Medium effects to the $N(1535)$ resonance and $\eta$ mesic nuclei
D. Jido$^a$, H. Nagahiro$^b$ and S. Hirenzaki$^b$

$^a$Research Center for Nuclear Physics, Osaka University, Ibaraki, Osaka 567-0047, Japan
$^b$Department of Physics, Nara Women’s University, Nara 630-8506, Japan

The structure of $\eta$-nucleus bound systems ($\eta$ mesic nuclei) is investigated as one of the tools to study in-medium properties of the $N(1535)$ ($N^*$) resonance. We show that, as a general consequence, the $\eta$-nucleus potential has a repulsive core at the nuclear center with an attractive part at the nuclear surface, if sufficient reduction of the mass difference of $N$ and $N^*$ stems from the in-medium effects to $N^*$. The $(d,^3\text{He})$ spectra are evaluated for the formation of these bound states to investigate the experimental feasibility.

1. Introduction

The study of the in-medium properties of hadrons has attracted continuous attention and is one of the most interesting topics of nuclear physics. In the contemporary point of view, in-medium properties of hadron are believed to be related to partial restoration of chiral symmetry, in which a reduction of the order parameter of the chiral phase transition in hot and/or dense matter takes place and causes modifications of the hadron properties.

In this paper we consider the $\eta$ mesic nucleus as one of the doorways to investigate the in-medium properties of the $N(1535)$ ($N^*$). The special features of the $\eta$ mesic nucleus are the following; (1) the $\eta$-$N$ system dominantly couples to the $N^*$ at the threshold region. (2) The isoscalar particle $\eta$ filters out contaminations of the isospin $3/2$ excitations in the nuclear medium. (3) Due to the $s$-wave nature of the $\eta NN^*$ coupling there is no threshold suppression like the $p$-wave coupling. The strong coupling of the $N^*$ to $\eta N$ makes the use of this channel particularly suited to investigate this resonance in a cleaner way than the use of $\pi N$ for the study of other resonances like the $N(1440)$ and $N(1520)$.

The $N(1535)$, which is the lowest lying parity partner of the nucleon, has been investigated from the point of view of chiral symmetry [1]. Considering the fact that the $N^*$ mass in free space lies only 50 MeV above the $\eta N$ threshold, the medium modification of the $N^*$ mass will strongly affect the in-medium potential of the $\eta$ meson through the strong $\eta NN^*$ coupling mentioned above.

2. Optical potential of $\eta$ with $N^*$ dominance

The $\eta$-mesic nuclei were studied by Haider and Liu [2] and by Chiang, Oset and Liu [3] systematically. There, the $\eta$-nucleus optical potential was expected to be attractive from the data of the $\eta$-nucleon scattering length and the existence of the bound states was predicted theoretically.
First of all, we show, as a general consequence, the possibility to have a repulsive $\eta$ optical potential in the nucleus due to a significant reduction of the mass difference of $N$ and $N^*$. Considering the self-energy of the $\eta$ meson at rest in nuclear matter in the $N^*$ dominance model, in analogy with the $\Delta$-hole model for the $\pi$-nucleus system, we obtain the $\eta$ optical potential in the nuclear medium in the heavy baryon limit [3] as:

$$V_\eta(r;\omega) = \frac{g_\eta^2}{2\mu \omega + m_N^*(\rho) - m_N^*(\rho) + i\Gamma_N^*(s;\rho)/2},$$

where $\omega$ denotes the $\eta$ energy, and $\mu$ is the reduced mass of the $\eta$ and the nucleus. The nucleon density distribution $\rho(r)$ is assumed to be a Fermi distribution in the finite nucleus. The “effective mass” of $N$ and $N^*$ in medium are denoted as $m_N^*$ and $m_N^{*\ast}$. The in-medium $N^*$ width $\Gamma_N^*$ includes the many-body decay channels. The $\eta NN^*$ vertex is taken as the isoscalar and scalar coupling with $g_\eta \simeq 2$.

Let us suppose no medium modifications for the masses of $N$ and $N^*$. This is nothing but the $T\rho$ approximation. In the case of small binding energy for the $\eta$, i.e. $\omega \simeq m_\eta$, we obtain an attractive potential independent of density because of $\omega + m_N - m_{N^*} < 0$. In this case, the shape of this potential is essentially the same as the Woods-Saxon type potential for a finite nucleus. On the other hand, if a sufficient reduction of the mass difference of $N$ and $N^*$ stems from the medium effects, there exists a critical density $\rho_c$ where $\omega + m_N^* - m_{N^*} = 0$, and then at densities above $\rho_c$ the $\eta$ optical potential turns to be repulsive. If $\rho_c$ is lower than the nuclear saturation density $\rho_0$, the optical potential for the $\eta$ is attractive around the surface of the nucleus and repulsive in the interior.

To make the argument more quantitative, we estimate the in-medium $N$ and $N^*$ masses and the $N^*$ width in the chiral doublet model [4], which is an extension of the $SU(2)$ linear sigma model for the nucleon incorporating the $N^*$ in a chiral symmetric way. The chiral doublet model represents the mass difference of $N$ and $N^*$ as a linear function of the chiral condensate, and gives the density dependence of the mass difference of $N$ and $N^*$ in the mean-field approximation [4] as

$$m_N^*(\rho) - m_N^{*\ast}(\rho) = (1 - C\rho/\rho_0)(m_N - m_{N^*}),$$

where we take a linear parameterization of the in-medium chiral condensate, $\langle \sigma \rangle = (1 - C\rho/\rho_0)\langle \sigma \rangle_0$, with $C=0.1$-0.3 [4]. The $C$ parameter represents the strength of the chiral restoration at the nuclear saturation density $\rho_0$.

The medium effects on the decay width of $N^*$ are taken into account by considering the Pauli blocking effect on the decaying nucleon, by changing the $N$ and $N^*$ masses and the $\pi NN^*$ coupling in medium according to the chiral doublet model, and also by considering the many-body decays of $N^*$, such as $N^*N \to NN$ and $N^*N \to \pi NN$.

In the present calculation, the chiral doublet model with the mirror assignment is used. The detail of this work is discussed in ref.[6].

### 3. Numerical Results

In Fig[1], we show the $\eta$-nucleus potential for the $^{132}$Xe case, as an example. In other nuclei, the potential shape is essentially same as the plotted one, but the radius of the repulsive core depends on the mass number $A$. As can be seen in Fig[1] for the $C \neq 0$
Figure 1. The \( \eta \)-nucleus optical potential for \(^{132}\text{Xe}\) system as a function of the radius coordinate \( r \). The left (a) and right (b) panels show the real and imaginary parts, respectively, for \( C = 0.0 \) (solid line), 0.1 (dashed line) and 0.2 (dotted line) with setting \( \omega = m_\eta \). The dot-dashed line indicates the potential strength for \( C = 0.1 \) with \( \omega = m_\eta - 50 \) [MeV].

In Fig. 1, we show the result with \( C = 0.0 \), which corresponds to the spectrum with the \( T \rho \) approximation in the optical potential. The results with the medium corrections are shown in Fig. 1(b) for the \( C = 0.2 \) case, where the \( \eta \) optical potential has the repulsive core in the center of nucleus. In Fig. 1(c) is shown the spectrum with the optical potential obtained in the chiral unitary model \([8]\), where \( N^* \) is dynamically generated in the meson-baryon scatterings. It is seen in Fig. 1(b) that, as a result of the repulsive nature of the \( \eta \) potential, the whole spectrum spreads out to the higher energy region. The difference of
these spectra is expected to be observed in the high resolution experiment.

4. Summary

We investigate the consequences of the medium effects to $N(1535)$ ($N^*$) through the $\eta$-mesic nuclei. We find that sufficient reduction of the in-medium mass difference makes the $\eta$ optical potential repulsive at certain densities, while in the low density approximation the optical potential is estimated to be attractive. This leads us the possibility of a new type of potential of the $\eta$ in nucleus that is attractive at the surface and has a repulsive core at the center of the nucleus. Unfortunately it is hard to form $\eta$ bound states in nucleus with the expected strength of the chiral restoration in nucleus ($C \sim 0.2$), due to the repulsive nature of the potential inside the nucleus and its large imaginary potential. We also evaluate the spectra of the recoilless $^{12}\text{C}(d,^3\text{He})$ reaction using optical potentials for different models. The shapes of these spectra are apparently different and the repulsive nature in the $C = 0.2$ case is seen. We believe that the present results are very important to investigate the chiral nature of $N$ and $N^*$ through $\eta$ bound states.

REFERENCES

1. C. DeTar and T. Kunihiro, Phys. Rev. D 39 (1989) 2805; D. Jido, M. Oka and A. Hosaka, Prog. Theor. Phys. 106 (2001) 873; D. Jido, Y. Nemoto, M. Oka and A. Hosaka, Nucl. Phys. A 671 (2000) 471.
2. Q. Haider and L. C. Liu, Phys. Lett. B 172 (1986) 257; L. C. Liu and Q. Haider, Phys. Rev. C 34 (1986) 1845.
3. H. C. Chiang, E. Oset and L. C. Liu, Phys. Rev. C 44 (1991) 738.
4. H. C. Kim, D. Jido and M. Oka, Nucl. Phys. A 640 (1998) 77.
5. T. Hatsuda, T. Kunihiro and H. Shimizu, Phys. Rev. Lett. 82 (1999) 2840; D. Jido, T. Hatsuda and T. Kunihiro, Phys. Rev. D 63 (2001) 011901
6. D. Jido, H. Nagahiro and S. Hirenzaki, Phys. Rev. C 66 (2002) 045202
7. R. S. Hayano, S. Hirenzaki and A. Gillitzer, Eur. Phys. J. A 6 (1999) 99.
8. T. Inoue and E. Oset, Nucl. Phys. A 710 (2002) 354