

Pseudoscalar Mesons in Nuclei and Partial Restoration of Chiral Symmetry

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Recent theoretical developments of hadrons in nuclei are briefly reviewed in the aspect of chiral symmetry in nuclei. We show a general sum rule connecting in-medium hadronic quantities and quark condensate, emphasizing that both pionic mode and particle-hole excitations in the nuclear medium are responsible for reduction of the chiral condensate in nuclear matter. We also discuss that few-body nuclear systems with kaons are good objects to investigate basic features of kaon-nucleus interactions, showing recent understandings of the structure of $\Lambda(1405)$ and possible bound states of $\bar{K}NN$ and $K \text{ bar}KN$. We also mention eta mesonic nuclei in connection with chiral symmetry of baryons.

§1. Introduction

One of the goals of the contemporary nuclear physics is to understand the QCD vacuum structure at finite density and/or temperature, especially the fate of dynamical (or spontaneous) breaking of chiral symmetry. The broken chiral symmetry at zero density and temperature is believed to be restored in certain high densities and temperatures. Such restoration of chiral symmetry may partially take place even in lower densities, such as nuclear density, with effective reduction of the quark condensate from the in-vacuum value. There are a lot of theoretical attempts being done to reveal the QCD phase structure. In phenomenological point of view, it is extremely necessary to make a connection of such theoretical investigations to experimental observations by confirming the probable partial restoration of chiral symmetry by hadronic experimental observations, and by finding out the density dependence of the quark condensate. One of the promising approaches to make the connection of finite density QCD with experimental observations is to investigate modification of hadron properties in nuclei, since nuclei provide us observable finite density systems in which one can create or inject hadrons by experiments. Thus, hadrons in nuclei are good research objects to investigate in-medium properties of hadrons both theoretically and experimentally. Especially, the Nambu-Goldstone bosons, π , K and η mesons, can be good probes to investigate chiral symmetry in nuclear medium.

What we can observe for meson properties in experiments are bound state structures of meson-nucleus systems, meson decay (or absorption) properties, and low-energy scattering of meson and nucleus. Recently, precise measurements of the level structure of deeply bound pionic atoms were performed,^{1),2)} and detailed determination of the pion optical potential parameters was carried out. Especially, the parameter for the repulsive enhancement of the isovector π^- -nucleus interaction was accurately extracted as $b_1^{\text{free}}/b_1 = 0.78 \pm 0.05$ at around $\rho \sim 0.6\rho_0$.²⁾ Since the b_1 parameter is related to the in-medium pion decay constant, if one assumes the in-medium Weinberg-Tomozawa relation,^{3),4)} the experimental finding of the b_1 en-

hancement is expected to be a signal of the reduction of the pion decay constant in nuclear matter. The b_1 repulsive enhancement was also seen in low-energy pion-nucleus scatterings.⁵⁾ These determinations of the pion optical potential parameters are useful also for giving basic constraints for pion condensation in neutron star.⁶⁾

§2. Quark condensate in nuclear medium and in-medium pion properties

A recently analysis showed an exact relation connecting the in-medium quark condensate to hadronic quantities in symmetric nuclear matter at the chiral limit:⁴⁾

$$\sum_{\alpha} \text{Re} \left[(N_{\alpha}^* + F_{\alpha}^*) G_{\alpha}^{*1/2} \right] = -\langle \bar{q}q \rangle^* , \tag{2.1}$$

where the in-medium quark condensate is given by $\langle \bar{q}q \rangle^* \equiv \langle \Omega | \frac{1}{2} \bar{\psi} \psi | \Omega \rangle$ with the quark field $\psi^T = (u, d)$ and the isospin symmetric matter ground state $|\Omega\rangle$ normalized by $\langle \Omega | \Omega \rangle = 1$, and the summation is taken over all of the zero modes α with the properties $\varepsilon_{\alpha} \rightarrow 0$ as $\vec{k}_{\alpha} \rightarrow \vec{0}$ in nuclear matter. In Eq. (2.1), hadronic quantities N_{α}^* , F_{α}^* and $G_{\alpha}^{*1/2}$ are matrix elements of the axial current A_{μ}^a and the pseudoscalar density $\phi_5^a \equiv \bar{\psi} i \gamma_5 (\tau^a / 2) \psi$ with the Pauli matrix τ^a in the flavor space, defined by

$$\langle \Omega_{\ell}^b(k) | \phi_5^a(x) | \Omega \rangle = \delta^{ab} G_{\ell}^{*1/2} e^{ik \cdot x} , \tag{2.2}$$

$$\langle \Omega | A_{\mu}^a(x) | \Omega_{\ell}^b(k) \rangle = i \delta^{ab} [n_{\mu} (n \cdot k) N_{\ell}^* + k_{\mu} F_{\ell}^*] e^{ik \cdot x} , \tag{2.3}$$

where $|\Omega_{\ell}^a\rangle$ with the isospin label ($a = 1, 2, 3$) are the eigenstates of the QCD Hamiltonian normalized by $\langle \Omega_{\ell}^a | \Omega_{\ell}^b \rangle = \delta^{ab} 2\varepsilon_{\ell} (2\pi)^3 V \delta_{\vec{p}, \vec{p}'}$ with the eigenvalue ε_{ℓ} measured from the ground state and spacial volume V , and the Lorentz four-vector n_{μ} specifies the frame of the nuclear matter. In the nuclear matter rest frame, $n_{\mu} = (1, 0, 0, 0)$, one empirically introduces the temporal and spacial “decay constant” as

$$\langle \Omega | A_0^a(0) | \Omega_{\alpha}^b \rangle = i \delta^{ab} \varepsilon_{\alpha} F_{\alpha}^t , \quad \langle \Omega | A_i^a(0) | \Omega_{\alpha}^b \rangle = i \delta^{ab} k_{i\alpha} F_{\alpha}^s , \tag{2.4}$$

which relate to N_{α}^* and F_{α}^* as

$$F_{\alpha}^t = N_{\alpha}^* + F_{\alpha}^* , \quad F_{\alpha}^s = N_{\alpha}^* . \tag{2.5}$$

The sum rule shown in Eq. (2.1) was derived using the operator relations of the axial current and the pseudoscalar density based on chiral symmetry.^{*)} Consequently, the sum rule is applicable for any hadronic density. In vacuum, the sum rule is reduced to the well-know Glashow-Weinberg relation⁷⁾ $F_{\pi} G_{\pi}^{1/2} = -\langle \bar{q}q \rangle$. One of the important consequences is that one has to sum up all the zero modes in nuclear matter to obtain the in-medium quark condensate. Because, in general, the pion mode is not only the zero mode in nuclear matter and particle-hole excitations also can be zero modes, the particle-hole excitations are also responsible for the in-medium modification of the quark condensate. Thus, in order to conclude reduction

^{*)} Details of the derivation are given in Ref. 4). Extension of the sum rule with finite quark masses is also discussed there.

of the quark condensate in nuclear medium, one does not have to separate the pion mode from nuclear many-body dynamics. For further quantitative discussion, one needs dynamical description of pion in nuclear matter for actual theoretical calculations of the matrix elements. Alternatively, once we extract the matrix elements N_α^* and F_α^* from experimental observables, the sum rule is available for experimental confirmation of partial restoration of chiral symmetry in nuclear medium.

The exact sum rule can be simplified at the low density. Since the one p - h excitation decouples from the sum rule and higher particle-hole excitations contribute beyond linear density, only the pion mode saturates the sum rule at linear density:

$$F_\pi^t G_\pi^{*1/2} = -\langle \bar{q}q \rangle^* \quad (2.6)$$

where F_π^t is the temporal component of the pion decay constant in nuclear medium and $G_\pi^{*1/2}$ represents in-medium wavefunction normalization. By taking a ratio of Eq. (2.6) and in-vacuum Glashow-Weinberg relation, we obtain a scaling law valid only for linear density:

$$\left(\frac{F_\pi^t}{F_\pi} \right) Z_\pi^{*1/2} = \frac{\langle \bar{q}q \rangle^*}{\langle \bar{q}q \rangle}, \quad (2.7)$$

where $Z_\pi^* \equiv G_\pi^*/G_\pi$ is the in-medium wavefunction renormalization. Thus, the in-medium modification of the quark condensate is represented by the in-medium change of the pion decay constant and the pion wavefunction renormalization. The importance of the wavefunction renormalization in in-medium chiral effective theory is also emphasized in Refs. 8) and 3). The in-medium modification of the pion decay constant F_π^t/F_π can be related to the repulsive enhancement of the s -wave isovector π -nucleus interaction observed in deeply bound pionic atoms and low-energy pion-nucleus scatterings using the in-medium Weinberg-Tomozawa relation.^{3),4)} The wavefunction renormalization at low density can be obtained by π -nucleon scattering.⁴⁾ Combining these two observation and using the low-density scaling law (2.7), reduction of the quark condensate in nuclei was confirmed in Ref. 4). It would be very interesting, if we could observe the wavefunction renormalization $Z_\pi^{*1/2}$ directly in pion-nucleus systems, since it enables us to conclude the reduction of the quark condensate from observations of pion-nucleus systems. It is also important to extend the scaling law (2.7) to higher density.

§3. Few-body systems with kaons

Kaon is one of the Nambu-Goldstone boson associated with spontaneous breaking of chiral symmetry. Although the connection of the in-medium properties of kaon to the fate of the $SU(3)_L \otimes SU(3)_R$ chiral symmetry in nuclear medium is not clear due to the heavy strange quark mass, in-medium properties of kaons are very interesting issues both theoretically and experimentally, giving fundamental information of kaon condensation in highly dense matter. Since $\bar{K}N$ interaction is strongly attractive, \bar{K} may be bound in nucleus, but the width of the bound states can be large due to strong absorption of \bar{K} into nucleons. This provides difficulties for direct experimental observations of \bar{K} bound states in nuclei. To understand fundamental

$\bar{K}N$ interaction, it may be better to investigate simpler kaonic nuclear systems first.

A recent study⁹⁾ has confirmed within the chiral unitary framework that the $\Lambda(1405)$ resonance can be a quasibound state of $\bar{K}N$ decaying to $\pi\Sigma$ with strong interaction. Thus, the $\Lambda(1405)$ resonance can be an elementary object of kaon in nucleus. The structure of the $\Lambda(1405)$ resonance is so interesting that the $\Lambda(1405)$ is composed by two states which have different coupling nature to meson-baryon state.¹⁰⁾ According to chiral dynamics, the state relevant for the $\bar{K}N$ interaction is located around 1420 MeV instead of the nominal position 1405 MeV, having a dominant coupling to $\bar{K}N$. Thus, it is very important to pin down experimentally the $\Lambda(1405)$ resonance position observed in $\bar{K}N \rightarrow \pi\Sigma$. One of the promising reactions for this purpose is $K^-d \rightarrow \pi\Sigma n$, in which the $\Lambda(1405)$ is produced by the $\bar{K}N$ channel, as discussed in Ref. 11). In fact, this process was already observed in an old bubble chamber experiment¹²⁾ and the resonance position was found around 1420 MeV. Further experimental investigation will be performed in forthcoming experiments at J-PARC¹³⁾ and DAFNE.¹⁴⁾

Developing the idea of the $\Lambda(1405)$ as a two-body $\bar{K}N$ quasibound further, we discuss three-body systems with kaons. Since a possible $\bar{K}NN$ quasibound state was theoretically predicted by Refs. 15) and 16), various approaches have been applied to this system^{17)–20)} for calculations of the binding energy and width. The present theoretical achievement is that the $\bar{K}NN$ is bound with a large width, but there is controversy over the detailed values of the binding energy and width. One of the important issues for the $\bar{K}NN$ system is whether the possible bound state could be described essentially by a $\bar{K}NN$ single channel or some coupled channel effects of $\pi\Sigma N$ should be implemented to describe the nature of the $\bar{K}NN$ bound state. The $\pi\Sigma$ dynamics is also relevant to the structure of the $\Lambda(1405)$, especially its lower state located around 1390 MeV with 100 MeV width.¹⁰⁾ Due to lack of experimental information of the $\pi\Sigma$ interaction, the pole position of the lower $\Lambda(1405)$ state is not precisely determined yet.²¹⁾ Detailed experimental information of the $\pi\Sigma$ dynamics, such as the scattering length and effective range of the $\pi\Sigma$ with $I = 0$,²²⁾ is favorable for further understanding of the $\Lambda(1405)$ and $\bar{K}NN$ system.

Recently, another kaonic three-body system, $K\bar{K}N$, was investigated in a non-relativistic potential model and a possible quasibound state with $I = 1/2$ and $J^P = 1/2^+$ (N^*) was found with a mass 1910 MeV and a width 90 MeV.²³⁾ Later this system was studied also in a three-body Faddeev approach with coupled channels and a very similar state was found.²⁴⁾ It was also found in the Faddeev approach²⁵⁾ that this quasibound state is essentially described by a $K\bar{K}N$ single channel, in which $\Lambda(1405)$ and $a_0(980)$ are formed in subsystems of $\bar{K}N$ and $\bar{K}K$, respectively.²³⁾ This quasibound state is a loosely bound system having a 20 MeV binding energy. It is found in Ref. 23) that the quasibound has a spatially larger size than typical baryon resonances by showing that the root mean squared radius is as large as 1.7 fm and the inter-hadron distances are comparable with nucleon-nucleon distances in nuclei. The main decay modes of this state may be three-body decays, such as $\pi\Sigma K$ and $\pi\eta N$ from the decays of the $\Lambda(1405)$ and $a_0(980)$ subsystems. The nucleon resonance with 1910 MeV mass and $J^P = 1/2^+$ proposed in Refs. 23)–25) as a quasibound state of $K\bar{K}N$ is not listed in the Particle data table yet. Experimentally this state could

be observed in $\gamma p \rightarrow K^+ \Lambda$. Further discussion on experimental observation of this N^* can be found in Ref. 26).

The quasibound states of $\bar{K}NN$ and $K\bar{K}N$ are analogous states in a sense that real kaons are the constituents in the systems and their subsystems, $\bar{K}N$ and $\bar{K}K$, have quasibound states with about 10 MeV binding energy. It would be very interesting if we could observe both states experimentally. Together with further detailed information of the positions of the double poles of $\Lambda(1405)$, experimental observations of the three-body bound states will give us fundamental knowledge of $\bar{K}N$ and \bar{K} -nucleus interactions.

§4. η mesonic nuclei

The η meson is also one of the Nambu-Goldstone bosons. It has a neutral charge and interacts with nuclei by strong force. Possible bound states of η in nuclei were first predicted in Ref. 27), which was based on the attractive ηN interaction. One of the interesting points in physics of η mesonic nuclei is that one could probe chiral symmetry for baryon with the formation spectra of the η mesonic nuclei²⁸⁾ since the ηN system strongly couples to the $N(1535)$ nucleon resonance and $N(1535)$ is a candidate of the chiral partner of nucleon.^{29),30)} If nucleon and $N(1535)$ are chiral partners, their mass difference is expected to be reduced as chiral symmetry is partially restored in nuclei. This reduction of the mass difference induces level crossing between the eta and N^* -hole modes in nuclei and it can be seen in the spectrum shape of the formation cross section of η mesonic nuclei.³¹⁾ For experimental formation of η mesonic nuclei, recoil-free reactions are essential to produce bound states selectively.^{32),33)} Further details of the formation spectra are discussed in Ref. 33).

§5. Summary

One of the promising ways to learn basic properties of the QCD vacuum structure at low density is that one produces hadrons in nuclei experimentally and investigates their properties. Deeply bound pionic atoms and low-energy pion-nucleus scatterings are most successful systems to complete our story connecting experimental observations with partial restoration of chiral symmetry in nucleus. This achievement was based on the recent theoretical finding of the exact sum rule showing connection between the in-medium hadronic quantities and quark condensate. This sum rule tells us that both pionic mode and particle-hole excitations contribute to in-medium quark condensate, and can be simplified in low density into the scaling law in which the in-medium change of the quark condensate is expressed by the in-medium modification of the pion decay constant and pion wavefunction renormalization. Investigation of mesons in nuclei is closely related to physics of baryon resonances in nuclei. For kaonic nuclei, one has to understand in-medium properties of $\Lambda(1405)$. For this purpose, as a first step, few-body nuclear systems with kaons, such as $\bar{K}NN$ and $K\bar{K}N$, are good to be investigated both theoretically and experimentally. For eta mesonic nuclei, the $N(1535)$ resonance may play an important role and one could probe chiral symmetry for baryons.

Acknowledgements

The author would like to thank T. Hatsuda, T. Kunihiro, Y. Kanada-En'yo, S. Hirenzaki, H. Nagahiro, T. Hyodo A. M. Torres and Y. Ikeda for their collaborations. This work was supported by the Grant-in-Aid for Scientific Research from MEXT and JSPS (Nos. 20028004, 2274016 and 22105507). This work was done in part under the Yukawa International Program for Quark-hadron Sciences (YIPQS).

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