formation of $\eta$ - and $\eta'$-mesic nuclei

$\eta$-mesic nuclei
properties of $N^{*}(1535)$ resonance in medium
Chiral doublet model
Chiral unitary model
$(d,^{3}\text{He}), (\gamma,p) \& (\pi^{+},p)$ reactions

$\eta'$-mesic nuclei
$U_{A}(1)$ anomaly effect in medium
Nambu-Jona-Lasinio model
$(\gamma,p)$ reaction
$\eta^{-}, \omega^{-} \& \eta'^{-}$-mesic nuclei formations @ $E_{\gamma} = 2.7$ GeV
\( \eta \)-Nucleus system

works for eta-mesic nuclei

- \((\pi^+, p)\)
  - Liu, Haider, PRC34(1986)1845
  - Chiang, Oset, and Liu, PRC44(1988)738
  - Chrien et al., PRL60(1988)2595

- \((d, ^3He)\)
  - Exp. at GSI (Yamazaki, Hayano group)

\( \eta \)-light nucleus system: TAPS @ MAMI (2004) (exp.), B.K. Jain et al. (thor.) etc...

etc… (ex. \((\gamma, \eta) \) @ 核理研, etc…)

properties of eta meson

**eta meson**

- \( m_\eta = 547.3 \) [MeV]
- \( I = 0, \quad J^P = 0^- \)
- \( \Gamma = 1.18 \) [keV] \((2\gamma, \quad 3\pi^0, \quad \pi^+\pi^-\pi^0, \ldots)\)

**eta-N system**

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

- \( \Gamma_{\pi N} \sim \Gamma_{\eta N} \sim 75 \) [MeV]

\( \eta N N^* \) system

- No \( I = \frac{3}{2} \) baryon contamination
- Large coupling constant
- No suppression at threshold (s-wave coupling)

\[
L_{\eta NN^*} = g_\eta \bar{N} \eta N^* + h.c.
\]
$\eta$-Nucleus Interaction

~ N* dominance model ~

**optical potential**

$$V_{\text{opt}} = \frac{g_\eta^2}{2\mu} \left( \omega + m_N(\rho) - m_{N^*}(\rho) + i\Gamma_N^*(s;\rho)/2 \right)$$

**potential nature**

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

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

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

**medium effect**

$m_N$ & $m_{N^*}$ change ??

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

N & N* properties in medium evaluated by two kinds of **Chiral Models**

(Chiang, Oset, Liu PRC 44(1991)738)


$g_\eta \simeq 2.0$

to reproduce the partial width

$\Gamma_{N^* \to \eta N} \simeq 75 \text{ MeV}$
at tree level.

General feature

@ KEK, Tsukuba, 3 Aug. 2006
Chiral models for N and N*

Chiral doublet model

DeTar, Kunihiro, PRD39 (89) 2805
Jido, Nemoto, Oka, Hosaka, NPA 671 (00) 471
Jido, Hatsuda, Kunihiro, PRL 84 (00) 3252
Jido, Oka, Hosaka, PTP 106 (01) 873

Extended SU(2) Linear Sigma Model for N and N^*

Lagrangian

\[ \mathcal{L} = \sum_{j=1,2} \left[ \bar{N}_j i \not{\partial} N_j - g_j \bar{N}_j (\sigma + (-)^{j-1} i \gamma_5 \vec{\tau} \cdot \vec{\pi}) N_k \right] - m_0 (\bar{N}_1 \gamma_5 N_2 - \bar{N}_2 \gamma_5 N_1) \]

Physical fields

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

N^* : chiral partner of nucleon

Mass difference

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

* C~0.2 : the strength of the Chiral restoration at the nuclear saturation density

* reduction of mass difference

Chiral unitary model

Kaiser, Siegel, Weise, PLB 362 (95) 23
Waas, Weise, NPA 625 (97) 287
Garcia-Recio, Nieves, Inoue, Oset, PLB 550 (02) 47
Inoue, Oset, NPA 710 (02) 354

A coupled channel Bethe-Salpeter eq.

\[ \{ \pi^- p, \pi^0 n, \eta n, K^0 \Lambda, K^+ \Sigma^-, K^0 \Sigma^0, \pi^0 \pi^- p, \pi^0 \pi^- n \} \]

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

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

* In this study, we directly take the eta-self-energy in the ref. NPA 710 (02) 354
$\eta$-Nucleus optical potential

energy $\omega$

$m_\eta - m_N$

doublet model $\rho/\rho_0$

repulsive core

associated with mass reduction

Chiral doublet (C=0.2 (M))

attractive pocket

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

Chiral doublet (C=0.0) [$\eta^-$]

no in-medium change of $\langle \sigma \rangle$

Chiral doublet (C=0.2 (M))

$\omega = m_\eta$

Chiral doublet (C=0.0 (M))

$\omega = m_\eta$

Chiral Unitary Model

$W$ [MeV]

$V$ [MeV]
Energy dependence of the optical potentials

Chiral Doublet Model (Mirror)
C=0.2

Chiral Unitary Model

This case also show the very different feature from other case

Chiral unitary model
Inoue, Oset, NPA710(02) 354, fig.6
Energy dependence of the optical potentials

Chiral Doublet Model
(C Mirror)
$\omega - m_\eta =$ -100 MeV

Chiral Unitary Model
$\omega - m_\eta =$ +100 MeV

Inoue, Oset, NPA710(02) 354, fig.6

Chiral unitary model

"現代の原子核物理 ~多様化進化する原子核の描像~"
@ KEK, Tsukuba, 3 Aug. 2006
Missing mass spectroscopy: one proton pick-up

- \((d,^3He)\): established by studies of pionic atom formation
  - theory ... S.Hirenzaki, H.Toki, T.Yamazaki, PRC44(91)2472, ...
  - experiment ... K.Itahashi et al., PRC62(00)025202, ...

- \((\gamma,p)\): smaller distortion effect
  - \(\omega\)-nucleus ... Marco, Weise, PLB502(01)59
  - \(\pi\)-atom ... Hirenzaki, Oset, PLB527(02)69

- \((\pi^+,p)\): could be performed at J-PARC?
  - secondary meson beam, \(\pi\), K, ...
  - Elementary cross section: \((d\sigma/d\Omega) \sim 2.4 \text{ mb/sr}\) [Crystal Ball: Prakhov et al., PRC72(05)015203]
$(\pi^+,p)$ spectra : $^{12}\text{C}$ target

$T_\pi = 820$ MeV ($p_\pi = 950$ MeV/c) : $\theta = 0$ deg. (Lab)

- It is difficult to observe the bound state as a peak
- We need to observe whole shape itself (not peak structures)

Chiral doublet model [$C=0.0$] (t-$\rho$ approx.)

Chiral doublet model [$C=0.2$]

Chiral unitary model

η production threshold (s-state proton-hole)

η production threshold at η threshold

recoilless at η threshold

ππ + $p$ spectra : $^{12}\text{C}$ target

$\pi\pi = 950$ MeV/$c$ : $\theta = 0$ deg. (Lab)
(\(\pi^+,p\)) spectra: past experiment in 1988

Chrien et al., PRL60(1988)2595

- \(p_\pi = 800\) MeV/c
- proton angle: 15 deg. (Lab.)
- targets: Li, C, O, Al
- search for predicted narrow bound state (ex. \(\Gamma \sim 10\) MeV)
- negative results (bound state was not observed)

Chrien et al., PRL60(1988)2595, Fig.1

Chiral doublet model

Chiral unitary model

preliminary
\(\eta'(958)\)-Nucleus system

- \(\eta'(958)\) meson …close connections with \(U_A(1)\) anomaly
  - some theoretical works
    - the effects of the \(U_A(1)\) anomaly on \(\eta'\) properties
    - at finite temperature/density
      - 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…
    - the possible character changes of \(\eta'\)
  - a poor experimental information
    - on the \(U_A(1)\) anomaly at finite density

- proposal for the formation reaction of the \(\eta'\)-mesic nuclei
  - using the \((\gamma,p)\) reactions
    - \(U_A(1)\) anomaly in medium from the viewpoint of “mesic nuclei”
    - the \(\eta'\) properties, especially mass shift, at finite density
Model for $\eta$ and $\eta'$ meson in medium

- **Nambu-Jona-Lasinio model** with the **KMT interaction**
  - unified treatment of the $\eta$ and $\eta'$ meson

$$\mathcal{L} = \bar{q}(i\slashed{\partial} - m)q + \frac{g_s}{2} \sum_{a=0}^{8} \left[ (\bar{q}\lambda_{a}q)^2 + (i\bar{q}\lambda_{a}\gamma_5 q)^2 \right]$$

$$+ g_D \left[ \det \bar{q}_i (1 - \gamma_5)q_j + h.c. \right]$$

explicit breaking the $U_A(1)$ sym.

Kobayashi, Maskawa, Prog.Theor.Phys.44, 1422 (70)

G. 't Hooft, Phys.Rev.D14,3432 (76)

One can reproduce the heavy $\eta'$ mass

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

Anomaly effect in vacuum
SU(2) symmetric matter $\rho_u = \rho_d, \rho_s = 0$

- we consider the SU(2) sym. matter as the sym. nuclear matter.

parameters (in vacuum)

$\Lambda = 602.3$ [MeV]
$g_S \Lambda^2 = 3.67$
$g_D \Lambda^5 = -12.36$
$m_{u,d} = 5.5$ [MeV]
$m_s = 140.7$ [MeV]

$M_{u,d} = 367.6$ [MeV]
$M_s = 549.5$ [MeV]
$\langle \bar{u}u \rangle^{1/3} = -241.9$ [MeV]
$\langle \bar{s}s \rangle^{1/3} = -257.7$ [MeV]
$m_{\eta'} = 958$ [MeV]
$m_\eta = 514$ [MeV]
$m_{\pi} = 135$ [MeV]

$\eta$ and $\eta'$ mass shifts @ $\rho_0$

$\Delta m_{\eta'} \sim -150$ MeV @ $\rho_0$
$\Delta m_\eta \sim +20$ MeV @ $\rho_0$

We can see the large medium effect even at normal nuclear density.
η- & η’-Nucleus optical potential

Real Part $V_0$

- evaluated by possible $\eta, \eta'$ mass shift at $\rho_0$

$$m_{\eta'}^2 \rightarrow m_{\eta'}^2(\rho) = (m_{\eta'} + \Delta m_{\eta'}(\rho))^2 \sim m_0^2 + 2m_0\Delta m(\rho)$$

$$\Delta m(\rho) \rightarrow V(\rho(\rho)) = V_0\frac{\rho(\rho)}{\rho_0}$$

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

optical potentials

$V_{\eta}(r)$

$V_{\eta'}(r)$

$\eta$: repulsive

$\eta'$: attractive
\( \eta^- \) & \( \eta'^- \)-Nucleus optical potential

**Real Part** \( V_0 \)

» evaluated by possible \( \eta, \eta' \) mass shift at \( \rho_0 \)

\[
m_{\eta'}^2 \rightarrow m_{\eta'}^2(\rho) = (m_{\eta'} + \Delta m_{\eta'}(\rho))^2 \sim m_0^2 + 2m_0\Delta m(\rho)
\]

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

**Imaginary Part** \( W_0 \) for \( \eta' \)

» estimated from AIP Conf.Proc.717 (04)837 (A.Sibirtsev, Ch.Elster, S.Krewald, J.Speth)

analysis of \( \gamma p \rightarrow \eta p \) data

\( \eta' \) 

N 

\( g \)

N*(1535)

fix a coupling \( g \)

\( \eta \)

\( \eta' \)

\( \eta' \) \( g \) \( \eta' \)

\( N^* \) \( (1535) \)

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

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

**Imaginary Part for** \( \eta \)

\( W_0 = -40 \text{ MeV} \)

D.Jido,H.N.,S.Hirenzaki, PRC66(02)045202,
H.N.,D.Jido,S.Hirenzaki, PRC68(03)035205,
Numerical results: $^{12}\text{C}(\gamma, p)^{11}\text{B}_{\eta, \omega, \eta'}$

$^{12}\text{C}(\gamma, p)^{11}\text{B}_{\eta, \omega, \eta'}$

- We only observe the quasi-free $\eta'$ peak.

- No medium effect

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

$$\left(\frac{d\sigma}{d\Omega}\right)_0 \sim 150 \text{ nb/sr}$$

Data: SAPHIR collaboration, PLB444(98)555-562
Chiang, Yang, PRC68(03)045202
Numerical results: $^{12}\text{C}(\gamma,p)^{11}\text{B}$

\[ V_0 = - (42.8 + 19.5i) \text{[MeV]} \]

(Lutz et al., NPA706(02)431)

Plot showing distributions for $\eta, \omega, \eta'$ with no medium effect and quasi-free interactions.
Numerical results: $^{12}\text{C}(\gamma,p)^{11}\text{B}_{\eta,\omega,\eta'}$

- No medium effect
- Quasi-free

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

(Weise et al., NPA650(99)299)
Numerical results: $^{12}\text{C}(\gamma,p)^{11}\text{B}_{\eta,\omega,\eta'}$

$g_D = -12.36/\Lambda^5$

$V_0 = -(156 + 29i) \text{[MeV]}$ (Weise)
Numerical results: $^{12}\text{C}(\gamma,p)^{11}\text{B}$

$g_D = \frac{-12.36}{\Lambda^5}$

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

Quasi-free

Mass reduction due to the medium effect through anomaly term

$g_D = \frac{-12.36}{\Lambda^5}$

$V_0 = -(156+29i) \text{[MeV]}$ (Weise)
Numerical results: $^{12}\text{C}(\gamma,p)^{11}\text{B}_{\eta,\omega,\eta'}$

$g_D = -12.36/\Lambda^5$

$V_0 = (-42.8 + 19.5i)$ [MeV]

Quasi-free overlap with bound $\eta'$
Summary

- Formations of mesic nuclei
  - in-medium properties of hadrons and QCD symmetries
  - \( \eta \)-nucleus systems
    - two different chiral models
      - different physical pictures of the \( \mathrm{N}^*(1535) \) resonance
  - \( \eta' \)-nucleus systems
    - New information on the \( \mathrm{UA}(1) \) anomaly at finite density

- experiments
  - \((d,^3\mathrm{He})\) experiment for \( \eta \)-nucleus system @ GSI (2005?6?)
    - Compare the spectra of \((\gamma,p)\) and \((d,^3\mathrm{He})\) : complementary information
  - \((\pi^+,p)\) reaction for \( \eta \)-nucleus system
    - possible at J-PARC?
  - \((\gamma,p)\) reaction for the formation of \( \omega \)-mesic nuclei @ SPring-8
    - information on \( \eta \) & \( \eta' \) also expected

- Future works
  - \( \eta \)-mesic nuclei
    - \((\pi^+,p)\) experiments by Chrien et al., (1988)
    - appropriate kinematical conditions
  - \( \eta' \)-mesic nuclei
    - relation with other models for \( \eta \) & \( \eta' \)