Introduction

Formation of eta-mesic nuclei
  » Optical Potential ~ N* dominance model ~
  » Chiral Doublet model
  » Chiral Unitary model

Numerical Results of (d,He) & (γ,p) reactions
  » 12C target
  » 40Ca target
  » 4He target [(d,He)]
  » 11Be target [(d,He)]

Summary
Introduction

Interests of meson bound systems

›› important information on in-medium hadron physics and symmetries of QCD

our works

›› $\eta$-mesic nuclei ... $N^*(1535)$ in medium $[(d,^{3}He), (\gamma,p)]$
  - D.Jido, H.N., S.Hirenzaki, PRC66(02)045202
  - H.N., D.Jido, S.Hirenzaki, PRC68(03)035205

›› $\eta'$-mesic nuclei ... $U_{A}(1)$ anomaly in medium $[(\gamma,p)]$

›› $\sigma$-mesic nuclei ... $m_{\sigma} \sim 2m_{\pi}$ enhancement? $[(d,t), (d,^{3}He), (\gamma,p)]$
  - H.Hirenzaki, H.N., T.Hatsuda, T.Kunihiro, NPA710(02)131

›› $\Theta^{+}$ in medium ... $S=+1$ hypernuclei $[(K^{+},\pi^{+})]$
Introduction: $\eta$-Nucleus system

works for eta-mesic nuclei

$\left(\pi^+, p\right)$

- Liu, Haider, PRC34(1986)1845
- Chiang, Oset, and Liu, PRC44(1988)738
- Chrrien et al., PRL60(1988)2595

$\left(d, ^3\text{He}\right)$

- Exp. at GSI (2005?) (Yamazaki, Hayano group)

properties of eta meson

**eta meson**

\[ m_\eta = 547.3 \text{ [MeV]} \]

\[ I = 0, \quad J^P = 0^- \]

\[ \Gamma = 1.18 \text{ [keV]} \quad (2\gamma, \ 3\pi^0, \ \pi^+\pi^-\pi^0, \cdots) \]

**eta-N system**

- Strong Coupling to N*(1535), $J^P = \frac{1^-}{2}$

\[ \Gamma_{\pi N} \sim \Gamma_{\eta N} \sim 75 \text{[MeV]} \]

**eta-N system**

$\eta NN^*$ system

- No $I = \frac{3}{2}$ baryon contamination
- Large coupling constant
- No suppression at threshold

(s-wave coupling)

\[ \mathcal{L}_{\eta NN^*} = g_\eta \bar{N} \eta N^* + h.c. \]
Our Motivation

$\eta$-Nucleus potential is sensitive to the in-medium properties of $N^*$

$\eta$ mesic nuclei as a probe of the in-medium modification of $N^*(1535)$

$N^*(1535)$ in-medium

» Different properties & behaviors of $N^*(1535)$
  described by two kinds of Chiral Models

* Chiral Doublet Model
* Chiral Unitary Model

Formation of the $\eta$ mesic nuclei by $(\gamma, p)$ and $(d, ^3\text{He})$ reactions

Consequences and Observables in $\eta$-nucleus system
\( \eta \)-Nucleus Interaction

~ \( N^* \) dominance model ~

**optical potential**

\[
V_{\text{opt}} = \frac{g_\eta^2}{2\mu} \frac{\rho}{\omega + m_N(\rho) - m_{N^*}(\rho) + i\Gamma^*_N(s;\rho)/2}
\]

**potential nature**

In free space \((V \sim t\rho)\)

\[
\omega + m_N - m_{N^*} < 0 \quad \rightarrow \text{attractive}
\]

\((m_\eta + m_N - m_{N^*} \sim -50\text{MeV})\)

**medium effect**

\[
\omega + m_N(\rho) - m_{N^*}(\rho) > 0 \quad \rightarrow \text{Repulsive}??
\]

\( m_N \& m_{N^*} \text{ change ??} \)

\( g_\eta \sim 2.0 \)

to reproduce the partial width

\( \Gamma_{N^* \rightarrow \eta N} \sim 75 \text{ MeV} \)

at tree level.

**General feature**

\( N \& N^* \) properties in medium evaluated

by two kinds of **Chiral Models**
Chiral models for N and N*

Chiral doublet model

DeTar, Kunihiro, PRD39 (89)2805
Jido, Oka, Hosaka, Nemoto, PTP106(01)873
Jido, Hatsuda, Kunirhiro, NPA671(00)471

Lagrangian

\[ \mathcal{L} = \sum_{j=1,2} \left[ \bar{N}_j i \not{\partial} N_j - g_j \bar{N}_j (\sigma + (-i)^{j-1}i\gamma_5 \vec{\tau} \cdot \vec{\pi}) N_k \right] \]

\[ -m_0 (\bar{N}_1 \gamma_5 N_2 - \bar{N}_2 \gamma_5 N_1) \]

Physical fields

\[ \begin{pmatrix} N \\ N^* \end{pmatrix} = \begin{pmatrix} \cos \theta & \gamma_5 \sin \theta \\ -\gamma_5 \sin \theta & \cos \theta \end{pmatrix} \begin{pmatrix} N_1 \\ N_2 \end{pmatrix} \]

\[ \text{eigenvector under the SU(2) chiral trans.} \]

N* : chiral partner of nucleon

N & N* masses

\[ m_{N,N^*}^* = \frac{1}{2} \left[ \sqrt{(g_1 + g_2)^2 \langle \sigma \rangle^2 + 4m_0^2} + (g_2 - g_1) \langle \sigma \rangle \right] \]

Medium effect

\[ \langle \sigma \rangle = \left( 1 - C \frac{\rho}{\rho_0} \right) \langle \sigma \rangle_0 \]

* C=0.1~0.3 : the strength of the Chiral restoration at the nuclear saturation density \( \rho_0 \)

Mass difference

\[ m_N(\rho) - m_{N^*}(\rho) = (1 - C \frac{\rho}{\rho_0})(m_N - m_{N^*}) \]

* reduction of mass difference

\[ m_0 \sim 270 \text{ MeV} \]

\[ m_N \sim 940 \text{ MeV} \]

\[ m_{N^*} \sim 1535 \text{ MeV} \]

\[ \Gamma_{N^* \rightarrow \pi N} \sim 75 \text{ MeV} \]
Chiral models for N and N*

Chiral unitary model

Kaiser, Siegel, Weise, PLB362(95)23
Waas, Weise, NPA625(97)287
Garcia-Recio, Nieves, Inoue, Oset, PLB550(02)47
Inoue, Oset, NPA710(02) 354

A coupled channel Bethe-Salpeter eq.
\[ \{\pi^-, \pi^0\eta, \eta\eta, K^0\Lambda, K^+\Sigma^-, K^0\Sigma^0, \pi^0\pi^-\eta, \pi^+\pi^-\eta\} \]

\[ \eta \quad \eta \quad = \quad \eta \quad \eta \]

Medium effect

In-medium propagators for intermediate Hadrons

\[ \eta \text{-propagator (self-consistent)} \]

* No mass shift of N* is expected in the nuclear medium.

* the N* is introduced as a resonance generated dynamically from meson-baryon scattering.

* In this study, we directly take the \( \eta \) self-energy in the ref. NPA710(02)354
$\eta$-Nucleus optical potential

**repulsive core** associated with mass reduction

Chiral doublet (C=0.2 (M))

Chiral Unitary Model
(Inoue, Oset, NPA710(02) 354)

Chiral doublet (C=0.0) [~ 'tp']
no in-medium change of $<\sigma>$

$\omega = m_\eta$

**attractive pocket**

Chiral doublet (C=0.2 (M))

Chiral doublet (C=0.0 (M)) $\omega = m_\eta$

$V$ [MeV]

$W$ [MeV]

$r$ [fm]
$\eta$-Nucleus optical potential

$^{132}\text{Xe}$  B.E. = 0 [MeV]  ($\omega=m_\eta$)

- Repulsive core
- Attractive pocket

C = 0.2
C = 0.1
C = 0.0
C = 0.0 ~ 'tp' potential
C = 0.1 (\omega=m_\eta-50 [MeV])
C = 0.1 (\omega=m_\eta-50 [MeV])
C = 0.1

V [MeV]
W [MeV]
r [fm]
Chiral unitary model
Inoue, Oset, NPA710(02) 354, fig.6
What should we observe?

**Bound State**

<table>
<thead>
<tr>
<th><em>Chiral Doublet model with C=0.0</em></th>
</tr>
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<tbody>
<tr>
<td></td>
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<tr>
<td>0s</td>
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<tr>
<td>0p</td>
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</tbody>
</table>

* Chiral Doublet model with C=0.2
  no bound state

<table>
<thead>
<tr>
<th><em>Chiral Unitary model</em></th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
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<td>0p</td>
</tr>
</tbody>
</table>

C.Garcia-Recio *et al.*, PLB550(02)47, Table 1.

---

**NOT Discrete**

Discrete

Observe (Many) Peaks

---

We need to observe

* whole spectral shape
* a few peaks

---

Toki *et al.*, NPA501(89)653
Missing mass spectroscopy

*(d, 3He)*

- established method ...
  - theory (S. Hirenzaki, H. Toki, T. Yamazaki, PRC44(91)2472, ...)
  - experiment (K. Itahashi et al. PRC62(00)025202, ...)

*missing mass spectroscopy
*recoilless condition

*(γ,p)*

- ω-nucleus (Marco, Weise, PLB502(01)59)
- π-atom (Hirenzaki, Oset, PLB527(02)69)

*missing mass spectroscopy
*recoilless condition
*small distortion
  * η/ω/σ-mesic nuclei case ... REAL-substitutional reactions
Distortion factor

[\text{Eikonal approx.}]

\[ \chi_f^*(\vec{r})\chi_i(\vec{r}) = \exp[i\vec{q} \cdot \vec{r}] F(\vec{b}) \]

distortion Factor reduction of the flux due to absorption

\[ F(b) = \exp \left[ -\frac{1}{2} \sigma_{iN} \int_{-\infty}^{z} dz' \rho_A(z', b) - \frac{1}{2} \sigma_{fN} \int_{z}^{\infty} dz' \rho_{A-1}(z', b) \right] \]

These two reactions have \textbf{different sensitivity} to the system.
Missing mass spectroscopy

\[ \begin{align*}
\text{(d,}^3\text{He)} & \quad \text{established method ... ex.) pion} \\
& \quad \text{theory (S. Hirenzaki, H. Toki, T. Yamazaki, PRC44(91)2472, ...)} \\
& \quad \text{experiment (K. Itahashi et al. PRC62(00)025202, ...)} \\
& \quad \text{missing mass spectroscopy} \\
& \quad \text{recoilless condition}
\end{align*} \]

\[ \begin{align*}
\text{(γ,p)} & \quad \text{ω-nucleus (Marco, Weise, PLB502(01)59)} \\
& \quad \text{π-atom (Hirenzaki, Oset, PLB527(02)69)} \\
& \quad \text{missing mass spectroscopy} \\
& \quad \text{recoilless condition} \\
& \quad \text{small distortion} \\
& \quad \text{η/ω/σ-mesic nuclei case ... REAL-substitutional reactions}
\end{align*} \]

\[ \begin{align*}
\text{* ELEMENTARY CROSS SECTIONS} \\
\text{d} + \text{p} & \rightarrow ^3\text{He} + \eta \\
\left( \frac{d\sigma}{d\Omega} \right)_{\text{Lab}} & = 150 \text{ [nb/sr]} \\
\text{γ} + \text{p} & \rightarrow \text{p} + \eta \\
\left( \frac{d\sigma}{d\Omega} \right)_{\text{Lab}} & = 3.4 \text{ [μb/sr]}
\end{align*} \]

[Ref] P. Berthet et al., NPA443(1985)589, [SATURNE]
[Ref] S. Homma et al., J.Phys.Soc.Jpn, 57(88)828, Fig.5.

\[ \begin{align*}
\text{* Green function Method} \\
\text{O. Morimatsu, K. Yazaki, NPA435,727(1985)} \\
\text{NPA483,495(1988)}
\end{align*} \]

to calculate the formation cross section of the quasi-stable eta-nucleus system
Momentum transfer

Recoilless condition

- momentum transfer
  \[ q = |\vec{k}_f - \vec{k}_i| \]

\[ T_i, k_i, m_i \quad T_f, k_f, m_f \]

\[ M_N \quad m_{\eta} \]

\[ T_d \sim 3.5 \text{ GeV} \]

\[ E_\gamma \sim 950 \text{ MeV} \]
Spectra of $^{12}$C target

$T_d = 3.5$ [GeV]
$E_Y = 950$ [MeV]
recoilless condition for the eta production

$$(d, ^3\text{He})$$

$$(0p_{3/2})^1_\rho \otimes \rho_\eta$$
$$(0s_{1/2})^1_\rho \otimes S_\eta$$

(binding region)
$\eta$-production threshold
quasi-free region

$E_{ex} - E_0$ [MeV]
($s$-wave)
$\eta$-production threshold
For s-state contribution, the eta-production threshold is shifted 18MeV corresponding to the difference of the separation energy.
Spectra of $^{12}$C target

$T_d = 3.5 \text{ [GeV]}$
$E_Y = 950 \text{ [MeV]}$

recoilless condition for the eta production

$(d, ^3\text{He})$ (d,3He)

These two models provide the significantly different spectra with $^{12}$C target case.

It seems impossible to observe b.s. from the spectrum.
Spectra of $^{12}$C target

$T_d = 3.5$ [GeV]
$E_Y = 950$ [MeV]

recoilless condition for the eta production

$(\gamma, p)$

We can see the difference between two models more clearly.

• enhanced
• It seems impossible to observe b.s. as a peak from the spectrum.

Bound state

We can see the difference between two models more clearly.
Spectra of $^{12}$C target

$T_d = 3.5 \text{ [GeV]}$
$E_\gamma = 950 \text{ [MeV]}$

*dist: x 10
*ele: x 20

recoilless condition for the eta production

Chiral Doublet Model [C=0.0]

Chiral Doublet Model [C=0.2]

Chiral Unitary Model

$\eta$-production threshold

(binding region)

 quasi-free region
Spectra of $^{40}$Ca target

- heavy target case
- **Chiral Doublet model**
  $C=0.0$ vs. $C=0.2$
Spectra of $^{40}\text{Ca}$ target

- heavy target case
- **Chiral Doublet model**
  C=0.0 vs. C=0.2

**Chiral Doublet model**

\[ C = 0.0 \text{ vs. } C = 0.2 \]

- $^{1}(1s_{1/2})_{p} \otimes s_{\eta}$
- $^{1}(0d_{3/2})_{p} \otimes d_{\eta}$
- $^{1}(0d_{5/2})_{p} \otimes d_{\eta}$
- $^{1}(0p_{3/2})_{p} \otimes p_{\eta}$
Spectra of $^{40}\text{Ca}$ target

- heavy target case
- **Chiral Doublet model**
  - $C=0.0$ vs. $C=0.2$

Whole spectra change reflecting the reduction of mass difference of $N$ & $N^*$. 
Summary

η-Nucleus system with
- Chiral Doublet model
- Chiral Unitary model

Potential nature
- repulsive nature (low-ρ attractive)
  - Chiral Doublet model
- attractive nature (for all ρ)
  - ‘t_p’ potential (by C=0.0 Chiral Doublet model)
  - Chiral Unitary model

N* is a pole
N* is a resonance
N* mass reduction
No mass shift of N*

Spectra of (d,^3He) & (γ,p)
» We can deduce the new information of eta-nucleus interaction from these experiments.
» By knowing the nature of the η-nucleus \( V_{opt} \), we will be able to study the in-medium properties of N*.
» (γ,p) : more sensitive to the potential nature
  » BUT, large background ? S/N ~ 1/20 ?? [ref. K.Baba et al., NPA415(84)462]

Future view
» (d,^3He) experiment at GSI (2005??)
» Information of Baryon Chiral Symmetry and its partial restoration
Formation of $\eta'(958)$ -mesic nuclei and axial $U_A(1)$ anomaly at finite density


- Introduction
- $U_A(1)$ anomaly & models with the NJL Lagrangian + KMT term
  - $\eta$ and $\eta'$ mass shifts
- phenomenological optical potential
- Numerical results of the ($\gamma$,p) reaction
- Summary
Introduction: $\eta'(958)$-mesic nuclei

**Interests of Meson Bound systems**
- important information on in-medium hadron properties
- $\eta$ mesic nuclei with chiral models

**$\eta'(958)$ meson**
- close connections with $U_A(1)$ anomaly
  - heavy $\eta'$ mass due to the existence of anomaly term
    \[ \partial_\mu (\bar{q} \gamma^\mu \gamma_5 q) = 2N_f \frac{g^2}{32\pi^2} \frac{1}{2} \varepsilon^{\mu\nu\lambda\rho} F^\alpha_{\mu\nu} F^\lambda_{\rho} \neq 0 \]
- some theoretical works
  - in vacuum / at finite temperature / at finite density
    - T. Kunihiro, T. Hatsuda, PLB206(88)385
    - T. Kunihiro, PLB219(89)363
    - R.D.Pisarski, R.Wilczek, PRD29(84)338
    - K.Fukushima, K.Onishi, K.Ohta, PRC63(01)045203
    - P. Costa *et al.*, PLB560(03)171, hep-ph/0408177
    - etc…
models with NJL Lagrangian + KMT interaction

\[ \mathcal{L} = \bar{q}(i \not\! \partial - m)q + \frac{g_s}{2} \sum_{a=0}^{8} \left[ (\bar{q} \lambda_a q)^2 + (i \bar{q} \lambda_a \gamma_5 q)^2 \right] + g_D [\det \bar{q}_i (1 - \gamma_5) q_j + h.c.] \]

Anomaly effect in vacuum

T. Kunihiro, T. Hatsuda, PLB206(88)385, Fig.3

\( \eta \) and \( \eta' \) masses due to the anomaly effect

KMT term

flavor mixing vertex

\( \Rightarrow \) heavier \( \eta \) and \( \eta' \) masses due to the anomaly effect
The strength of the anomaly term at finite $T/\rho$ at finite temperature and at finite density.

At finite temperature:

T.Kunihiro, PLB219(89)363, Figs. 2, 3

$g_D : \text{const}$

$g_D = g_0 e^{-\left(\frac{T}{T_0}\right)^2}$

$T_0 = 100$ MeV

Case I

Case II

At finite density:

P. Costa, M. C. Ruivo, Yu. L. Kalinovsky

PLB560(03)171, Fig. 2

$g_D : \text{const}$

Figure 2: Temperature dependence of the meson spectra in the case I.

Figures 3: Temperature dependence of the meson spectra in the case II.
Our motivation & present work

- a poor experimental information on the $U_A(1)$ anomaly at finite density

- proposal for the formation reaction of the $\eta'$-mesic nuclei
  - $U_A(1)$ anomaly in medium from the viewpoint of “mesic nuclei”
  - discuss the possibility of the $h'$-nucleus bound states
  - the $h'$ properties, especially mass shift, at finite density
    » new information on the properties of $U_A(1)$ anomaly?

- start from a phenomenological treatment
  » We are in beginning stage on this research.
\( \eta^- \) & \( \eta' \)-Nucleus optical potential

\[ U(r) = (V_0 + iW_0) \frac{\rho(r)}{\rho_0} \]

- **Real Part** \( V_0 \)
  - evaluated by possible \( \eta, \eta' \) mass shift at \( \rho_0 \)
  
  \[ m_{\eta'}^2 \rightarrow m_{\eta'}^2(\rho) = (m_{\eta'} + \Delta m_{\eta'}(\rho))^2 \sim m_0^2 + 2m_0 \Delta m(\rho) \]

  \[ \Delta m(\rho) \rightarrow V(\rho(r)) = V_0 \frac{\rho(r)}{\rho_0} \]

- **Imaginary Part** \( W_0 \) for \( \eta' \)
  - estimated from nucl-th/0303044 (A.Sibirtsev, Ch.Elster, S.Krewald, J.Speth) analysis of \( \gamma p \rightarrow \eta' p \) data

  \[ \text{fix a coupling } g \]

  \( \text{in analogy with } \Delta \text{-hole model for the } \pi \text{-nucleus system} \)

  \[ U \sim \frac{g^2}{2m_{\eta'}} \frac{\rho}{m_{\eta'} + M_N - M_{N^*} + i\Gamma_{N^*}/2} = (+77 \text{ MeV}, -8 \text{ MeV}_i) \frac{\rho}{\rho_0} \]

\[ W_0 = -5, -20 \text{ MeV (parameter)} \]
Numerical Results: $^{12}\text{C}(\gamma,p)^{11}\text{B}_{\eta'}$

- $V_0 = 0$
- $W_0 = -5$ MeV

- $V_0 = -100$ MeV
- $W_0 = -5$ MeV

- $V_0 = 0$
- $W_0 = -20$ MeV

- $V_0 = -100$ MeV
- $W_0 = -20$ MeV
consideration together with $\eta$ meson

**case 1) constant $g_D$ in medium**

P. Costa et al., PLB560(03)171, Fig.2

$\Delta m_{\eta'} \sim -150$ MeV @ $\rho = \rho_0$

$\Delta m_\eta \sim +20$ MeV @ $\rho = \rho_0$

**case 2) $g_D$ changes in medium**

... no information ...

→ T.Kunihiro, T.Hatsuda, PLB206(88)385, Fig.3

we try to simulate the effect of effective restoration of $U_A(1)$ anomaly

$\Delta m_{\eta'} \sim -150$ MeV @ $\rho = \rho_0$

$\Delta m_\eta \sim -100$ MeV @ $\rho = \rho_0$
formation of mesic-nuclei

**momentum transfer**

(γ,p) reaction

(d,3He) reaction

\[
\gamma, p \rightarrow n - 
\]

missing mass spectroscopy
small distortion effect
nearly(?) recoilless condition

\(~ E_\gamma = 2.7 \text{ GeV} \)

(γ,p) reaction

ω-nucleus (Marco, Weise, PLB502(01)59)
π-atom (Hirenzaki, Oset, PLB527(02)69)
η/ω/σ-nucleus (Nagahiro, Jido, Hirenzaki, in preparation)

**Green function method**

[O.Morimatsu, K.Yazaki, NPA435, 727(85)
NPA483,493(88)]

to calculate the formation cross section of the quasi-stable η'-nucleus system
Reactions Parameters

- $(\gamma, p)$ reaction @ $E_\gamma = 2.7$ GeV
- target ... $^{12}$C
- Forward ($\theta \sim 0$ deg.)
- Elementary cross section for $\gamma p \rightarrow \eta' p$

$$
\left( \frac{d\sigma}{d\Omega} \right)_{0^\circ}^{Lab} \sim 150 \text{ nb/sr}
$$

Data: SAPHIR collaboration, PLB444(98)555-562
Chiang, Yang, PRC68(03)045202

$\omega$-mesic nuclei
- $m_\eta \sim 547 \text{ MeV}$
- $m_\omega \sim 783 \text{ MeV}$
- $m_{\eta'} \sim 958 \text{ MeV}$
- plan of experiment for the formation of $\omega$-mesic nuclei @ SPring-8, 2005
- two different predictions for optical potentials
  - 【attractive】 $V = -(156 + 29 \text{ i}) \rho/\rho_0 \text{ MeV}$ [Klingl, Waas, Weise NPA650(99)299]
  - 【repulsive】 $V = -(42.8 + 19.5 \text{ i}) \rho/\rho_0 \text{ MeV}$ [Lutz, Wolf, Friman NPA706(02)431]
- elementary cross section $\sim 150 \text{ nb/sr}$
  - event $# [\eta] \sim [\omega] \sim [\eta']$ @ test experiment at SPring-8
    [N.Muramatsu, private communication]

$\eta$-mesic nuclei
- elementary cross section $\sim 150 \text{ nb/sr}$
Numerical results: $^{12}\text{C}(\gamma,p)^{11}\text{B}_{\eta,\omega,\eta'}$

Numerical results:

$V_0 = -(156+29i) \text{ [MeV]}$

$V_0 = -(100+40i) \text{ [MeV]}$

(Weise)

$V_0 = -(150+5i) \text{ [MeV]}$

Quasi-free

$\eta$

$\omega$

$\eta'$

Mass $\rightarrow$ Small
Numerical results: $^{12}\text{C}(\gamma,p)\text{^{11}B}_{\eta,\omega,\eta'}$

Quasi-free

$V_0 = -(150+20i) \text{ [MeV]}$

(Weise)

$V_0 = -(156+29i) \text{ [MeV]}$

Mass $\rightarrow$ small

$V_0 = -(100+40i) \text{ [MeV]}$
Numerical results: $^{12}\text{C(}\gamma,p\text{)}^{11}\text{B}$ \(\eta,\omega,\eta'\)

Numerical results:

\[ V_0 = - (156+29i) \text{ [MeV]} \]

(Weise)

\[ V_0 = - (-20+40i) \text{ [MeV]} \]

Mass \(\to\) large

\[ V_0 = - (150+20i) \text{ [MeV]} \]

quasi-free
Numerical results: $^{12}\text{C}(\gamma,p)^{11}\text{B}_{\eta,\omega,\eta'}$

$V_0 = -(-20+40i)$ [MeV] (Lutz)

$V_0 = -(150+20i)$ [MeV]

mass $\rightarrow$ large
Numerical results: $^{12}\text{C}(\gamma,p)^{11}\text{B}_{\eta,\omega,\eta'}$

$V_0 = - (150 + 20i)$ [MeV]  

(Lutz) 

$V_0 = - (100 + 40i)$ [MeV]  

mass $\rightarrow$ small
Summary

- (γ,p) spectra of both η and η' with ω meson
- Reasonably large cross sections observation
  - S/N ~ 1/10 ... N.Muramatsu, private communication
  - the experiment for the formation of ω-mesic nuclei
    @ SPring-8, → Coming soon
    (information on η & η' as byproducts ?)

in Future

- What the peak position means?
  - more microscopic estimation for η'-nucleus optical potential
- Other treatments
  - topological susceptibility (Fukushima et al., PRC63(01)045203) etc…
- relation with other models for η & η'
  - chiral doublet model & chiral unitary approach for the η-mesic nuclei
  - Real(V) > 0 in N*(1535) loop calculation for η' ?