Mesic Nuclei Formation by $(\gamma,p)$ reactions

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1. Introduction and Motivation

2. Missing Mass Spectroscopy (ex. $\pi$ atoms)

3. Recent Topics
   ($\eta$, $\omega$, $\eta'$)

4. Summary
1. Introduction and Motivation

- **Object**
  - Hadron – Nucleus bound systems.
  - Coulomb + Strong ••• Exotic Atoms
    (Deeply Bound) $\pi$ atom, Kaonic Atom, $\bar{p}$ atom …
  - Strong ••• Exotic Nuclei
    Mesic Nuclei, Hypernuclei, …

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Kaonic Atoms
And
Kaonic Nuclei
By J. Yamagata
1. Introduction and Motivation

- 1. Exotic Many Body Physics

Exotic Many Body Physics

- 2. Hadron Physics at finite density

Hadron Physics at finite density

Fundamental theory (QCD)

\[ \leftrightarrow \] Effective theory

\[ \leftrightarrow \] Hadron property at finite \( \rho \)

\[ \leftrightarrow \] Infinite System \( \leftrightarrow \) Finite System

\[ \leftrightarrow \] Mesic Atoms and Mesic Nuclei

Pionic Atoms in halo nuclei

Co-existence of Pion-Neutron-halo

Nuclear radius of \( ^{15}_\text{N} \)
• Higgs mechanism
• Spontaneous Chiral Symmetry Breaking
• $U_A(1)$ Anomaly Effect

Anomaly effect in vacuum

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

The NJL Model : $J^P = 0^-$

Pseudoscalar meson spectrum from the NJL model (Klimt et al. 1990), showing the chiral and flavour symmetry breaking pattern. Calculated and experimental masses are given in MeV.
2. Missing Mass Spectroscopy

In-Medium Dispersion Relation

\[ \left[-\nabla^2 + m^2 + \Pi(\rho(r), \omega)\right] \phi = \omega^2 \phi \]
Deeply Bound Pionic Atom by \((d, ^3\text{He})\)

Umemoto et al., PRC62 (2000) (Theory Spectra)


GOR relation + Tomozawa-Weinberg Relation

\[
\frac{\langle qq \rangle}{\langle qq \rangle_0} \sim \frac{f_{\pi}^2}{f_{\pi}^2} \sim \frac{b_1^{\text{free}}}{b_1^*(\rho)} = 0.78 \pm 0.05 \ @ \ \rho \simeq 0.6\rho_0
\]

\[
\sim 0.64 \ @ \ \rho = \rho_0
\]
Information on $\Pi$ at finite $\rho \sim \rho_0$, $(T=0)$

- Eigen state observation $\leftrightarrow$ Invariant Mass Method
- Quantum number fixed $\leftrightarrow$ Selective information

$\Pi = 2\mu V_{\text{opt}}$

$$\begin{align*}
\Pi &= -4\pi [b(r) + \varepsilon_2 B_0 \rho^2(r)] \\
&\quad + 4\pi \nabla \cdot [c(r) + \varepsilon_2^{-1} C_0 \rho^2(r)] L(r) \nabla
\end{align*}$$

with

$$\begin{align*}
b(r) &= \varepsilon_1 \{b_0 \rho(r) + b_1 \left[ \rho_n(r) - \rho_p(r) \right] \} \\
c(r) &= \varepsilon_1^{-1} \left[ c_0 \rho(r) + c_1 \left[ \rho_n(r) - \rho_p(r) \right] \right] \\
L(r) &= \left\{ 1 + \frac{4}{3} \pi \lambda [c(r) + \varepsilon_2^{-1} C_0 \rho^2(r)] \right\}^{-1}
\end{align*}$$

Umemoto et al., PRC62 (2000)

FIG. 1. The binding energies with finite-size Coulomb potential only $B_{\text{Coul}}$ and Coulomb plus optical potential $B_{\text{full}}$ are calculated. The energy shifts $B_{\text{Coul}}B_{\text{full}}$ are shown as the solid bars for pionic 1s, 2p, and 3d states for $^{115}$Sn and $^{207}$Pb. The shifts due to the real local terms in the potential are shown by dashed bars. Dotted bars are the results with all real terms (local plus nonlocal) in the optical potential.
A(γ, N) reaction

- Mesic-Atom ... It's another Method.
  S. Hirenzaki, E. Oset
  

- Mesic-Nuclei ... It has an Advantage
  
  \[ t \sim \int \chi_f^* \phi_M^* \psi_N \chi_i d^3 r \]
  
  Substitutional vs. Quasi-Substitutional at recoilless kinematics.
  
  Deep Mesic State needs Deep Nuclear State!
\( Q = m_\pi \quad 2m_\pi \quad m_\sigma \quad m_\eta \quad m_\omega \)

\( \omega \) mesic Nuclei by \((\gamma, p)\)

E. Marco, W. Weise

\[ E_\gamma = 2.75 \text{ [GeV]} \]

Distortion factor

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

**distortion Factor** reduction of the flux due to the absorption

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

(\(\gamma,p\)) case:

**(\(\gamma,p\)) case:** more sensitive to the Center of the nucleus.
3-1. $\eta$ – Nucleus system : Nature of Baryon Resonance

eta-mesic nuclei

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

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

properties of eta meson

$\eta$ meson

$$\eta$$

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

$$I = 0, \quad J^P = 0^-$$

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

$\eta$-N system

- Strong Coupling to $N^*(1535)$,
  $$\Gamma_{\pi N} \sim \Gamma_{\eta N} \sim 75\text{[MeV]}$$

- No $I = \frac{3}{2}$ baryon contamination
- Large coupling constant
- No suppression at threshold
  $$(s\text{-wave coupling})$$
  $$\mathcal{L}_{\eta NN^*} = g_\eta \bar{N}\eta N^* + h.c.$$
Chiral model for N and N*

Chiral doublet model

DeTar, Kunihiro, PRD39 (89)2805
Jido, Oka, Hosaka, Nemoto, NPA671(00)471, PTP106(01)873
Jido, Hatsuda, Kunihiro, PRL84(00)3252

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

Lagrangian

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

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

* In this study, we directly take the eta-self-energy in the ref. NPA710(02)354
A coupled channel Bethe-Salpeter eq.

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

\[
\begin{array}{l}
\eta - \Pi \eta \\
\eta \\
T
\end{array}
\]

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

* the N* is introduced as a resonance generated dynamically from meson-baryon scattering.
$\eta$-nucleus interaction ~ $N^*$ dominance

optical potential

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

$g_\eta \simeq 2.0$ to reproduce the partial width $\Gamma_{N^*\rightarrow\eta N} \simeq 75$ MeV at tree level.

$\eta$-nucleus optical potential ~ sensitive to the in-medium properties of N and $N^*$
Energy dependence of the optical potentials

Chiral unitary model
Inoue, Oset, NPA710(02) 354, fig.6

Chiral Doublet Model (Mirror)
$C=0.2$

Chiral Unitary Model

$\omega - m_\eta = -100$ MeV
$\omega - m_\eta = +100$ MeV

$\omega - m_\eta = -70$ MeV
$\omega - m_\eta = -50$ MeV
$\omega - m_\eta = 0$ MeV
We can see the difference between two models more clearly.

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

recoilless condition for the eta production

\( (\gamma,p) \)

Is seems impossible to observe b.s. as a peak from the spectra.

We can see the difference between two models more clearly.
Spectra of $^{40}\text{Ca}$ target

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

\begin{align*}
(1s_{1/2})^1_p \otimes s_\eta \\
(0d_{5/2})^1_p \otimes d_\eta \\
(0d_{5/2})^1_p \otimes d_\eta \\
(0p_{3/2})^1_p \otimes p_\eta
\end{align*}
Spectra of $^{40}$Ca target

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

\[ (1s_{1/2})_p^1 \otimes s_\eta \]
\[ (0d_{3/2})_p^1 \otimes d_\eta \]
\[ (0d_{5/2})_p^1 \otimes d_\eta \]
\[ (0p_{3/2})_p^1 \otimes p_\eta \]

The spectra for $(d,^3\text{He})$ and $(\gamma,p)$ reactions are shown with significant changes in the spectra for different values of C, indicating a shift a few MeV according to the change of C.
• heavy target case
• Chiral doublet model
  C=0.0 vs. C=0.2

• Whole spectra change reflecting the reduction of mass difference of N and N*!!
3-2. $\eta$ and $\eta'(958)$ mesic nuclei with NJL model
- quark picture of mesons -

- $\eta'(958)$ 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
      - S. D. Bass and A. W. Thomas, PLB634(06)368
  - 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
  (inspired by discussion with T. Hatsuda)
  - discuss the possibility of the $\eta'$-nucleus bound states
    (Previous estimation of b.s. by K. Tushima, NPA670(00)198c : But, $\Gamma$ is fixed to be 0)
  - the $\eta'$ properties, especially mass shift, at finite density
we consider the SU(2) sym. matter as the sym. nuclear matter.

parameters (in vacuum)

\[ \Lambda = 602.3 \text{ [MeV]} \]
\[ g_S \Lambda^2 = 3.67 \]
\[ g_D \Lambda^5 = -12.36 \]
\[ m_{u,d} = 5.5 \text{ [MeV]} \]
\[ m_s = 140.7 \text{ [MeV]} \]
\[ M_{u,d} = 367.6 \text{ [MeV]} \]
\[ M_s = 549.5 \text{ [MeV]} \]
\[ \langle \bar{u}u \rangle^{1/3} = -241.9 \text{ [MeV]} \]
\[ \langle s\bar{s} \rangle^{1/3} = -257.7 \text{ [MeV]} \]
\[ m_{\eta'} = 958 \text{ [MeV]} \]
\[ m_{\eta} = 514 \text{ [MeV]} \]
\[ m_{\pi} = 135 \text{ [MeV]} \]

\[ \Delta m_{\eta'} \sim -150 \text{ MeV} @ \rho_0 \]
\[ \Delta m_{\eta} \sim +20 \text{ MeV} @ \rho_0 \]

Large mass silt at normal nuclear density
η- & η’-Nucleus optical potential

Real Part $V_0$

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

$$m^2_{\eta'} \rightarrow m^2_{\eta'}(\rho) = (m_{\eta'} + \Delta m_{\eta'}(\rho))^2 \sim m^2_0 + 2m_0 \Delta m(\rho)$$

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

Possible density dependence of $g_D(\rho)$

$g_D$: constant

$V_\eta$, $V_{\eta'}$: attractive

G.W. Carter, D. Diakonov, NPA642(98) c78;
PRD60(99)016004.
H. Kiuchi, M. Oka, PTP114, 813, (2005)
Momentum transfer

\[(\gamma, p)\) reactions

SPring-8 energy

(d, \(^3\)He) reaction

\eta'

\[q [\text{MeV}]

\[T_i [\text{GeV}]

BE=0
BE=50 \text{ MeV}
BE=100 \text{ MeV}
BE=150 \text{ MeV}
Numerical Results: $^{12}\text{C}(\gamma,p)^{11}\text{B}_{\eta'}$

- $V_0 = 0$
  - $W_0 = -5\text{ MeV}$

- $V_0 = -100\text{ MeV}$
  - $W_0 = -5\text{ MeV}$

- $V_0 = 0$
  - $W_0 = -20\text{ MeV}$

- $V_0 = -100\text{ MeV}$
  - $W_0 = -20\text{ MeV}$
Numerical results: $^{12}\text{C}(\gamma,p)^{11}\text{B}_{\eta,\omega,\eta'}$

- $g_D = -12.36/\Lambda^5$

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

- [Klingl, Waas, Weise NPA650(99)299]
Study of possible $\omega$ bound states in nuclei with the $(\gamma, p)$ reaction

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Momentum transfer at 0 deg. and 10 deg.

Figure 1: Momentum transfers are shown as a function of the incident photon energy $E_{\gamma}$ in the $(\gamma,p)$ reaction. The solid, dashed and dotted lines show the momentum transfers at $\omega$ energy $E_{\omega} = m_\omega$, $E_{\omega} = m_\omega - 50$ MeV and $E_{\omega} = m_\omega - 100$ MeV, respectively. The thick lines indicate the forward reaction cases and the thin lines the cases for the ejected proton in the final state with the finite angle $\theta_p^{\text{Lab}} = 10.5 \text{ degree}$. The vertical dashed lines show the incident energies $E_{\gamma} = 1.2 \text{ GeV}$ and $2.0 \text{ GeV}$. 
E=2.0 GeV, 0 deg & 10 deg, 3 potentials

\((V_0, W_0) = -(0, 50)\) MeV

\((V_0, W_0) = -(100, 50)\) MeV

\((V_0, W_0) = -(156, 29)\) MeV

Figure 2: Formation spectra of the \(\omega\) mesic nucleus in \(^{12}\text{C}(\gamma, p)\) reaction at emitted proton angle (a) \(\theta_p^{\text{Lab}} = 0\) degree and (b) \(\theta_p^{\text{Lab}} = 10.5\) degree calculated with the potential depth \((V_0, W_0) = -(156, 29)\) MeV as in Eq. (2e). The incident photon energy is \(E_\gamma = 2.0\) GeV. The thick solid lines show the total spectra and the dashed lines the subcomponents as indicated in the figures. The assumed experimental resolutions are also indicated in the figures.
Fusion spectra of the \( \omega \) mesic nucleus in \( {}^{13}\text{C}(\gamma,p) \) reaction at emitted proton angle (a) \( \theta^\text{lab}_p = 0 \) degrees and (b) \( \theta^\text{lab}_p = 10.5 \) degrees calculated with the potential depth \((V_0,W_0) = -(156,29)\) MeV as in Eq. (2c). The incident photon energy is \( E_\gamma = 1.2\) GeV. The thick solid lines show the total spectra and the dashed lines the subcomponents as indicated in the figures. The assumed experimental resolutions are also indicated in the figures.
Production of $\Theta^+$ hypernuclei with the $(K^+, \pi^+)$ reaction

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Fig. 2. Calculated Θ bound states formation cross section shown as a function of the emitted pion energy $\omega_p$ at forward angles for a $^{12}$C target. The incident kaon kinetic energy, $T_K$, is 300 MeV, and the shallow Θ nuclear potential $V(r) = -60 \rho(r)/\rho_\Theta$ MeV is used. The total spectrum is shown by the thick-solid line and the dominant subcomponents are also shown by the thin lines as indicated in the figures. The Θ production threshold leaving the residual nucleus in its ground state is shown by the vertical line.

Fig. 3. Calculated Θ bound states formation cross section shown as a function of the emitted pion energy $\omega_p$ at forward angles for a $^{12}$C target. The incident kaon kinetic energy, $T_K$, is 300 MeV, and the deep Θ nuclear potential $V(r) = -120 \rho(r)/\rho_\Theta$ MeV is used. The total spectrum is shown by the thick-solid line and the dominant subcomponents are also shown by the thin lines as indicated in the figure. The Θ production threshold leaving the residual nucleus in its ground state is shown by the vertical line.
4. Summary

Mesic Atoms and Mesic Nuclei

= Nucleus as Finite Density Laboratory
= Exotic Nuclei with Meson impurities

We are interested in …

= how to connect to the fundamental theory
= how to get reliable experimental information

Several Attempts: Not satisfactory in both sense!!

(gamma,p) reaction is interesting