η' bound states in nuclei and partial restoration of chiral symmetry

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We discuss the in-medium mass of the η' meson under partial restoration of chiral symmetry. The chiral SU(3)⊗SU(3) symmetry tells us the flavor singlet pseudoscalar meson η' should degenerate with the octet η meson in the SU(3) flavor limit, when chiral symmetry is restored in spite of $U(1)_A$ anomaly in the flavor single axial current. The suppression of the anomaly effect induces an order of 100 MeV reduction for the η' mass at the saturation density without introducing a large absorption width. We show the formation spectrum of the η' mesonic bound state in a nucleus as a possible observation of the η' mass reduction.

1 Introduction

Dynamical chiral symmetry breaking and its partial restoration in finite density systems is one of the important subjects of hadron physics. Recently, spectroscopy of deeply bound pionic atom of Sn [1] and low-energy pion-nucleus scattering [2], with helps of theoretical analyses [3], have suggested that the partial restoration does take place in nuclei with order of 30% reduction of the quark condensate. The reduction of the quark condensate in nuclear medium also leads to various phenomena, for instance, attractive enhancement of scalar-isoscalar $\pi\pi$ correlation in nuclei and the suppression of the mass difference between the chiral partners. Mass reduction of the η' meson is also induced by partial restoration of chiral symmetry [4]. The experimental observations of these phenomena, such as the reduction of the N-$N(1535)$ mass difference in the η mesonic nuclei formation [5], can be further confirmation of partial restoration of chiral symmetry in nucleus.

2 η' mass under chiral symmetry restoration

Experimentally, a strong mass reduction of η' ($\gtrsim$ 200 MeV) has been reported in Ref. [6] at RHIC. On the other hand, a small scattering length ($\sim$ 0.1 fm) has been suggested in Ref. [7] which indicates small mass reduction around 10 MeV at normal saturation

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density in the linear density approximation. The transparency ratio of the η' meson in nuclei has suggested the absorption width of the η' meson in nuclei is around 30 MeV [8]. Theoretically, NJL model calculations suggested around 200 MeV mass reduction at the saturation density [9,10]. In the instanton picture, rapid decrease of the effects of instantons in finite energy density hadronic matter induces a reduction of the η' mass [11]. An effective model which is consistent to the $\eta' p$ scattering length data [7] was also proposed recently [12].

The basic idea of the present work is that, if density dependence of the $U(1)_A$ anomaly is moderate, a relatively large mass reduction of the η' meson is expected at nuclear density due to the partial restoration of chiral symmetry [4]. This is based on the following symmetry argument. Both the flavor single and octet pseudoscalar mesons composed of a $\bar{q}$-q pair belong to the same $(\mathbf{3}, \bar{\mathbf{3}}) \oplus (\bar{\mathbf{3}}, \mathbf{3})$ chiral multiplet of the $SU(3)_L \otimes SU(3)_R$ group. Therefore, when the $SU(3)_L \otimes SU(3)_R$ chiral symmetry is manifest, the flavor singlet and octet mesons should degenerate, no matter how the $U(1)_A$ anomaly effect depends on the density. In other words, the chiral singlet gluonic current, which makes the η' mass lift up, cannot couple to the chiral pseudoscalar state without breaking chiral symmetry. Hence, the η and η' mass splitting can take place only with (dynamical and/or explicit) chiral symmetry breaking, meaning that the $U(1)_A$ anomaly effect does push the η' mass up but necessarily with the chiral symmetry breaking. In this way the mass splitting of the η-η' mesons is a consequence of the interplay of the $U(1)_A$ anomaly effect and the chiral symmetry breaking. Assuming 30% reduction of the quark condensate in nuclear medium, for instance, and that the mass difference of η and η' comes from the quark condensate linearly, one could expect an order of 100 MeV attraction for the η' meson coming from partial restoration of chiral symmetry in nuclear medium.

The present mechanism of the η' mass reduction in finite density has a unique feature. Although some many-body effects introduce an absorptive potential for the η' meson in medium, the mass reduction mechanism does not involve hadronic intermediate states and, thus, the attraction dose not accompany an additional imaginary part. Furthermore, in the present case, since the suppression of the $U(1)_A$ anomaly effect in nuclear medium induces the attractive interaction, the influence acts selectively on the η' meson and, thus, it does not induce inelastic transitions of the η' meson into lighter mesons in nuclear medium. Consequently the η' meson bound state may have a smaller width than the binding energy.

3 Formation spectrum of the η' mesonic nuclei

Now we discuss the η' bound states in a nucleus based on the above observation and show expected spectra of the η' mesonic nucleus formation in a $^{12}C(\pi^+, p)^{11}C \otimes \eta'$ reaction [4,13]. We perform a simple estimation of the η' bound states and, thus, assume a phenomenological optical potential of the η' meson in nuclei as $V_{\eta'}(r) = V_0 \rho(r)/\rho_0$, with the Woods-Saxon type density distribution $\rho(r)$ for nucleus and the saturation density $\rho_0 = 0.17\ \mathrm{fm}^{-3}$. The

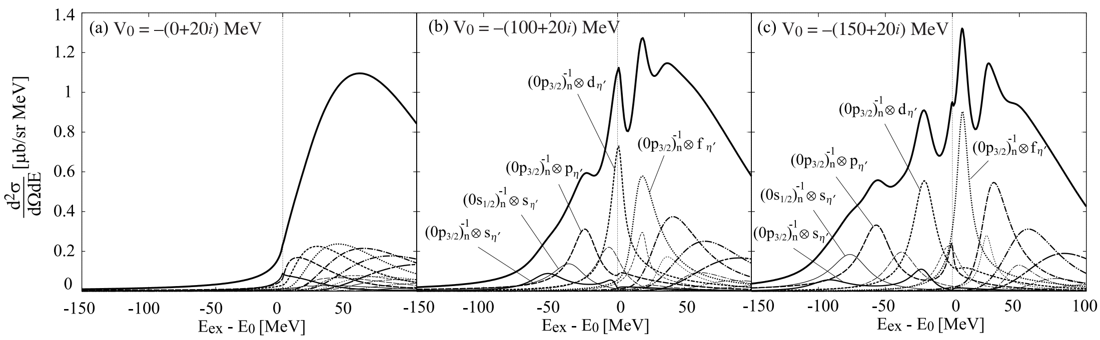

Figure 1: Calculated spectra of the ^{12}C$(\pi^+, p)^{11}$C$\otimes\eta'$ at $p_\pi = 1.8$ GeV as functions of the exitation energy $E_{\rm ex}$ with (a) $V_0 = -(0 + 20i)$ MeV, (b) $V_0 = -(100 + 20i)$ MeV and (c) $V_0 = -(150 + 20i)$ MeV. The thick solid lines show the total spectra, and the dominant subcomponents are labeled by the neutron-hole state $(n\ell_j)_n^{-1}$ and the η' state $\ell_{\eta'}$.

depth of the attractive potential is an order of 100 MeV at the normal nuclear density as discussed above and the absorption width is expected to be less than 40 MeV [8] which corresponds to the 20 MeV imaginary part of the optical potential. The formation spectrum is calculated in the approach developed in Ref. [5, 14] using the impulse approximation and the Green's function method.

In Fig. 1, we show the calculated ^{12}C$(\pi^+, p)^{11}$C$\otimes\eta'$ cross sections with three different potential parameters. In the figure, the vertical line indicates the η' production threshold in vacuum. In the case of no attractive potential, there is no structure in the η'-binding region but some bump in the quasi-free region. Finding so prominent peaks in the η'-binding region as to be possibly observed in future experiments, we conclude that with an order of 100 MeV mass reduction and a 40 MeV absorption width at the saturation density we have a chance to observe the η'-nucleus bound states in the ^{12}C(π^+, p) reaction. We see also clear peaks around the η' production threshold, for instance $(0p_{3/2})_n^{-1} \otimes d_{\eta'}$ in plot (b) and $(0p_{3/2})_n^{-1} \otimes f_{\eta'}$ in plot (c). They are not signals of the bound states, however, these are remnants of the bound states which could be formed if the attraction would be stronger. Therefore, such peak structure also can be signals of the strong attractive potential.

4 Conclusion

We point out that partial restoration of chiral symmetry in a nuclear medium induces suppression of the U$(1)_A$ anomaly effect to the η' mass. Consequently, we expect a large mass reduction of the η' meson in nuclear matter with a relatively smaller absorption width. The mass reduction could be observed as η'-nucleus bound states in the formation reactions. The interplay between the chiral symmetry restoration and the U$(1)_A$ anomaly effect can be a clue to understand the η' mass generation mechanism. Therefore, experimental observations of the deeply η'-nucleus bound states, or even confirmation of nonexistence of such deeply bound states, is important to solve the $U(1)_A$ problem.

Acknowledgments

This work was partially supported by the Grants-in-Aid for Scientific Research (No. 22740161, No. 20540273, and No. 22105510). This work was done in part under the Yukawa International Program for Quark- hadron Sciences (YIPQS).

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