MESON PROPERTIES AT FINITE DENSITY FROM MESIC ATOMS AND MESIC NUCLEI*

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The properties of $\eta'(958)$ meson at finite nuclear density is considered to have close connection with the effects of $\mathrm{U_A}(1)$ anomaly at finite density. In this context, we are very much interested in the study of the $\eta'(958)$-mesic nuclei. As for the η-mesic nuclei, which have been studied for a long time, we think it is interesting and important to consider both effects of the coupling of ηN system to $N^*(1535)$ and of the mixing of η with $\eta'(958)$. In this article, we briefly summarize recent results of our studies concerning with $\eta'(958)$- and η-mesic nuclei.

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1. Introduction

In contemporary hadron physics, the light pseudoscalar mesons are considered as the Nambu–Goldstone bosons associated with the spontaneous breaking of the QCD chiral symmetry. The complicated mass spectrum of these mesons and the heavier $\eta'(958)$ meson observed in experiments is believed to be the consequence of the explicit breaking of flavor symmetry by current quark masses and of the breaking of the axial $\mathrm{U_A}(1)$ symmetry at the quantum level referred as the $\mathrm{U_A}(1)$ anomaly. In Fig. 1, we show a schematic view of the pseudoscalar meson mass spectra in various chiral symmetry breaking patters [1, 2]. In the left, the chiral symmetry is manifest with neither 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 by the quark condensate and explicitly by finite quark masses.

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One of the most important subjects in the hadron physics is to reveal the aspects of the QCD symmetry in various environment and get deeper insights of the strong interaction. As shown in Fig. 1, the mass of the hadron is believed to have close connection to the symmetry breaking pattern of QCD. Thus, the properties of the mesons including masses in nuclei are expected to provide very important information on the symmetry at finite density [3], and, in this context, the $\eta'(958)$- and η-mesic nuclei discussed in this article are very interesting.

The results shown in this article have been reported in Refs. [1, 2, 4, 5].

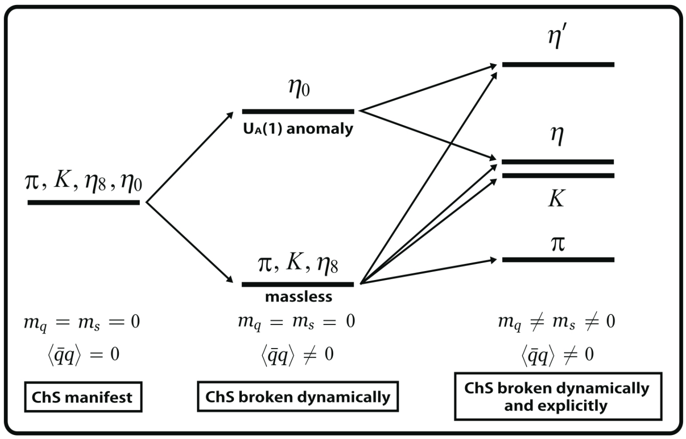

Fig. 1. Light pseudoscalar meson spectrum in the various patterns of the SU(3) chiral symmetry breaking [1, 2].

2. $\eta'(958)$-mesic nuclei

The $\eta'(958)$ meson at finite density has been discussed for a long time [6–11] and the possible formation spectra of the $\eta'(958)$-mesic nucleus was first investigated in Ref. [4] with the (γ, p) reaction. Recently, it was pointed out theoretically that the anomaly effect can contribute to the $\eta'(958)$ mass only with the presence of the chiral symmetry breaking [1]. Thus, even if density dependence of the $\mathrm{U_A}(1)$ anomaly effect is small, a relatively large mass reduction of $\eta'(958)$ is expected at nuclear saturation density because of the partial restoration of the chiral symmetry, which may indicate the existence of the $\eta'(958)$-mesic nucleus.

On the other hand, it was reported in Ref. [12] that the experimental observation of the $\eta'(958)$-mesic nucleus is considered to be possible by the missing-mass spectroscopy using (p, d) reaction on nuclear targets at existing facilities like GSI. The comprehensive theoretical results of the expected (p, d) spectra for the formation of the $\eta'(958)$-mesic nucleus are also reported in Ref. [2].

The momentum transfer of the (p, d) reaction is shown in Fig. 2 as functions of the incident energy, where we can find that the recoilless condition is never satisfied for $\eta'(958)$. The momentum transfer q is around $q = 400$–500 MeV$/c$ at the proton kinetic energy $T_p = 2.5$ GeV, where the experimental feasibility was investigated [12], and thus, various combinations of $\eta'(958)$-particle and neutron-hole states will contribute to the spectrum. This is completely different situation from deeply bound pionic atom formation reaction [3] which was performed at the kinematics satisfying the recoilless condition. However, we have an advantage for $\eta'(958)$-mesic nucleus case. We have large ambiguities for the potential depth of the $\eta'(958)$-nucleus optical potential and for the binding energies of the $\eta'(958)$-mesic nucleus. In this exploratory level, the experiments should be designed to cover wide possibilities of the quantum numbers of the bound state. The reaction with large momentum transfer enables us to widen the 'visible' combinations of the quantum numbers in the experiments as the threshold enhancement [1, 2, 12].

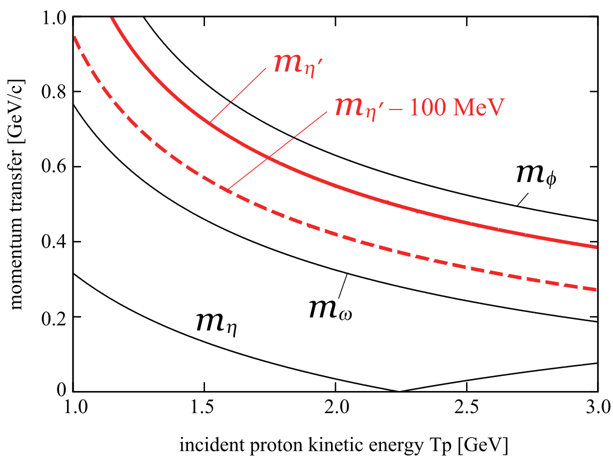

Fig. 2. Momentum transfer of the ^{12}C(p, d) reactions as functions of the incident proton kinetic energy T_p [2]. Thick lines correspond to $\eta'(958)$-meson production with binding energies of 0 and 100 MeV, and thin lines to η, ω and ϕ meson productions as indicated in the figure for comparison.

We show in Fig. 3 the typical results of theoretical calculations of the ^{12}C(p, d) reactions for the formation of the $\eta'(958)$-mesic nucleus. As we mentioned, we can see the peak structure in the spectra at the threshold energy for both cases with significantly different potential depth. We also show the spectra for the γ induced reaction in Fig. 4 [4], where we can also see the spectrum shape without the attractive potential ($V_0 = 0$) case.

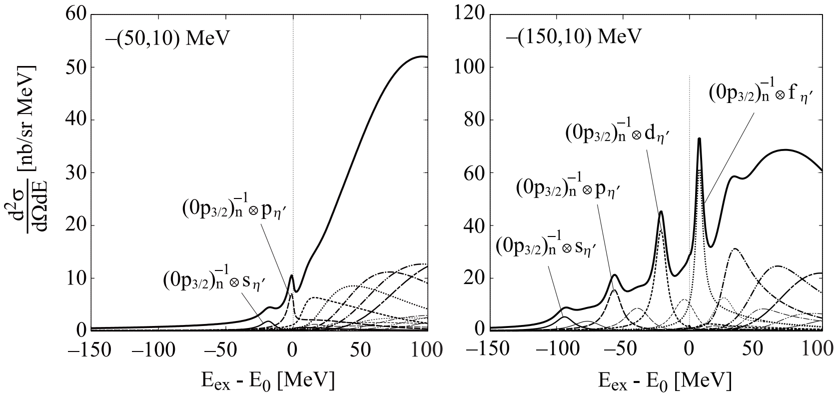

Fig. 3. Calculated spectra of the ^{12}C(p,d) reaction for the formation of $\eta'(958)$-nucleus systems with the proton kinetic energy $T_p = 2.5$ GeV at forward deuteron angle [2]. The thick solid lines show the total spectra and dashed lines indicate subcomponents. The strengths of the $\eta'(958)$-nucleus complex optical potential are indicated in the figure.

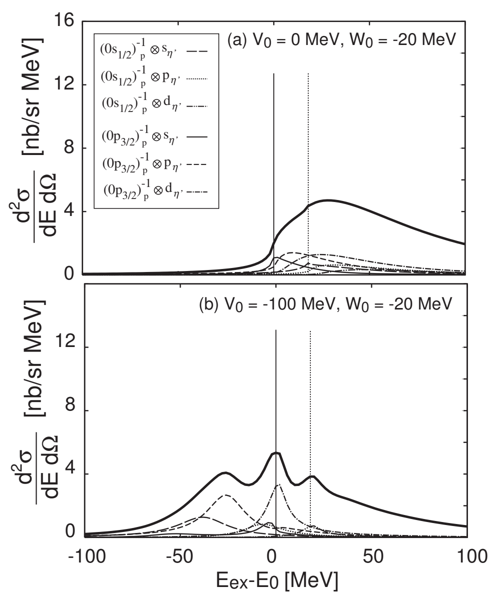

Fig. 4. Calculated spectra of the ^{12}C(γ,p) reaction for the formation of $\eta'(958)$-nucleus systems with the photon energy $E_\gamma = 3$ GeV at forward proton angle [4]. The thick solid lines show the total spectra and dashed lines indicate subcomponents. The strengths of the $\eta'(958)$-nucleus complex optical potential are indicated in the figure.

3. η-mesic nuclei

Bound state of the η meson in nucleus were predicted by Haider and Liu in 1980s [13]. After that, many works were devoted to studies of the structure of the bound states, the formation reactions of the η-mesic nuclei, and in-medium properties of the η meson. Recently, the η meson in the nuclear medium has been investigated in the aspect of chiral symmetry. We can find some of the latest results in Refs. [5, 8, 14].

In the studies of the η-nucleus systems, we think it is important to consider both effects of the coupling of ηN system to $N^*(1535)$ and of the mixing of η with $\eta'(958)$. In our latest paper [5], we have calculated the theoretical η-nucleus optical potential for various energies and showed that the potential has the strong energy dependence as we can see in Fig. 5. This is due to the existence of the $N^*(1535)$ resonance close to the ηN threshold. Thus, we should be very careful for the coupling to the $N^*(1535)$ resonance and energy dependence of the potential when we apply it to the studies of the bound states [5, 14, 15]. The mixing of η with η' should be also considered in a theoretical framework to study the η- and $\eta'(958)$-mesic nucleus in a unified manner [8, 16].

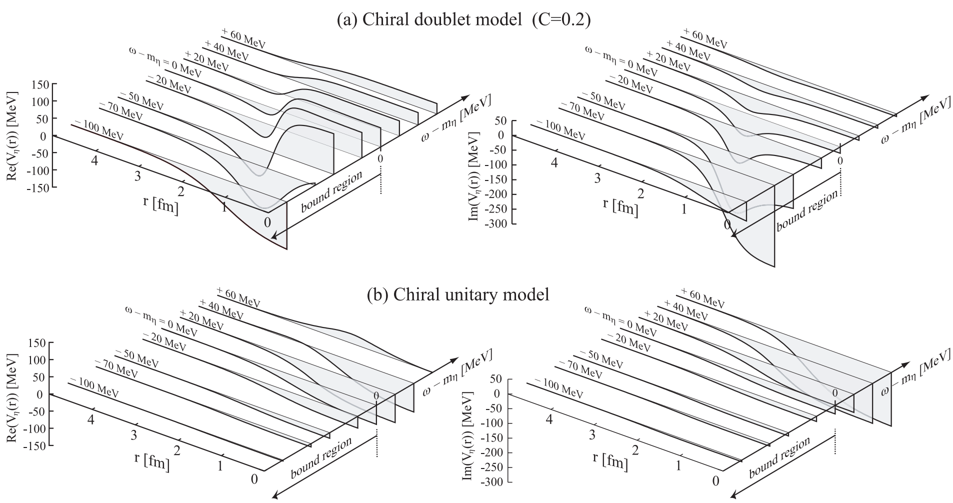

Fig. 5. The η-nucleus optical potentials with (a) the chiral doublet model and (b) the chiral unitary model as functions of the radial coordinate r for various η-energies as indicated in the figure [5]. Left and right panels show the real and imaginary parts of the optical potential, respectively.

Finally, we show a comparison of theoretical results [5] with experimental data [17] in Fig. 6. The data were reported in 1980s at the very early stage in the study of η-mesic nucleus and lead to the negative conclusion in Ref. [17].

However, as we can see in Fig. 6, it seems very difficult to deduce the decisive conclusion from the data and the existence of the η-mesic nucleus is still controversial.

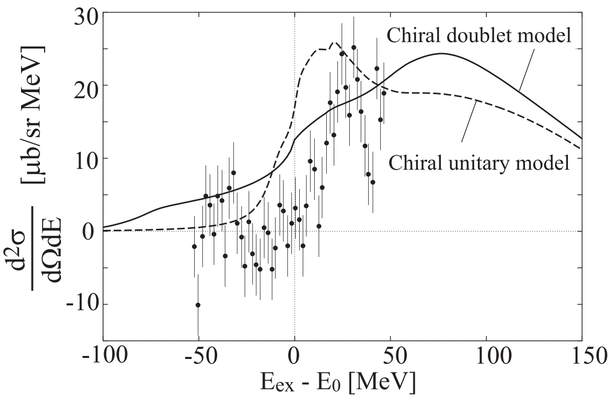

Fig. 6. Comparison of the calculated spectra and the experimental data in Ref. [17] of the $^{12}\mathrm{C}(\pi^+, p)$ reaction for the formation of the η-mesic nucleus at $p_\pi = 800$ MeV/c and $\theta_p = 15°$ [5].

4. Summary

In this article, we have briefly summarized recent results of our studies concerning with $\eta'(958)$- and η-mesic nuclei. The serious efforts for observation of the $\eta'(958)$-mesic nucleus has just begun [2, 12]. So far, the observation of the $\eta'(958)N$ scattering length indicated the relatively weak interaction of $\eta'(958)$ and could not be consistent to the existence of the deeply bound states [18]. On the other hand, the observation of the transparency ratio indicated the relatively weak absorptive potential of the $\eta'(958)$ in the nucleus [19] which can help to form quasi stable bound states in nucleus. We expect to have new information on $\eta'(958)$ properties and $\mathrm{U_A}(1)$ effects at finite density in near future.

The study of the η-mesic nucleus has a long history, however, it is still controversial whether there exists the quasi-stable bound state or not. We think we need further theoretical studies of structure and formation reaction of the bound states, and further experimental efforts to get clear signals like in Refs. [20, 21].

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