Possible level crossing of $N^*(1535)$-*hole* and η modes and formation of η mesic nuclei induced by pion beam

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Abstract

We investigate the properties of the η-nucleus interaction by postulating the $N^*(1535)$ dominance for η-N system. Since the mass gap of N^* and N is very close to the η meson mass, if the gap becomes small for some reason, we can see the level crossing phenomena with η mode in finite density. Indeed we find that such a level crossing might occur associated with the partial restoration of chiral symmetry in medium based on the chiral doublet model and can be observed in the formation cross sections of η-mesic nuclei with (π, N) reactions which can be performed at existing and/or forthcoming facilities like J-PARC. We show the calculated spectra and also discuss the experimental feasibilities.

1 Introduction

The study of the in-medium properties of hadrons is one of the most important subjects in contemporary nuclear physics and has attracted continuous attention. The detailed investigation of hadron-nucleus bound systems clarifies quantitative features on basic hadron-nucleus interactions. The recent interests reach the extension to the systems with heavier neutral mesons, such as the η and ω mesons, purely governed by strong interaction in contrast to the atomic states of mesons with negative charge.

In Refs. [1–3] for studying the η-nucleus system in the chiral doublet model, we found repulsive nature of the η optical potential inside the nucleus which is associated with reduction of the mass difference of N and $N^*(1535)$ caused by partial restoration of chiral symmetry. This repulsive nature of the optical potential reflecting the N^* mass reduction strongly affects the formation cross sections of the η-mesic nuclei, consequently the expected spectra could be distinguished [2, 3] from that of the chiral unitary approach where the N^* mass shift is predicted to be small [4, 5].

In this report, we would like to discuss the η-nucleus system from a different viewpoint. In Ref. [6], we have the discussion of the level crossing between N^*-*hole* and η modes in medium associated with the partial restoration of the chiral symmetry using the chiral doublet model [6]. We conclude that we can see deep bound states of η in a nucleus and an enhancement of the N^*-*hole* mode in the η quasi-free region as a consequence of the level crossing. These phenomena are very interesting and will be an evidence of the level crossing and also the partial restoration of chiral symmetry if they are really observed. In this report, we also show the formation spectra of the η-mesic nuclei by (π^+, p) reactions and find that we can get a signal of the level crossing in the formation spectra of the η-mesic nuclei. We also find that the appropriate kinetic energy of the injecting pion in this reaction can be attained by the the Japan Proton Accelerator Research Complex (J-PARC) facility.

In Ref. [6], we discussed the level crossing phenomena in detail, and, in Ref. [7] we will have more detail discussion of the (π, N) spectra reconsidering the past theoretical studies and experiment [8–10] and discuss the present experimental feasibilities.

2 Level Crossing of the N*-hole and η meson

In the beginning of the discussions, we briefly explain the level crossing phenomena between the N^*-*hole* and η modes reported in Ref. [6].

In-medium η propagator is given by,

$$D_\eta(\omega, k; \rho)^{-1} = \omega^2 - k^2 - m_\eta^2 - \Pi_\eta(\omega, k; \rho), \tag{1}$$

where ω and k denote the energy and momentum of the η meson, m_η is its mass, and Π_η denotes the η self-energy in the nuclear medium. Because of the strong coupling of the ηN system to the $N^*(1535)$ resonance, $N^*(1535)$-*hole* mode dominates the η self-energy. Therefore, we assume the N^* dominance throughout this paper and evaluate the η self-energy Π_η as,

$$\Pi_\eta(\omega, k = 0; \rho) = \frac{g_\eta^2 \rho}{\omega + m_N^*(\rho) - m_{N^*}^*(\rho) + i\Gamma_{N^*}(\omega, \rho)/2} + \text{(cross term)}. \tag{2}$$

Here, g_η is the couling constant of the ηNN^* vertex and determined to be $g_\eta \simeq 2.0$ to reproduce the partial width $\Gamma_{N^* \to \eta N} \simeq 75$ MeV at tree level. $m_N^*(\rho)$ and $m_{N^*}^*(\rho)$ are effective masses of N and N^* in the nuclear medium, respectively.

The η propagator (1) has two poles corresponding to the η meson and N^*-*hole* modes in nuclear medium [4–6]. This means that the η spectral density S_η given by

$$S_\eta(\omega, \rho) = -\frac{1}{\pi} Im(D_\eta(\omega, k = 0; \rho)) \tag{3}$$

has two peaks as a function of energy at a certain density. In Fig. 1(a), we show the contour maps of the η spectral density as functions of baryon density and η energy in the case that the effective masses of N^* and N do not change in-medium. We can see the behaviors of two branches corresponding to two modes indicated by dotted lines in Fig. 1(a) and their strength also. In this case, two branches slightly come away from each other for higher ρ as a result of the level repulsion, and the strength of the lower mode is always larger than the upper mode as shown in Fig. 2. The similar behavior of the spectral function based on the chiral unitary approach were also reported by Waas, Weise [4] and Inoue, Oset [5] where the N^* mass shift is very small.

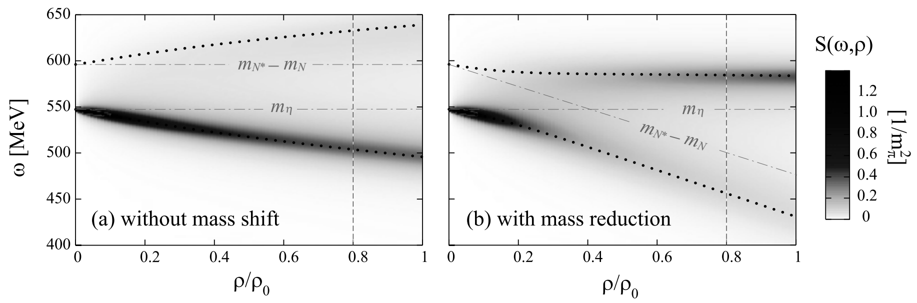

Figure 1: Contour maps of the η meson spectral densities in nuclear matter as functions of the baryon density and η energy (a) without the mass shift of N^* and N and (b) with the 20% mass reduction of $m_{N^*} - m_N$ at the normal nuclear density ρ_0. The spectral functions at $\rho/\rho_0 = 0.8$ (dashed lines) are shown in Fig. 2.

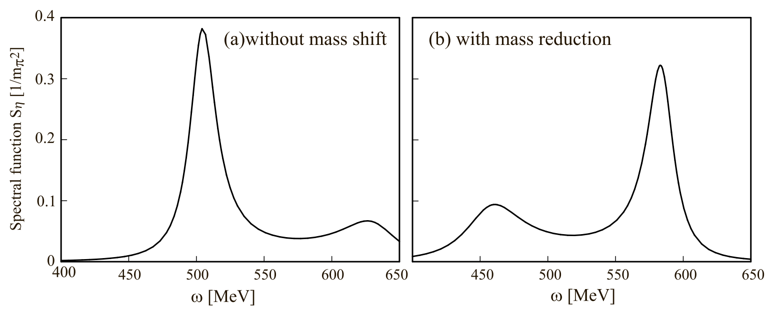

Figure 2: Spectral functions of the η meson as functions of the η energy at $\rho/\rho_0 = 0.8$ (indicated by dashed lines in Fig. 1) (a) without mass shift and (b) with 20% mass gap reduction of N^* and N.

However, if the mass gap becomes small in medium for some reason, the properties of the η spectral density changes significantly. Since the mass gap $m_{N^*} - m_N$ lies only fifty MeV above the η meson mass, if the mass gap becomes small in medium for some reason, two levels of N^*-*hole* and η modes are easy to cross each other even at a low density as shown in Fig. 1(b). As a consequence, the strength of the upper mode becomes stronger (see Fig. 2(b)) as a result of the stronger level mixing due to the level crossing, and the lower mode shifts downwards considerably as the density increases (see Fig. 1(b)). The detailed discussions are given in Ref. [6].

Indeed, the possibility of the mass gap reduction like this has been pointed out based on the chiral doublet model [11] as a result of the partial restoration of the chiral symmetry as,

$$m_{N^*}^*(\rho) - m_N^*(\rho) = \left(1 - C\frac{\rho}{\rho_0}\right)(m_{N^*} - m_N), \tag{4}$$

where m_N and m_{N^*} are the N and N^* masses in free space, respectively. Here the parameter C represents the strength of the chiral restoration at the normal nucleon saturation density ρ_0, and its empirical value lies from 0.1 to 0.3 [12]. Figures 1(b) and 2(b) correspond to the case with $C = 0.2$ in the chiral doublet model.

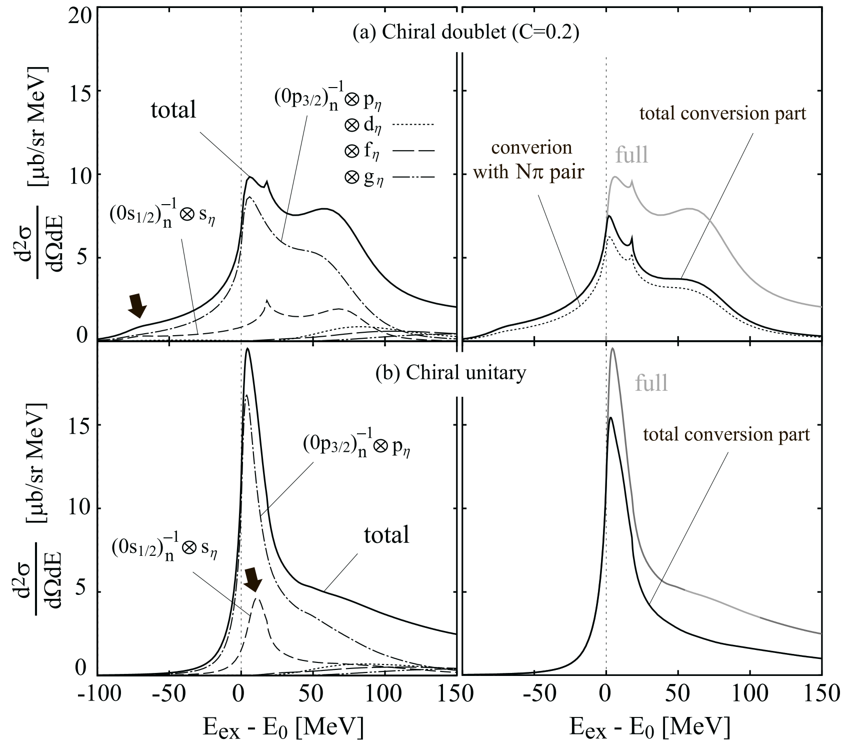

Figure 3: Calculated spectra of ^{12}C(π^+,p)^{11}C$\otimes\eta$ reaction at $T_\pi = 820$ MeV as functions of the excited energy $E_{\rm ex}$. E_0 is the η production threshold. The η-nucleus interaction is calculated by (a) the chiral doublet model with $C = 0.2$ and (b) the chiral unitary model. The neutron-hole states are indicated as $(n\ell_j)_n^{-1}$ and the η states as ℓ_η. Solid arrow indicates the peak corresponding to the bound state in each model. The left figures show the decomposition to the subcomponents and the right figures show the contributions coming from the conversion parts.

Thus, this characteristic phenomena caused by the level crossing could be the signal of the chiral symmetry restoration in medium, and we expect that they can be observed in the experimental spectrum as discussed in following section.

3 Formation spectra of η mesic nuclei

3.1 missing mass spectra by (π^+, p) reaction

In Fig.3, we show the ^{12}C(π^+,p)^{11}C$\otimes\eta$ cross sections for the formation of the η-^{11}C system in the chiral doublet model with $C = 0.2$ (Fig. 3(a)) and the chiral unitary model (Fig. 3(b)). The incident pion kinetic energy T_π is 820 MeV corresponding to the recoilless at the η threshold, and this energy can be reached at J-PARC project. The theoretical framework used in this paper is same as Ref. [3]. The detailed discussions will be reported in Ref. [7]. In this report, we would like to note the following two points:

Bound State Signatures For the case with the doublet model, we find the deep η bound state at (B.E., Γ)=(91.3, 26.3) MeV as $0s$ bound state and (75.1, 33.0) MeV as $1s$ state. The $0s$ bound state appears in the spectrum as a bump around $E_{\rm ex} - E_0 \sim -70 - -80$ MeV (indicated by solid arrow in Fig. 3(a)). This deep bound state can be considered as the deep lower mode shown in Figs. 1(b) and 2(b) and thus can be an evidence of the partial restoration of the chiral symmetry. Unfortunately, however, this bump is too small to be observed in experiments because the strength of the lower mode becomes small due to the level crossing as shown in Fig. 1(b).

Bump Structure at Quasi-Free Region In quasi-free region $E_{\rm ex} - E_0 > 0$ we find interesting feature in the spectrum with the doublet model. We see considerably large bump structure around $E_{\rm ex} - E_0 \sim 60$ MeV as shown in Fig. 3(a). This peak comes from the N^*-*hole* mode coupled to the η meson in the medium, namely the upper mode shown in Fig. 1(b). As discussed in Sec. 2, the upper mode in the chiral doublet model is enhanced as a consequence of the level crossing and of the partial restoration of the chiral symmetry in medium for $C = 0.2$ case. We can expect to observe this enhancement in the formation spectra.

3.2 Coincident observation

In order to discuss the experimental feasibilities, it is important to discuss expected backgrounds. In the references of the past (π^+,p) experiment [10] and its theoretical predictions [8], they considered that the background came from quasi-free knockout, multiple pion and proton scattering, and pion absorption, and estimated the S/N ratio $\sim 1/10$. In the present case with the forward nucleon emission, we also have to expect almost same amount of the background as in Ref. [10] if we observe the only emitted nucleon. Therefore, in order to avoid too large background, we can consider to take some coincidence accompanying the η meson production in a nucleus, for example simultaneous observation of $N\pi$ pair coming from N^* decay in a nucleus [13].

In Fig. 3(a)(right), we show the contributions associated with $N^* \to N\pi$ and $N^*N \to NN\pi$ processes. The expected spectra with the coincidence of the $N\pi$ pair from N^* is indicated by the dotted line in the figure. The black solid line in Fig.3(a)(right) includes both of the one-body and two-body absorption of N^* with the doublet model in this study. We find that, in the doublet model case, the strength of the peak structure in the quasi-free region corresponding to the N^*-*hole* mode is reduced to be about half by taking the coincidence of $N\pi$ pair from N^*. In Fig. 3(b)(right), we plot the same figure as Fig. 3(a)(right) but in the chiral unitary approach case. Since we don't have any information on the details of η absorption processes described in the chiral unitary approach, we plot only the total conversion part of the spectrum. We expect that the difference between two approaches with and without the N^* mass reduction is still large even we take the coincidence of the N^* decay. The estimation of the background reduction by this method, however, still remains as a future work, which needs a completely different formalism to calculate.

4 Conclusion

We discussed the level crossing phenomena of N^*-*hole* and η modes in the η-mesic nuclei and showed the formation spectra in order to investigate the in-medium properties of the $N^*(1535)$ resonance. Especially, the N^* mass shift in the nuclear medium has been discussed by several chiral models. In the chiral doublet model, $N^*(1535)$ is regarded as a chiral partner of nucleon and its mass is expected to be reduced in the nuclear medium associated with the partial restoration of the chiral symmetry in medium. On the other hand, in the chiral unitary approach, $N^*(1535)$ is introduced as a resonance dynamically generated and described as a quasi-bound state of the Kaon and Hyperon, and its mass shift is predicted to be small in finite density. We conclude that we can get new information on the in-medium N^* properties through this kind of experiments. We also discussed expected background and its reduction by the simultaneous observation of $N\pi$ pair from the N^* decay in medium. We found that the difference between two treatments of in-medium N^* with and without its mass shift are not largely affected by the coincidence observation.

We believe that the present theoretical results are important to stimulate both theoretical and, especially, experimental activities to study the hadron properties in-medium and to obtain new information on the partial restoration of the chiral symmetry in finite density.

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