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Formation of $\eta'(958)$ mesic nuclei

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Abstract. In this report, we show the theoretical results of the formation spectra of the η'-nucleus systems in the (p,d) reactions based on the latest theoretical considerations of the η' properties in nucleus. The results shown here are important to give predictions and supports to the future experiment, and to make clear relations between the η' mesic nucleus formation spectra and the modifications of the η' properties at finite density, which will give us new information on the η' mass generation mechanism.

1 Introduction

The $\eta'(958)$ meson is an interesting and important particle because of its exceptionally large mass and connection to the $U_A(1)$ problem, where the gluon dynamics is believed to play an important role to give a peculiarly larger mass to the η' meson than those of the other pseudoscalar mesons, π, K, and η. However, we have not yet understood the η' mass generation mechanism quantitatively.

Recently, two important developments have been reported in theoretical [1] and experimental [2] point of view for the study of the η' mass in nuclei. Theoretically, it has been pointed out [1,3] that the anomaly effect can contribute to the η' mass only with the presence of the chiral symmetry breaking. This naturally leads to a conclusion of a relatively large mass reduction ($\sim$ 100 MeV) of the η' mass at normal nuclear density due to the partial restoration of chiral symmetry. The mass reduction at finite density is considered to be equivalent to the attractive meeson-nucleus interaction in the equation of motion, which can support the existence of the bound states, η' mesic nuclei. Actually, the recent study based on the theoretical optical potential has also concluded the possible existence of the bound states [4] assuming the sign of the real part of the $\eta' N$ scattering length which is not known. Thus, the study of the η' properties at finite density by observing the η' mesic nuclei is extremely interesting for the studies of the η' mass generation mechanism and the $U_A(1)$ problem. The formation reaction of the η' mesic nuclei was first considered in [5] and has been found to be possible in the actual experiments of the (p,d) reaction at GSI [2] recently.

2 Formulation

To evaluate the formation cross section of the $\eta'(958)$-nucleus systems in the (p,d) reaction, we use the Green's function method [6,7]. In this method, the reaction cross section is assumed to be separated into the nuclear response function $R(E)$ and the elementary cross section of the $pn \to d\eta'$ process with the impulse approximation:

$$\left(\frac{d^2\sigma}{d\Omega dE}\right)_{A(p,d)(A-1)\otimes\eta'} = \left(\frac{d\sigma}{d\Omega}\right)^{lab}_{n(p,d)\eta'} \times R(E), \qquad (1)$$

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where the nuclear response function $R(E)$ is given in terms of the in-medium Green's function $G(E)$ as

$$R(E) = -\frac{1}{\pi}\mathrm{Im}\sum_f \int d\mathbf{r}d\mathbf{r}'\mathcal{T}_f^\dagger(\mathbf{r})G(E;\mathbf{r},\mathbf{r}')\mathcal{T}_f(\mathbf{r}') \ . \tag{2}$$

Here, the summation is inclusively taken over all possible final states. The amplitude $\mathcal{T}_f$ describes the transition of the incident proton to a neutron hole and the outgoing deuteron:

$$\mathcal{T}_f(\mathbf{r}) = \chi_d^*(\mathbf{r})\left[Y_{l_{\eta'}}^*(\hat{r})\otimes\psi_{j_n}(\mathbf{r})\right]_{JM}\chi_p(\mathbf{r}) \tag{3}$$

with the neutron hole wavefunction ψ_{j_n}, the distorted waves of proton and the ejected deuteron χ_p and χ_d, and the η' angular wavefunction $Y_{l_{\eta'}}(\hat{r})$. For the neutron hole, we use the harmonic oscillator wavefunction for simplicity. The Green's function $G(E)$ contains the η'-nucleus optical potential in the Hamiltonian as

$$G(E;\mathbf{r},\mathbf{r}') = \langle n^{-1}|\phi_{\eta'}(\mathbf{r})\frac{1}{E - H_{\eta'} + i\epsilon}\phi_{\eta'}^\dagger(\mathbf{r}')|n^{-1}\rangle \tag{4}$$

where $\phi_{\eta'}^\dagger$ is the η' creation operator and $|n^{-1}\rangle$ is the neutron hole state. The elementary cross section in the laboratory frame in Eq. (1) was evaluated to be 30 μb/sr at the proton kinetic energy $T_p = 2.5$ GeV in Ref. [2].

For the η'-nucleus optical potential, we simply assume an empirical form as,

$$V_{\eta'} = (V_0 + iW_0)\frac{\rho(r)}{\rho_0}, \tag{5}$$

with the nuclear density distribution $\rho(r)$ and the normal saturation density $\rho_0 = 0.17$ fm^{-3}. The mass term in the Klein-Gordon equation for the η' meson at finite density can be written as

$$\begin{aligned} m_{\eta'}^2 \to m_{\eta'}^2(\rho) &= (m_{\eta'} + \Delta m(\rho))^2 \\ &\sim m_{\eta'}^2 + 2m_{\eta'}\Delta m_{\eta'}(\rho), \end{aligned} \tag{6}$$

where $m_{\eta'}$ is the mass of the η' meson in vacuum and $m_{\eta'}(\rho)$ the mass at finite density ρ. The mass shift $\Delta m_{\eta'}(\rho)$ is defined as $\Delta m_{\eta'}(\rho) = m_{\eta'}(\rho) - m_{\eta'}$. Thus, we can interpret the mass shift $\Delta m_{\eta'}(\rho)$ as the strength of the real part of the optical potential in the Klein-Gordon equation

$$V_0 = \Delta m_{\eta'}(\rho_0)\ , \tag{7}$$

using the mass shift at normal saturation density ρ_0.

The theoretical optical potentials obtained in Ref. [4], which are obtained by a theoretical $\eta' N$ scattering length [8] using the standard many body theory, are also considered in Ref. [9] to calculate the η'-nucleus states and the formation cross sections.

Here we assume the nuclear density distribution $\rho(r)$ to be of an empirical Woods-Saxon form as

$$\rho(r) = \frac{\rho_N}{1 + \exp(\frac{r-R}{a})}, \tag{8}$$

where $R = 1.18A^{\frac{1}{3}} - 0.48$ fm, $a = 0.5$ fm with the nuclear mass number A, and ρ_N a normalization factor such that $\int d^3r\rho(r) = A$. We obtain the in-medium Green's function in Eq. (4) by solving the Klein-Gordon equation with the optical potential $V_{\eta'}$ in Eq. (5) with the appropriate boundary condition and use it to evaluate the nuclear response function $R(E)$ in Eqs. (1) and (2).

3 Numerical Results

We show the calculated results for the potential strength $(V_0, W_0) = -(0, 10)$ and $-(100, 10)$ MeV cases in Fig. 1. As we can see from the figure, the existence of the attractive interaction and bound

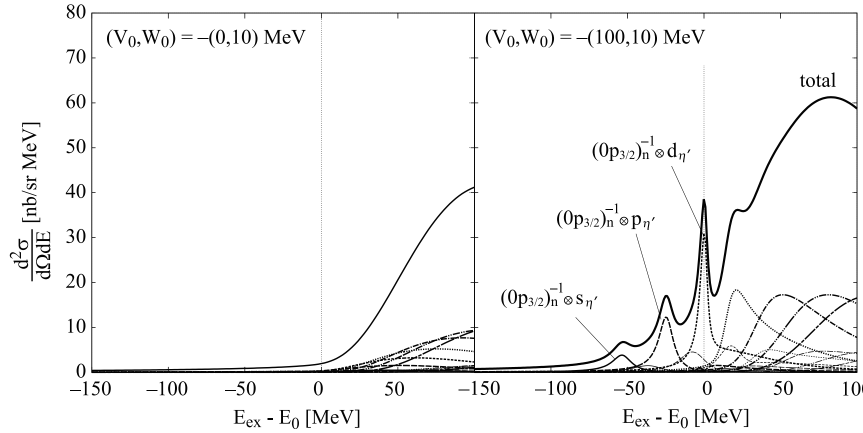

Fig. 1. Calculated spectrum of $^{12}C(p, d)^{11}C\otimes\eta'$ reaction for the formation of the η'-nucleus systems with the proton kinetic energy $T_p = 2.5$ GeV and the deuteron angle $\theta_d = 0°$ as a function of the excited energy E_{ex} [9]. E_0 is the η' production threshold. The depth of the η'-nucleus optical potential is (a) $(V_0, W_0) = -(0, 10)$ MeV, and (b) $(V_0, W_0) = -(100, 10)$ MeV. The thick solid line shows the total spectrum and dashed lines indicate subcomponents. The neutron-hole states are indicated as $(n\ell_j)_n^{-1}$ and the η' states as $\ell_{\eta'}$.

states can be seen as the peak structures in the (p, d) spectrum. We find that there is a clear difference between the cases with attractive and non-attractive potentials.

In Fig. 2, we show the effects of the absorption interaction by varying the strength of the imaginary part W_0 of the optical potential. We can see the clear peaks corresponding to bound states in the s, p and d states, although the width of each peak becomes wider as W_0 is increased. We also find that there are peak structures in the $f_{\eta'}$-wave component just above the threshold ($E_{ex} - E_0 = 0$) owing to the so-called threshold enhancement. While there are no bound states in the $f_{\eta'}$ state of η', the attractive η'-nucleus interaction pulls this low energy scattering wave of η' closer to the daughter nucleus. This enhances the overlap of the η' and nucleon wavefunctions, and consequently produces a larger cross section. Therefore, we can consider this enhancement as an indication of the attractive η'-nucleus interaction if observed. We find that, even in the large imaginary case of $-(150, 20)$ MeV, we can see a clear peak corresponding to this threshold enhancement indicating the attractive nature of the η'-nucleus optical potential. (We should recall that the strength of the absorptive potential is indicated as $|W_0| \lesssim 12.5$ MeV in Ref. [10].) In ref. [9], the spectra for various cases of the strength of the real optical potentials are shown to see the experimental feasibility systematically. We find that, in the weak attraction $V_0 = -50$ MeV case, we cannot see peak structures with larger absorption $|W_0| \gtrsim 15$ MeV, while in the strong attraction $|V_0| \gtrsim 100$ MeV case we can see clear peaks even in the large absorption $W_0 = -20$ MeV, which corresponds to the absorption width $\Gamma = 40$ MeV [9] .

4 Summary

We have calculated the formation spectra of the $\eta'(958)$-nucleus systems by the (p, d) reaction. The kinetic energy of the incident proton beam is set to be $T_p = 2.5$ GeV that could be reached at existing facilities like GSI [2]. We have shown the numerical results for various strengths of the η'-nucleus optical potentials including no attraction case as $(V_0, W_0) = -(0, 10)$ MeV. We find that, in the strong attraction case $|V_0| \gtrsim 100$ MeV, that is the expected strength of the attraction by the NJL calculation, we can see clear peaks around the η' production threshold even with the large absorption case as $W_0 = -20$ MeV. In some cases, the peaks around the threshold do not indicate the existence of the bound states but the so-called threshold enhancements which are also consequences of the attractive nature of the η'-nucleus interaction. The robustness of the appearance of the peak structure around the threshold for an attractive interaction, which is independent on the detail of the theory, is an interesting and important finding of this study. We conclude that we can see clear signal of the possible attractive

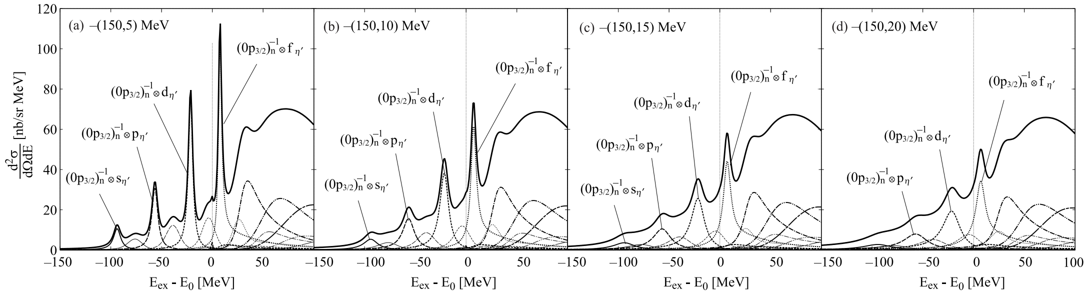

Fig. 2. Calculated spectra of $^{12}C(p,d)^{11}C\otimes\eta'$ reaction for the formation of the η'-nucleus systems with the proton kinetic energy $T_p = 2.5$ GeV and the deuteron angle $\theta_d = 0°$ as functions of the excited energy E_{ex} [9]. E_0 is the η' production threshold. The η'-nucleus optical potential are (a) $(V_0, W_0) = -(150, 5)$ MeV, (b) $-(150, 10)$ MeV, (c) $-(150, 15)$ MeV, and (d) $-(150, 20)$ MeV. The thick solid lines show the total spectra and dashed lines indicate subcomponents. The neutron-hole states are indicated as $(n\ell_j)_n^{-1}$ and the η' states as $\ell_{\eta'}$.

potential of the η'-nucleus system by the (p,d) reaction with ^{12}C targets. The conversion spectra accompanied by different absorption processes of η' in nucleus are also discussed in Ref. [9], which give useful information to the coincident measurements of the decay particles from the η' bound states.

In any case, an experimental search for a bound η' in nuclei would provide an important information on the properties of η'. We believe that the present theoretical results are much important for such experimental activities to obtain the deeper insight of the meson mass spectrum.

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