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Level Crossing of N* (1535)-hole and η Modes and Partial Restoration of Chiral Symmetry in η-mesic Nuclei*

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Abstract: We investigate the properties of the η-nucleus interaction by postulating the N* (1535) dominance for ηN system. Since the mass gap of N* and N is very close to the η meson mass, there is the possibility of the level crossing between the N*-h and η modes in finite density. We postulate the N* (1535) resonance for the ηN system and consider quite distinct N* properties in finite density which are predicted by two independent chiral models. We find that we can obtain clearer information on the in-medium N* properties and also on the η-nucleus interaction through the formation of the η-mesic nuclei by (π, N) reactions under the appropriate experimental conditions, which can be performed at existing and/or forthcoming facilities like J-PARC.

Key words: A eta-mesic nuclei; N* (1535) in medium; partial restoration of chiral symmetry
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1 Introduction

The study of the meson-nucleus bound systems has been considered to be an important subject in nuclear physics since the detailed investigations of them provide us quantitative information on 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 Ref. [6], we had 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 concluded that we could 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 in-

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teresting and will be an evidence of the level crossing and also of the partial restoration of chiral symmetry if they are really observed.

In this report, we 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 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 Meson

In-medium η propagator is given by

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

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. Considering the strong coupling of the ηN system to the N^*(1535) resonance, we assume the N^* dominance throughout this report and evaluate the η self-energy Π_η as

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

Here, g_η is the coupling 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

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

has two peaks as a function of energy at a certain density. In Fig. 1, we show the contour maps of the η spectral density as functions of baryon density and η energy. Fig. 1(a) shows the behaviors of two branches corresponding to two modes indicated by dotted lines and also their strengths in the case that the effective masses of N^* and N do not change in medium.

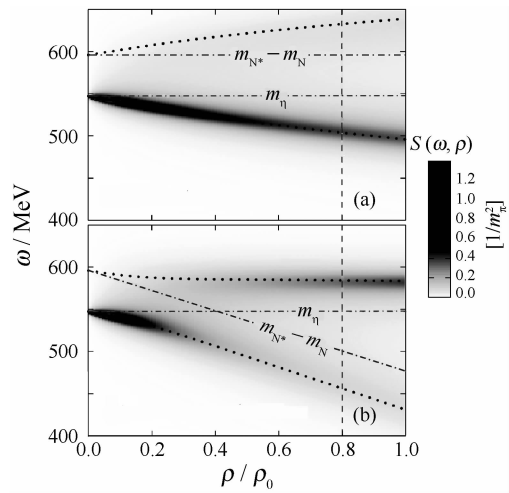

Fig. 1 Contour maps of the η meson spectral densities in nuclear matter as functions of the baryon density and η energy. (a) without the mass shift of N^* and N and (b) with the 20% mass reduction of $m_{N^*}-m_N$ at the normal nuclear density ρ_0. ⋯ indicate the real parts of the poles of the η propagator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

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 that of the upper mode as shown in Fig. 2(a) where the spectral function as a function of the η energy at $\rho=0.8\rho_0$ is shown. 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.

However, if the mass gap becomes smaller in medium for some reason, the properties of the η

spectral density changes significantly. Suppose that the N^* and N mass gap reduces by 20% at ρ_0, the level crossing takes place around $\rho \approx 0.4\rho_0$ 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].

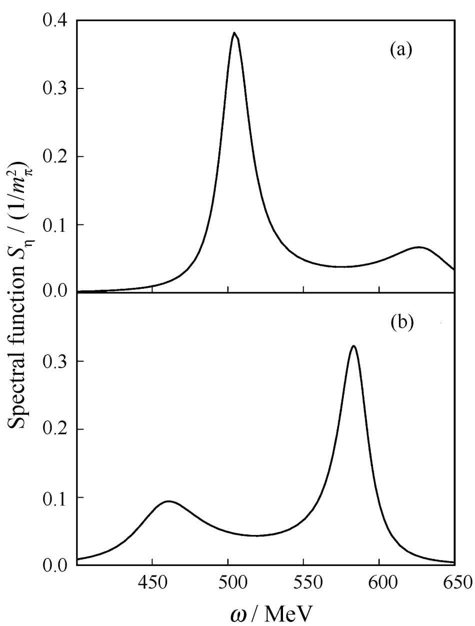

Fig. 2 Spectral functions of the η meson as functions of the η energy at $\rho/\rho_0 = 0.8$ (indicated by --- in Fig. 1. (a) without mass shift and (b) with 20% mass gap reduction of N^* and N.

The possibility of the mass gap reduction 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 density ρ_0, and its empirical value lies from 0.1 to 0.3[12]. Figs. 1(b) and 2(b) correspond to the case with $C=0.2$ in the chiral doublet model.

These characteristic phenomena caused by the level crossing could be the signal of the chiral symmetry restoration in medium, and they can be expected to 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 $^{12}C(^+, p)^{11}C\otimes\eta$ cross sections for the formation of the $\eta-^{11}C$ 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, corres-

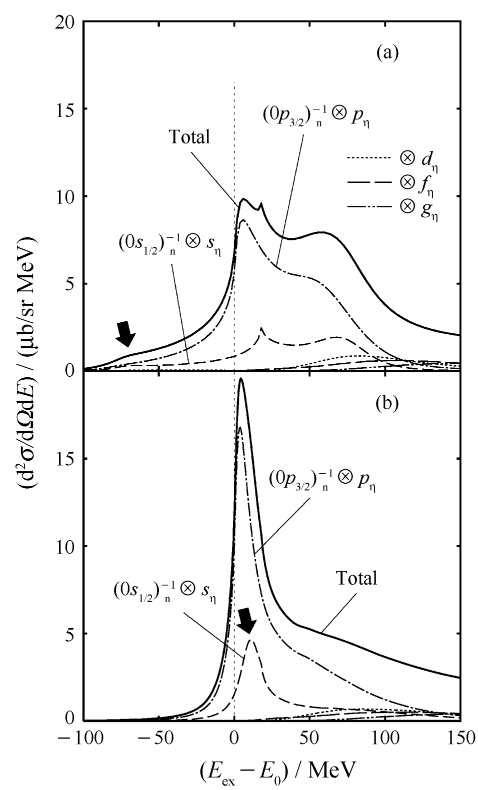

Fig. 3 Calculated spectra of $^{12}C(\pi^+, p)^{11}C\otimes\eta$ reaction at T_π =820 MeV as functions of the excited energy E_{ex}. E_0 is the η production threshold. The η-nucleus interaction is calculated by (a) the chiral doublet model with $C=0.2$ and (b) the chiral unitary model. The neutron-hole states are indicated as $(nl_j)_n^{-1}$ and the η states as l_η. Solid arrow indicates the peak corresponding to the bound state in each model.

ponding to the recoilless at the η threshold, and can be reached at J-PARC project. The theoretical framework used in this paper is the same as Ref. [3]. The detailed discussions will be reported in Ref. [7].

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 and they appear in the spectrum as a bump around $E_{ex}-E_0\approx-70$—-80 MeV (indicated by solid arrow in Fig. 3(a)). This deep bound state corresponds to 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, if they are observed. 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).

In Fig. 3(a), we see large bump structure around $E_{ex}-E_0\approx 60$ MeV, which comes from the N*-hole mode, namely the upper mode shown in Fig. 1(b). As discussed in previous section, the upper mode in the doublet model is enhanced as a consequence of the level crossing caused by the partial restoration of chiral symmetry in medium for $C=0.2$ case, therefore this enhancement also could be an evidence of the partial restoration of the chiral symmetry.

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 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 the η-mesic nuclei formations.

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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