proceed more phenomenological studies, such as reproduction of the η' production reactions using chiral perturbation theory implementing the aspect discussed here.

Acknowledgments

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