Mesic Nuclei Formation by (γ,p) reactions

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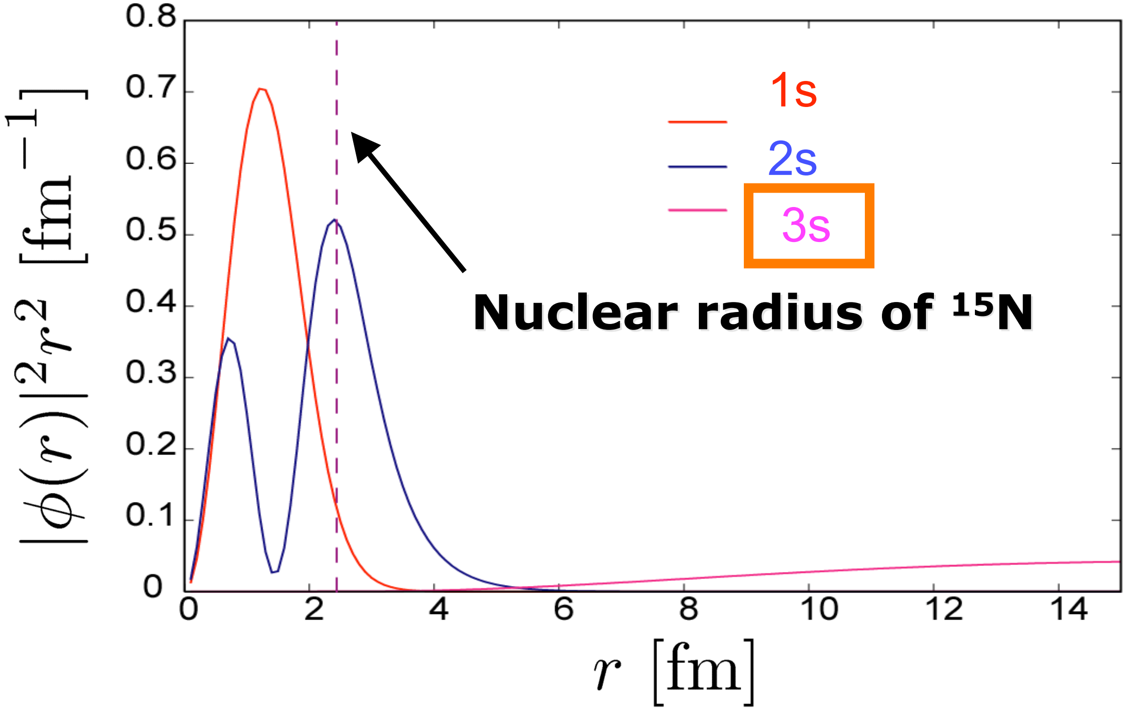
LEPS2 workshop@RCNP, Jan. 2007

- 1. Introduction and Motivation
- 2. Missing Mass Spectroscopy (ex. π atoms)
- 3. Recent Topics
  (η, ω, η')
- 4. Summary

1. Introduction and Motivation

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



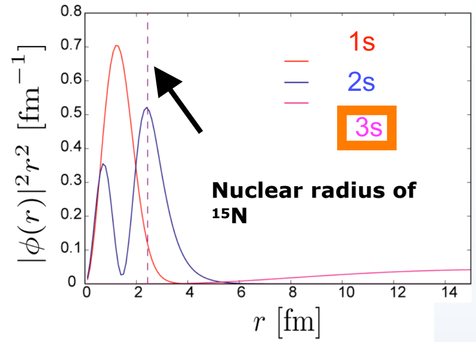
Kaonic Atoms

And

Kaonic Nuclei

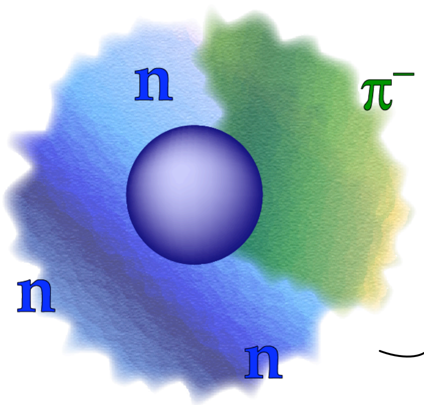
By J. Yamagata

1. Introduction and Motivation



- 1. Exotic Many Body Physics

Ex.)

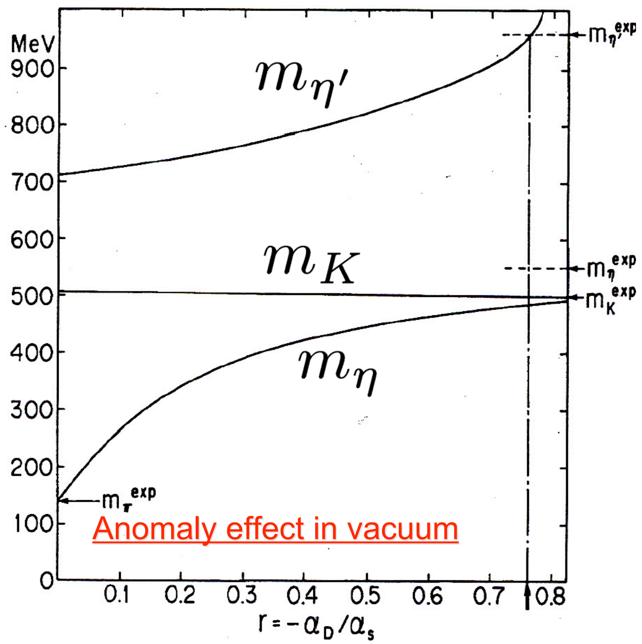


Pionic Atoms in halo nuclei
Co-existence of Pion-Neutron-halo

- 2. Hadron Physics at finite density

Fundamental theory (QCD)
(↔ Effective theory)
↔ Hadron property at finite ρ
↔ Infinite System ⇔ Finite System
↔ Mesic Atoms and Mesic Nuclei

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



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

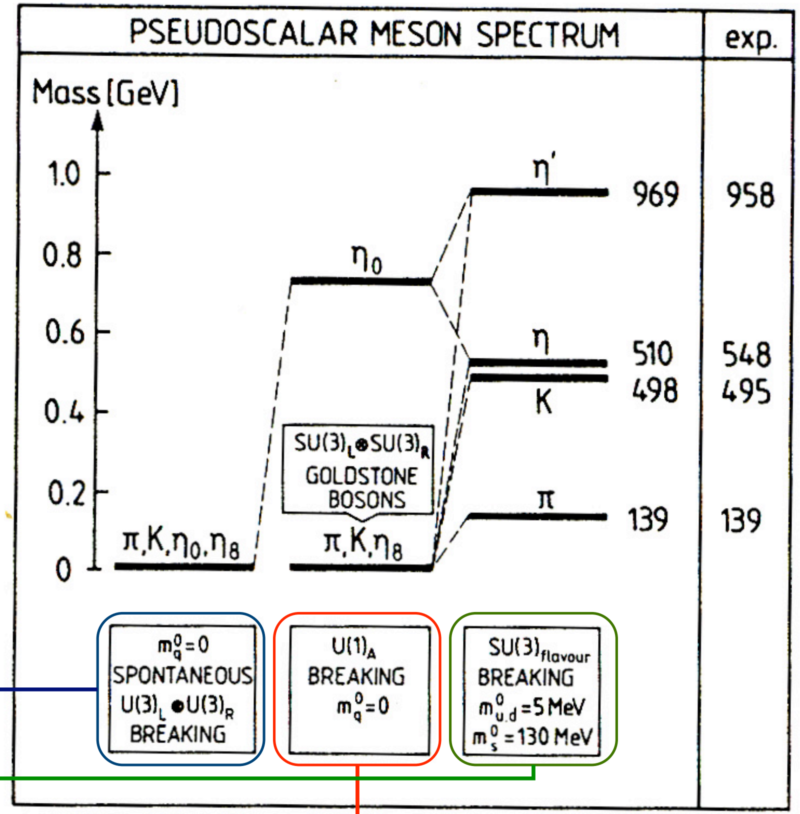
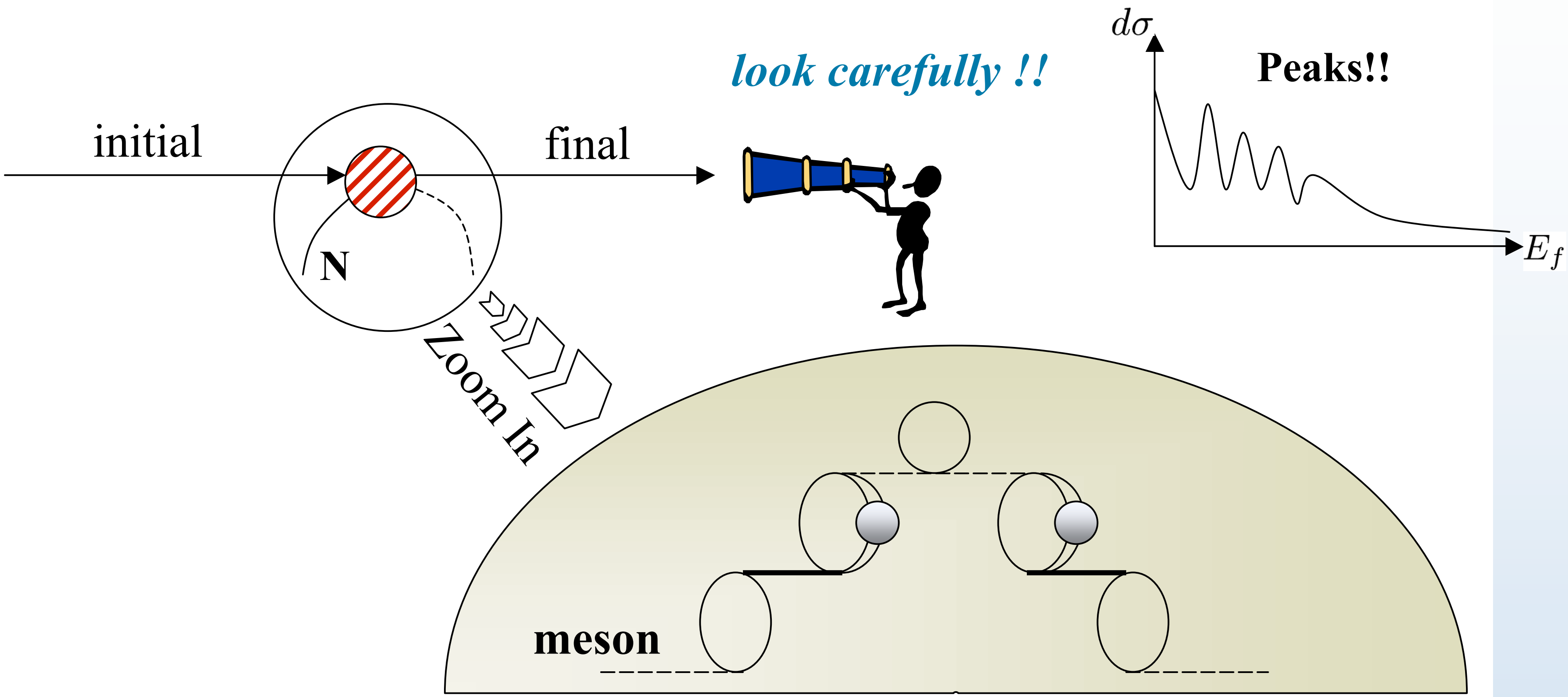


Fig. 10. *Pseudoscalar meson spectrum from the NJL model (Klimt et al. 1990), showing the chiral and flavour symmetry breaking pattern. Calculated and experimental masses are given in MeV.*

- Higgs mechanism
- Spontaneous Chiral Symmetry Breaking
- $U_A(1)$ Anomaly Effect

2. Missing Mass Spectroscopy

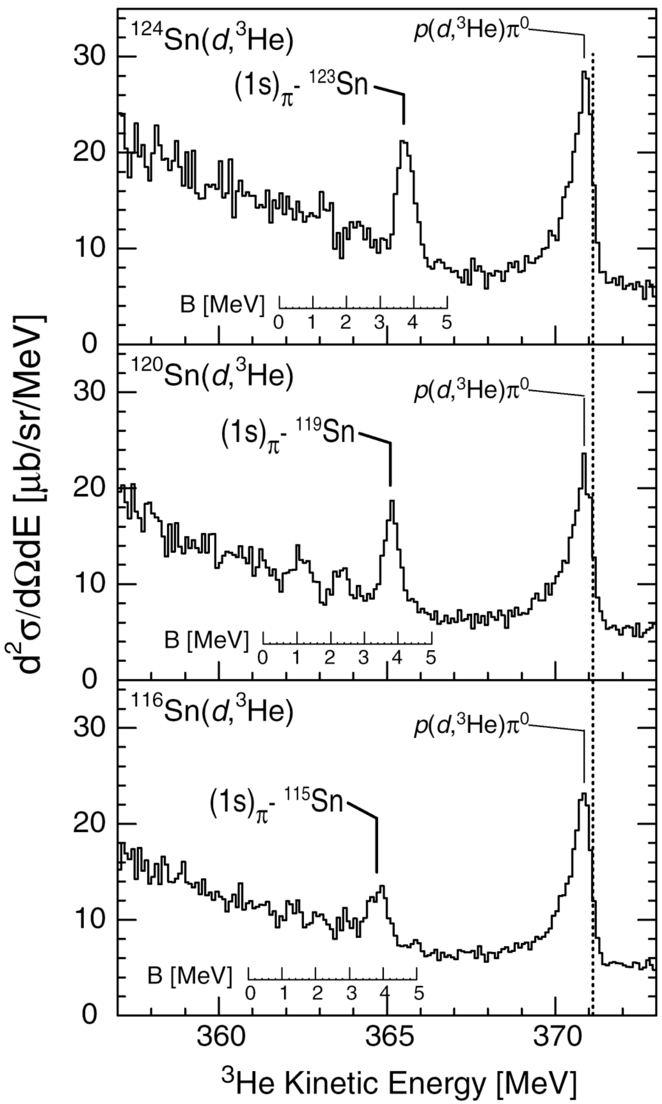


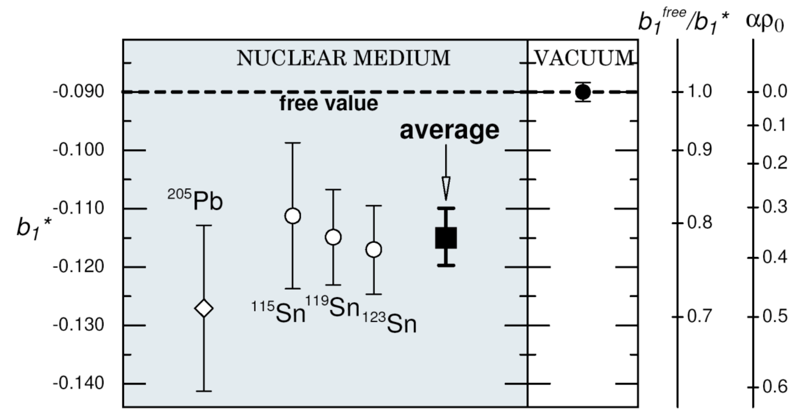
In-Medium Dispersion Relation

Medium Effects

$$[-\nabla^2 + m^2 + \Pi(\rho(r), \omega)]\phi = \omega^2 \phi$$

Deeply Bound Pionic Atom by (d,^{3}He)





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

K. Suzuki *et al.* Phys. Rev. Lett. 92(2004) 072302

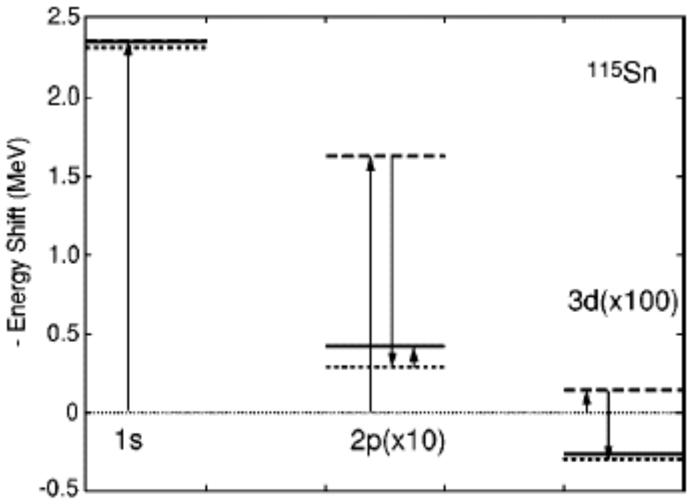
GOR relation + Tomozawa-Weinberg Relation

$$\frac{\langle \bar{q}q \rangle_\rho}{\langle \bar{q}q \rangle_0} \simeq \frac{f_\pi^{*2}}{f_\pi^{\ 2}} \simeq \frac{b_1^{\mathrm{free}}}{b_1^*(\rho)} = 0.78 \pm 0.05 \ @ \ \rho \simeq 0.6\rho_0$$

$$\sim 0.64 \ @ \ \rho = \rho_0$$

- Information on Π at finite $\rho \sim \rho_0$, (T~0)

- Eigen state observation ⟺ Invariant Mass Method
- Quantum number fixed ⟹ Selective information



Umemoto et al., PRC62 (2000)

FIG. 1. The binding energies with finite-size Coulomb potential only B_{Coul} and Coulomb plus optical potential B_{full}, are calculated. The energy shifts B_{Coul}-B_{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.

Ericson-Ericson, Ann. Phys. **36** (66) 323
Seki-Masutani, Phys. Rev. **C27**(83)2799

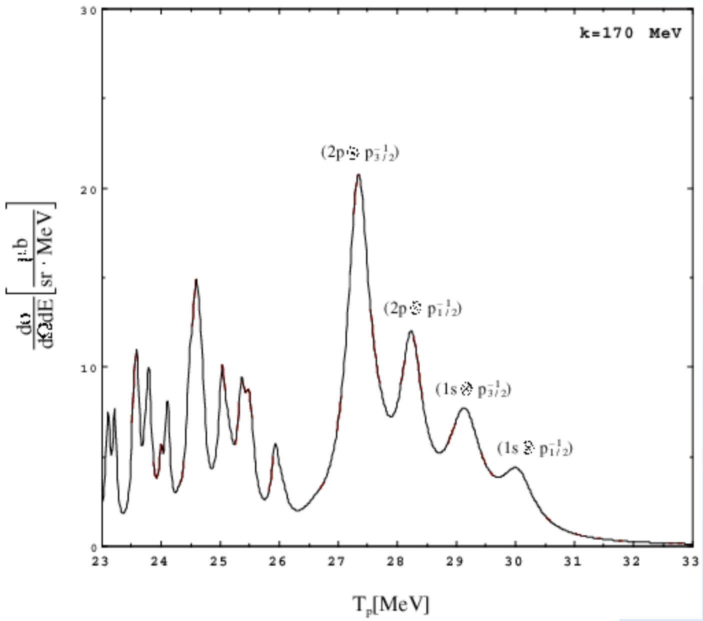
$$\Pi = 2\mu V_{\mathrm{opt}}$$
$$= -4\pi[b(r) + \varepsilon_2 B_0 \rho^2(r)] + 4\pi\nabla\cdot[c(r) + \varepsilon_2^{-1} C_0 \rho^2(r)]L(r)\nabla$$

with
$$b(r) = \varepsilon_1\{b_0\rho(r) + b_1[\rho_n(r) - \rho_p(r)]\}$$
$$c(r) = \varepsilon_1^{-1}\{c_0\rho(r) + c_1[\rho_n(r) - \rho_p(r)]\}$$
$$L(r) = \{1 + \tfrac{4}{3}\pi\lambda[c(r) + \varepsilon_2^{-1} C_0 \rho^2(r)]\}^{-1}$$

A(γ, N) reaction

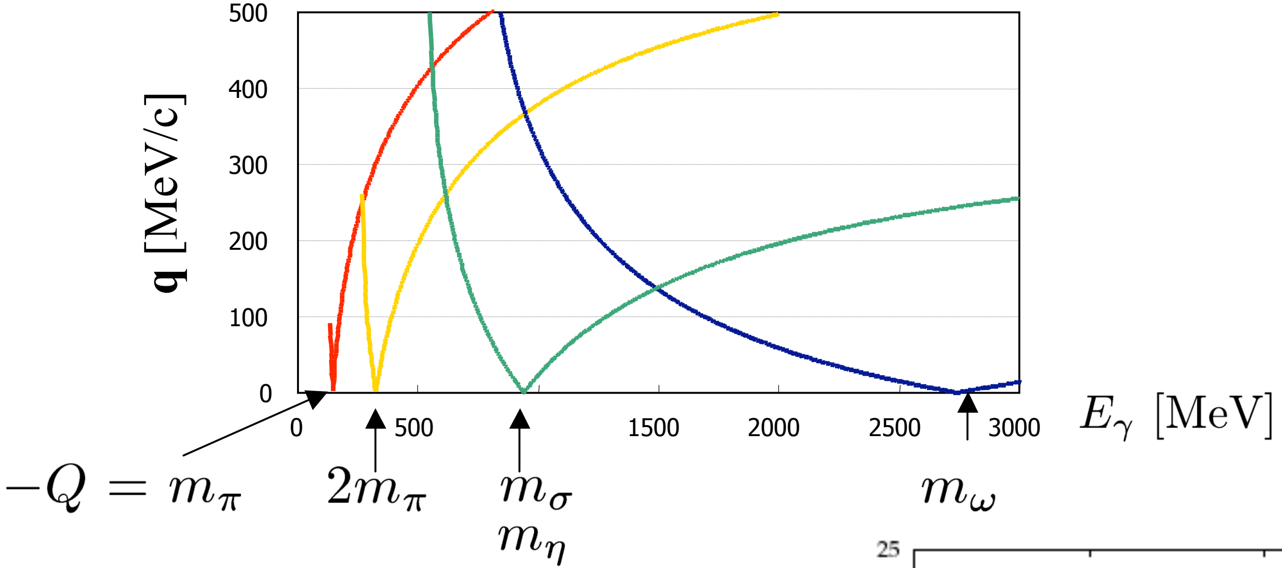
- Mesic-Atom ... It's another Method.
  S. Hirenzaki, E. Oset

  Phys. Lett. **B527**(2002)69



- Mesic-Nuclei ... It has an Advantage
  ⟹ TRANSPARENCY cf. (d, ^{3}He)
  - $t \sim \int \chi_f^* \phi_M^* \psi_N \chi_i d^3 r$
  - Substitutional vs. Quasi-Substitutional at recoilless kinematics.
  - Deep Mesic State needs Deep Nuclear State !

Kinematics (γ, N) forward

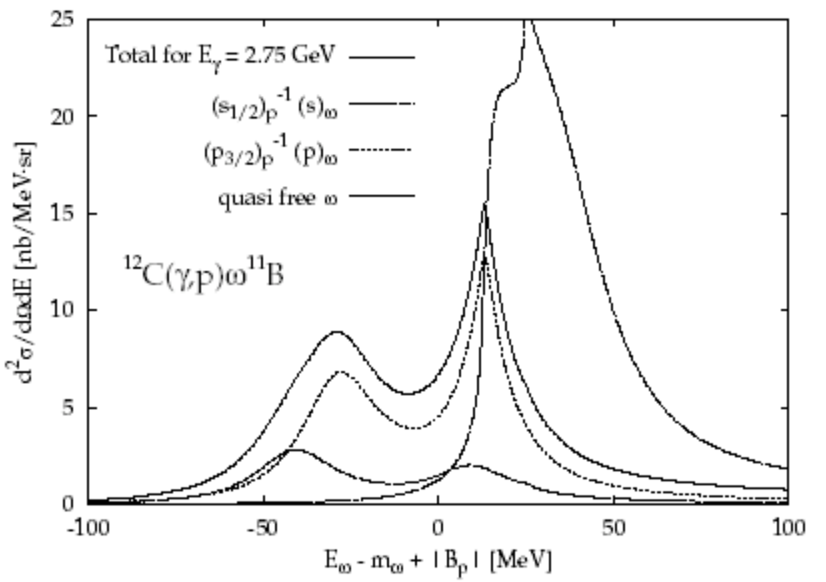


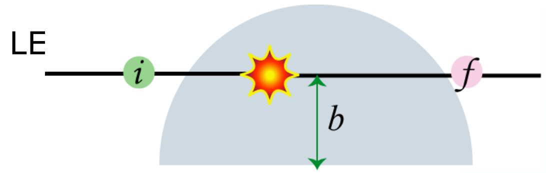
ω mesic Nuclei by (γ, p)

E. Marco, W. Weise

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

Phys. Lett. B502 (2001) 59





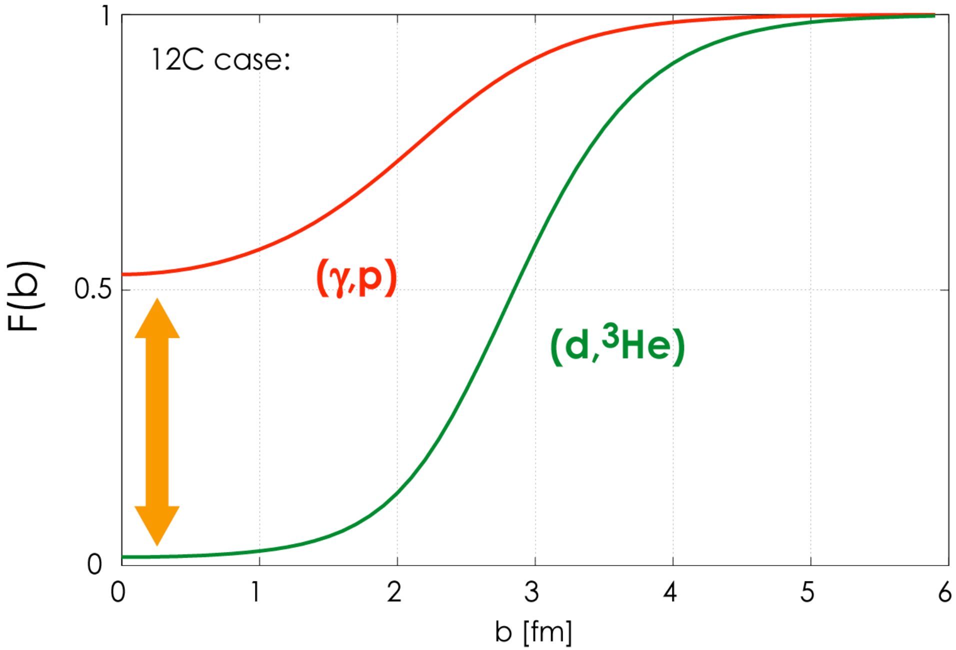
Distortion factor

[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 the absorption

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



(γ,p) case:

more sensitive to the Center of the nucleus.

3-1. η – Nucleus system : Nature of Baryon Resonance

H. Nagahiro and D. Jido

eta-mesic nuclei

» (π^+, p)
* Liu, Haider, PRC34(1986)1845
* Chiang, Oset, and Liu, PRC44(1988)738
•Chrien *et al.*, PRL60(1988)2595

» **(d,^{3}He)**
• Kohno, Tanabe, Phys.Lett.B231:219-223,1989.
* Hayano, Hirenzaki, Gilltzer, Eur.Phys.J.A6(1999)99
* D. Jido, H.Nagahiro, S.Hirenzaki PRC66(2002)045202

properties of eta meson

η meson

» $m_\eta = 547.3$ [MeV] » $\mathrm{I} = 0,\ \mathrm{J^P} = 0^-$

» $\Gamma = 1.18$ [keV] $(2\gamma,\ 3\pi^0,\ \pi^+\pi^-\pi^0, \cdots)$

η-N system

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

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

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

eta-Nucleus system → **Doorway to N*(1535)**

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, Kunirhiro, PRL84(00)3252

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

Lagrangian

$$\mathcal{L} = \sum_{j=1,2} [\bar{N}_j i \partial\!\!\!/ N_j - g_j \bar{N}_j (\sigma + (-)^{j-1} i\gamma_5 \vec{\tau}\cdot\vec{\pi}) N_k] - m_0(\bar{N}_1\gamma_5 N_2 - \bar{N}_2\gamma_5 N_1)$$

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**

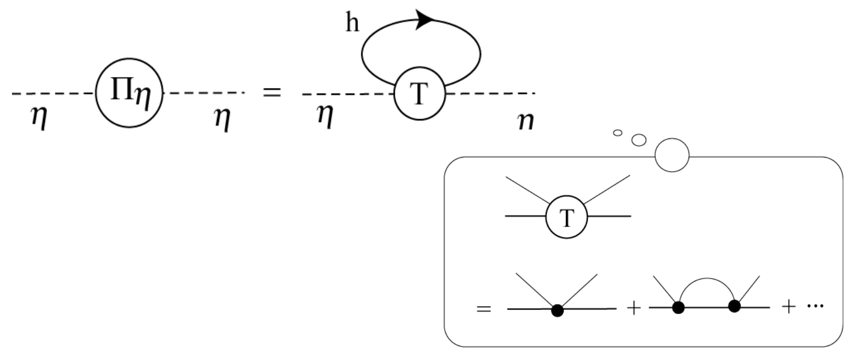
Chiral unitary model

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.

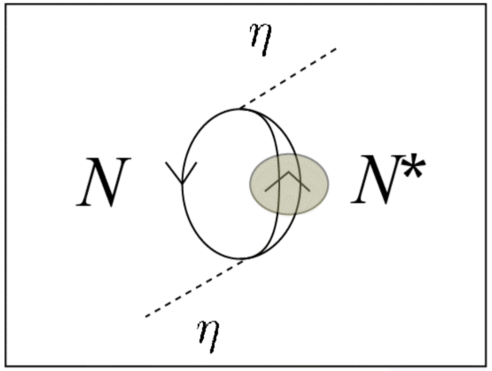
$$\{\pi^- p, \pi^0 n, \eta n, K^0\Lambda, K^+\Sigma^-, K^0\Sigma^0, \pi^0\pi^- p, \pi^+\pi^- n\}$$



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

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

η-nucleus interaction ~ N* dominance

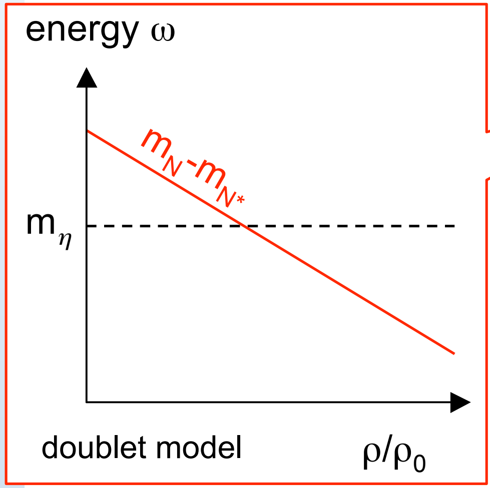


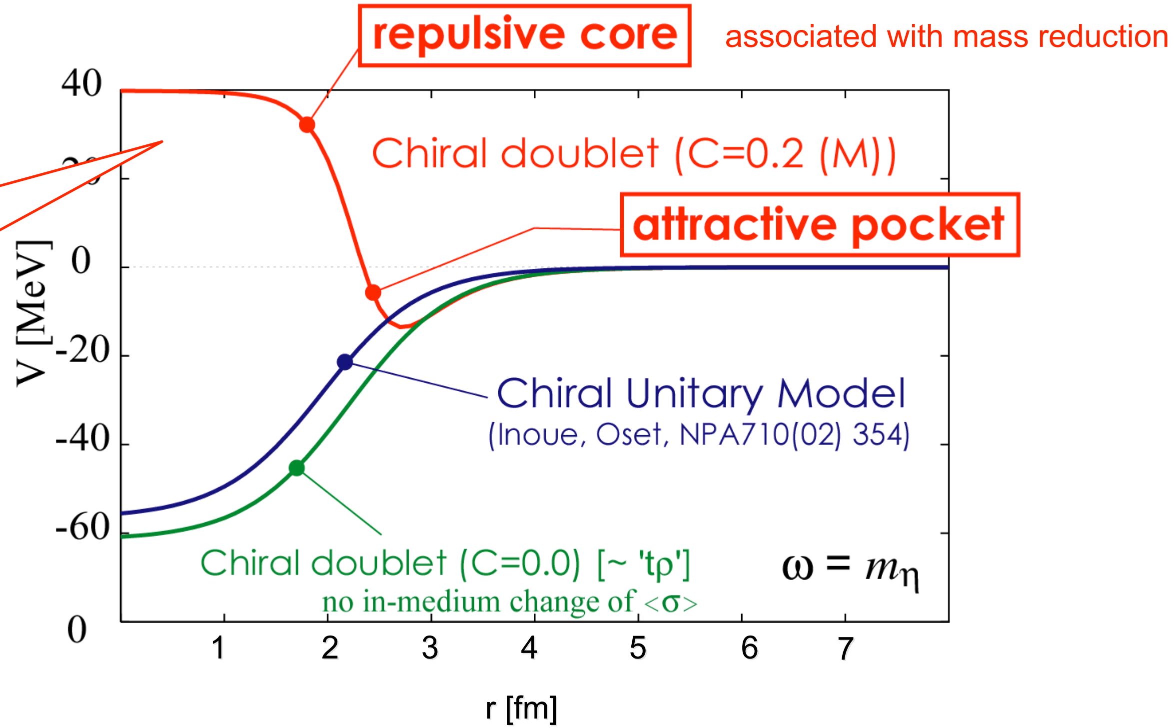
optical potential

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

(Chiang, Oset, Liu PRC44(1991)738)
(D.Jido, H.N., S.Hirenzaki, PRC66(2002)045202)

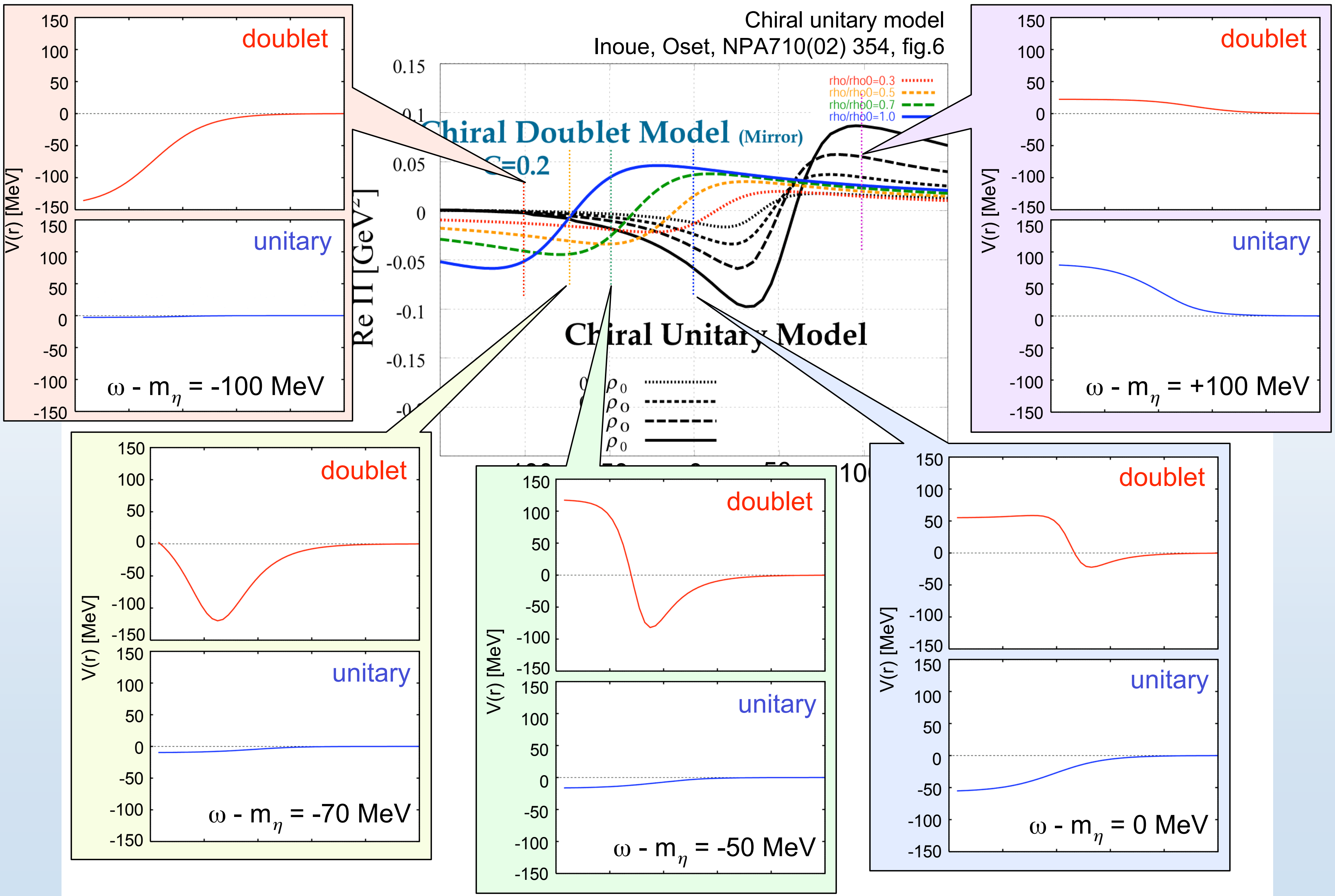
$g_\eta \simeq 2.0$ to reproduce the partial width $\Gamma_{N^* \to \eta N} \simeq 75\ \mathrm{MeV}$ at tree level.





η-nucleus optical potential → sensitive to the in-medium properties of N and N*

Energy dependence of the optical potentials



Spectra of ^{12}C target

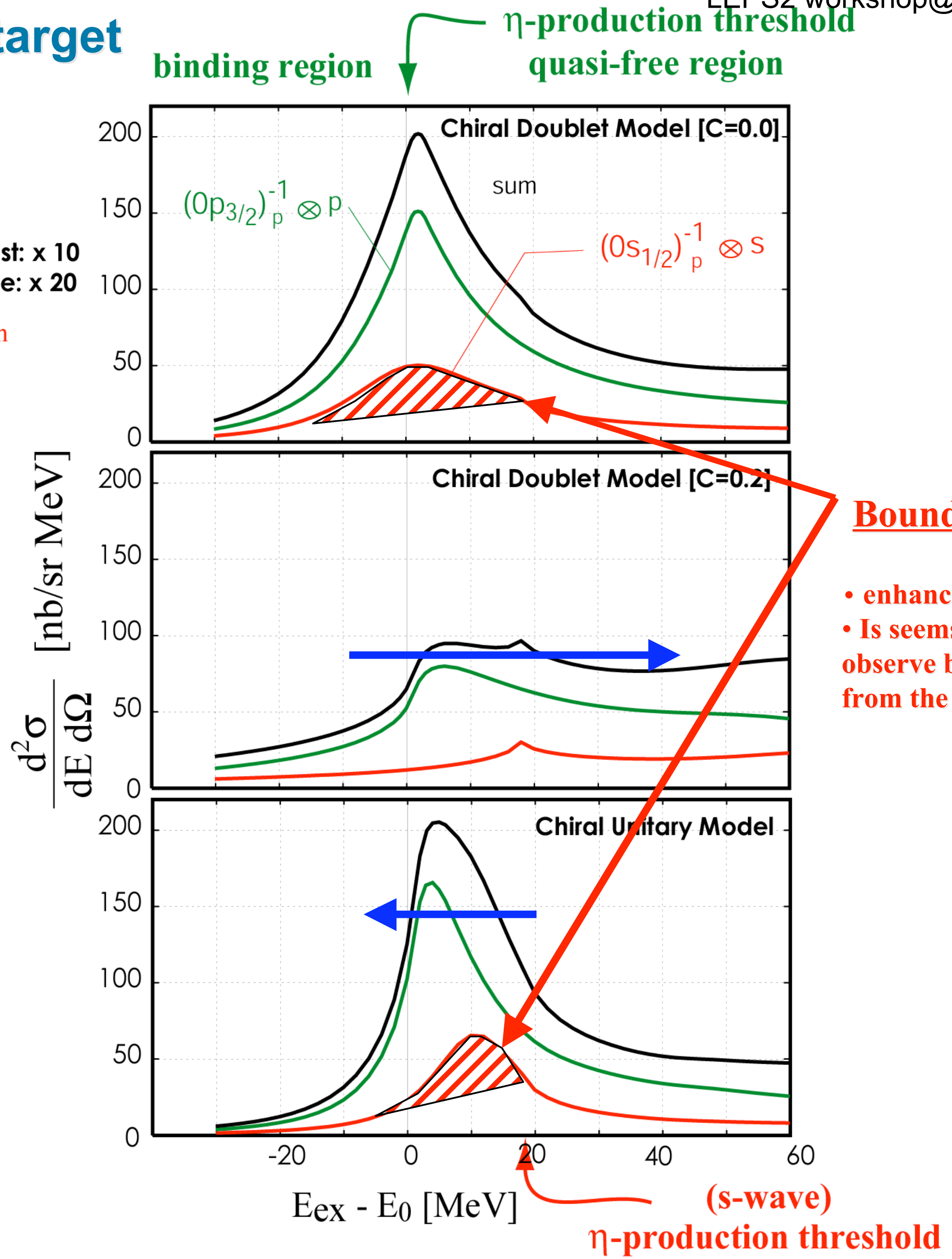
T_d = 3.5 [GeV]
E_γ = 950 [MeV]

recoilless condition for the eta production

*dist: x 10
*ele: x 20

(γ,p)

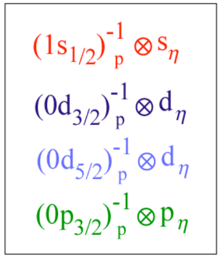
We can see the difference between two models more clearly.



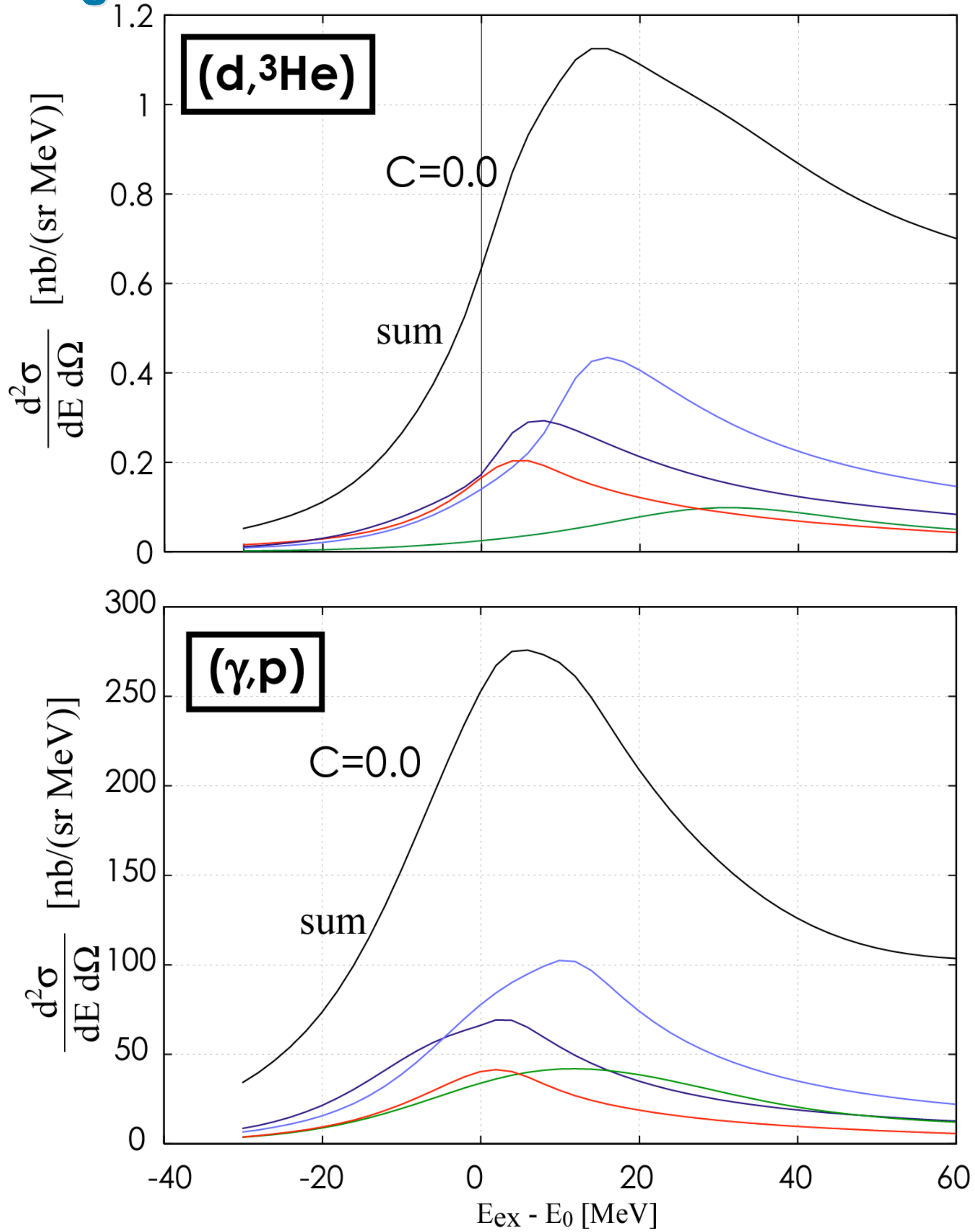
Bound state

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

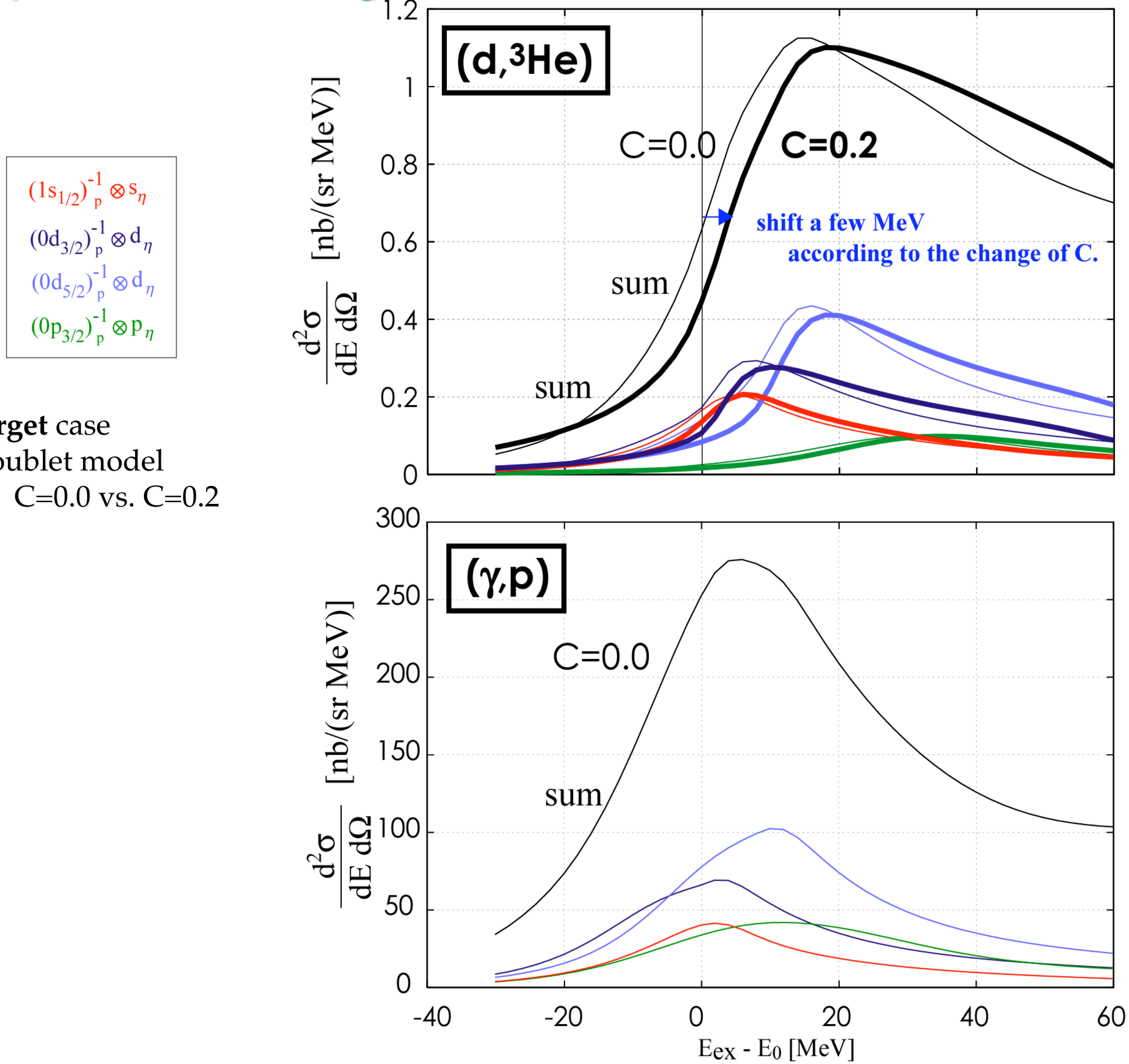
Spectra of ^{40}Ca target



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

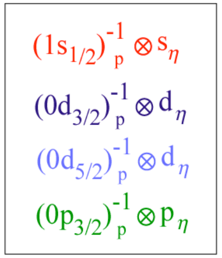


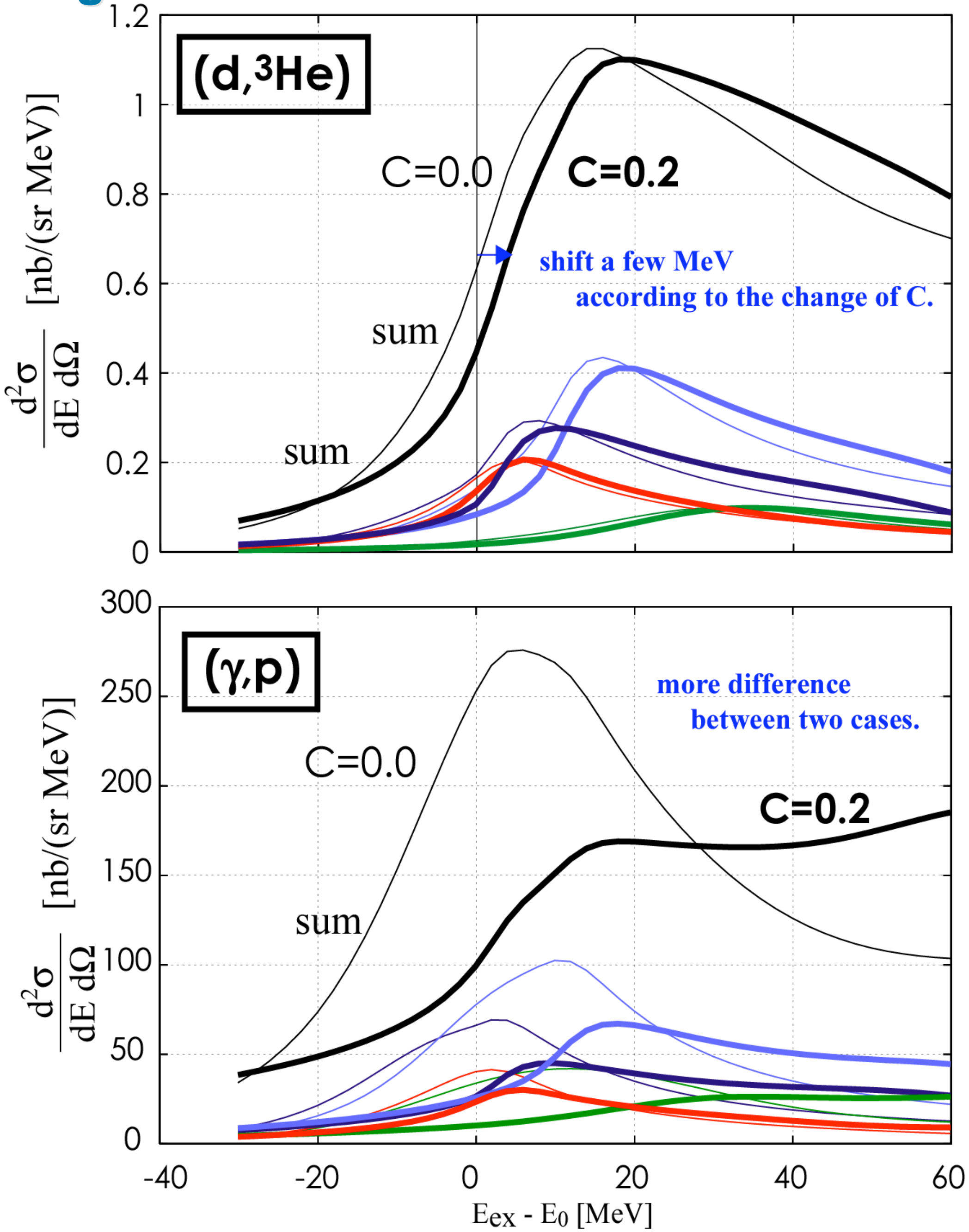
Spectra of ^{40}Ca target



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

Spectra of ^{40}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 and N* *!!*

3-2. η and η'(958) mesic nuclei with NJL model

- quark picture of mesons -

H. Nagahiro,S.Hirenzaki, PRL(2005)
H. Nagahiro, M. Takizawa, S. Hirenzaki, PRC(2006)

- η'(958) meson …close connections with $U_A(1)$ anomaly
  - some theoretical works
    - the effects of the $U_A(1)$ anomaly on η' 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 η'**
  - a poor experimental information on the $U_A(1)$ anomaly at finite density

Nagahiro and Takizawa

- proposal for the formation reaction of the η'-mesic nuclei

(inspired by discussion with T. Hatsuda)

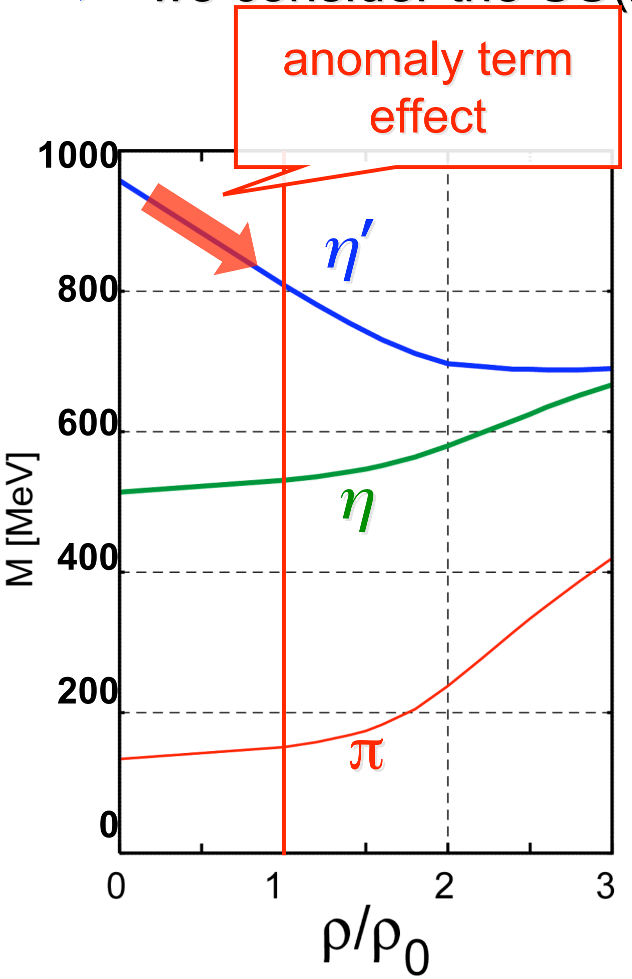
  - discuss the possibility of the η'-nucleus bound states

    (Previous estimation of b.s. by K.Tushima, NPA670(00)198c : But, Γ is fixed to be 0)

  - the η' properties, especially mass shift, at finite density

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)

P. Rehberg, et al., PRC53(96)410.

Λ = 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_η = 514 [MeV]
m_π = 135 [MeV]

η and η' mass shifts @ ρ_0

$\Delta m_{\eta'} \sim -150$ MeV @ ρ_0

$\Delta m_\eta \sim +20$ MeV @ ρ_0

Large mass sift at normal nuclear density

η- & η'-Nucleus optical potential

~ potential description

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

Real Part V_0

- evaluated by possible η, η' mass shift at ρ_0

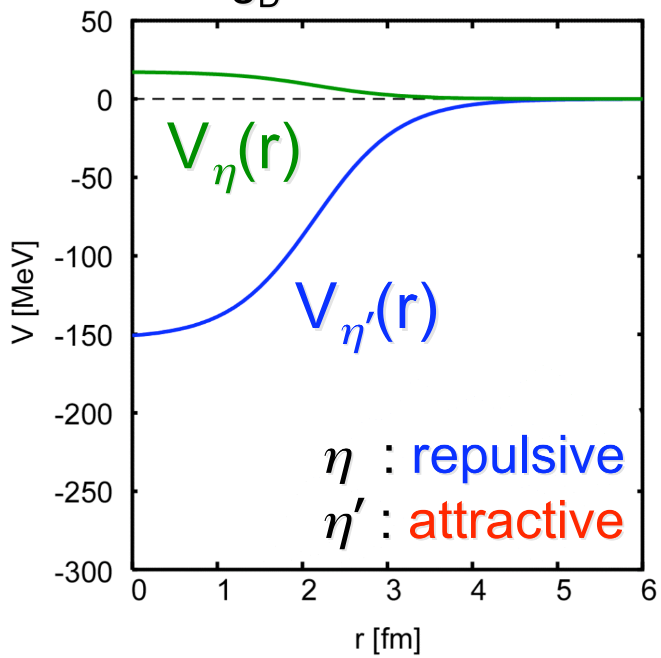
$$m_{\eta'}^2 \to m_{\eta'}^2(\rho) = (m_{\eta'} + \Delta m_{\eta'}(\rho))^2 \quad \sim m_0^2 + 2m_0\Delta m(\rho)$$

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

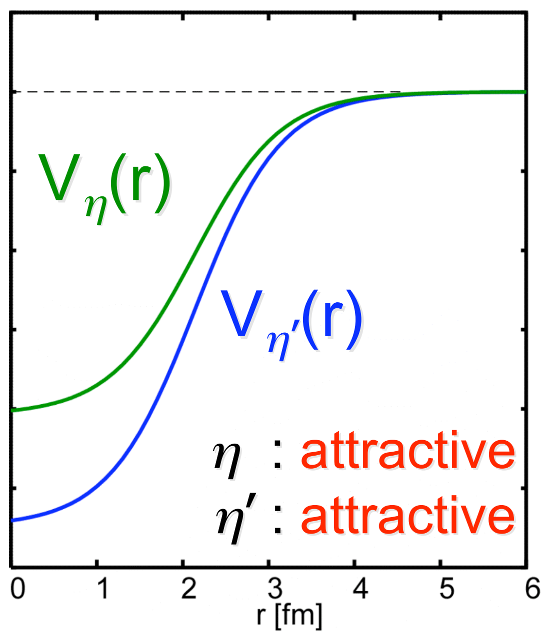
G.W.Carter, D.Diakonov, NPA642(98) c78; PRD60(99)016004.

H. Kiuchi, M. Oka, PTP114, 813, (2005)

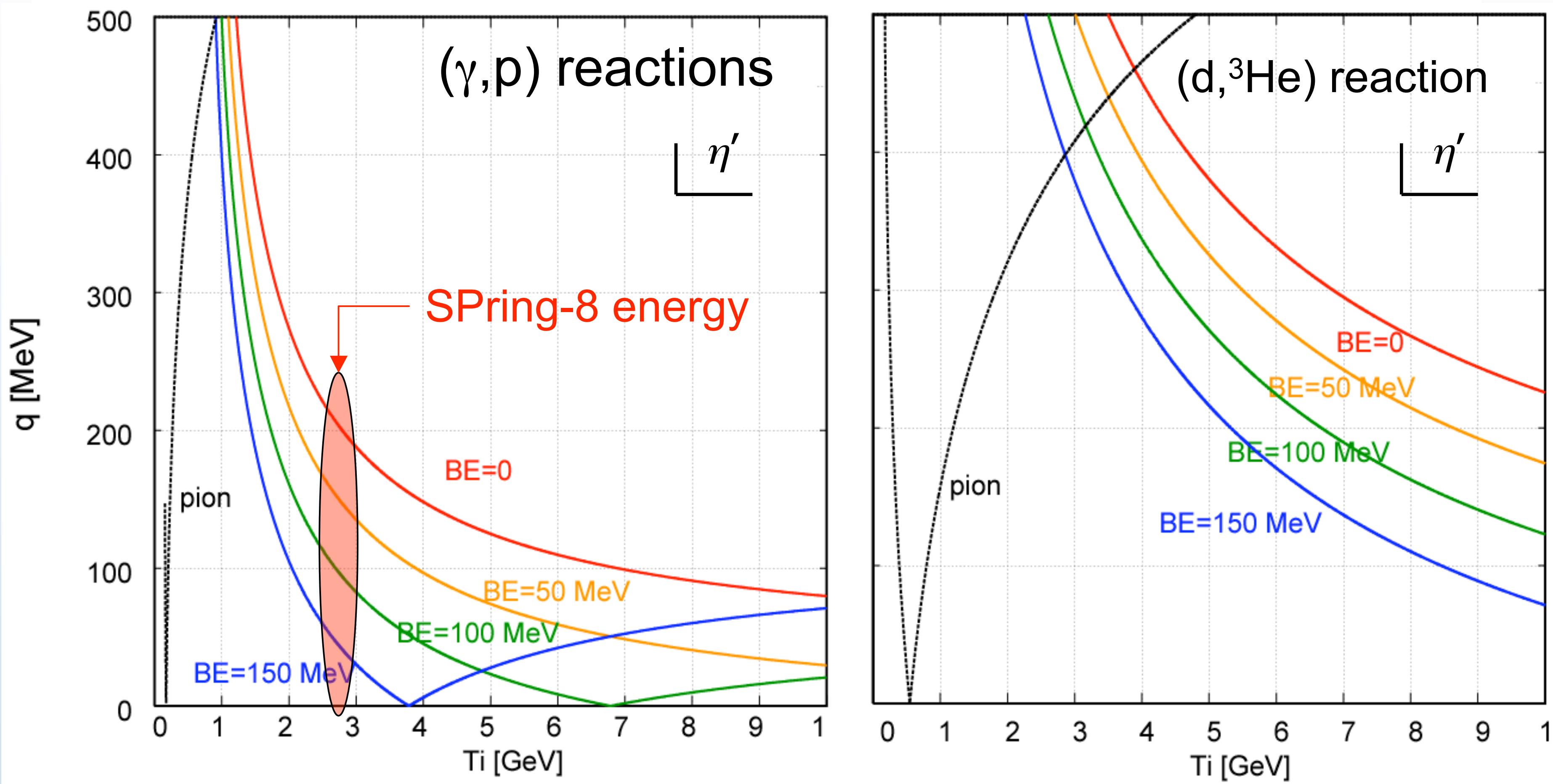
g_D : constant



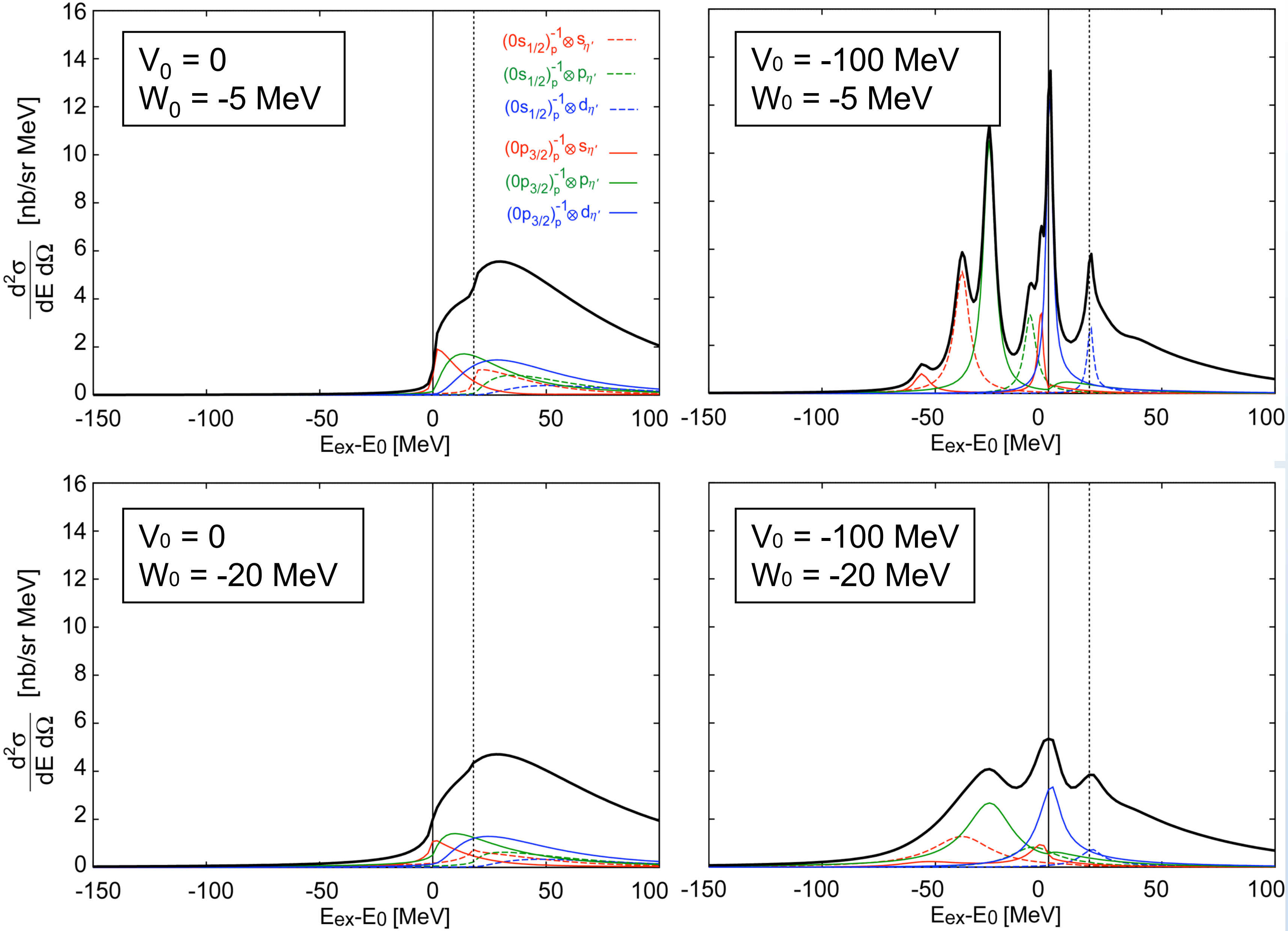
Possible density dependence of $g_D(\rho)$



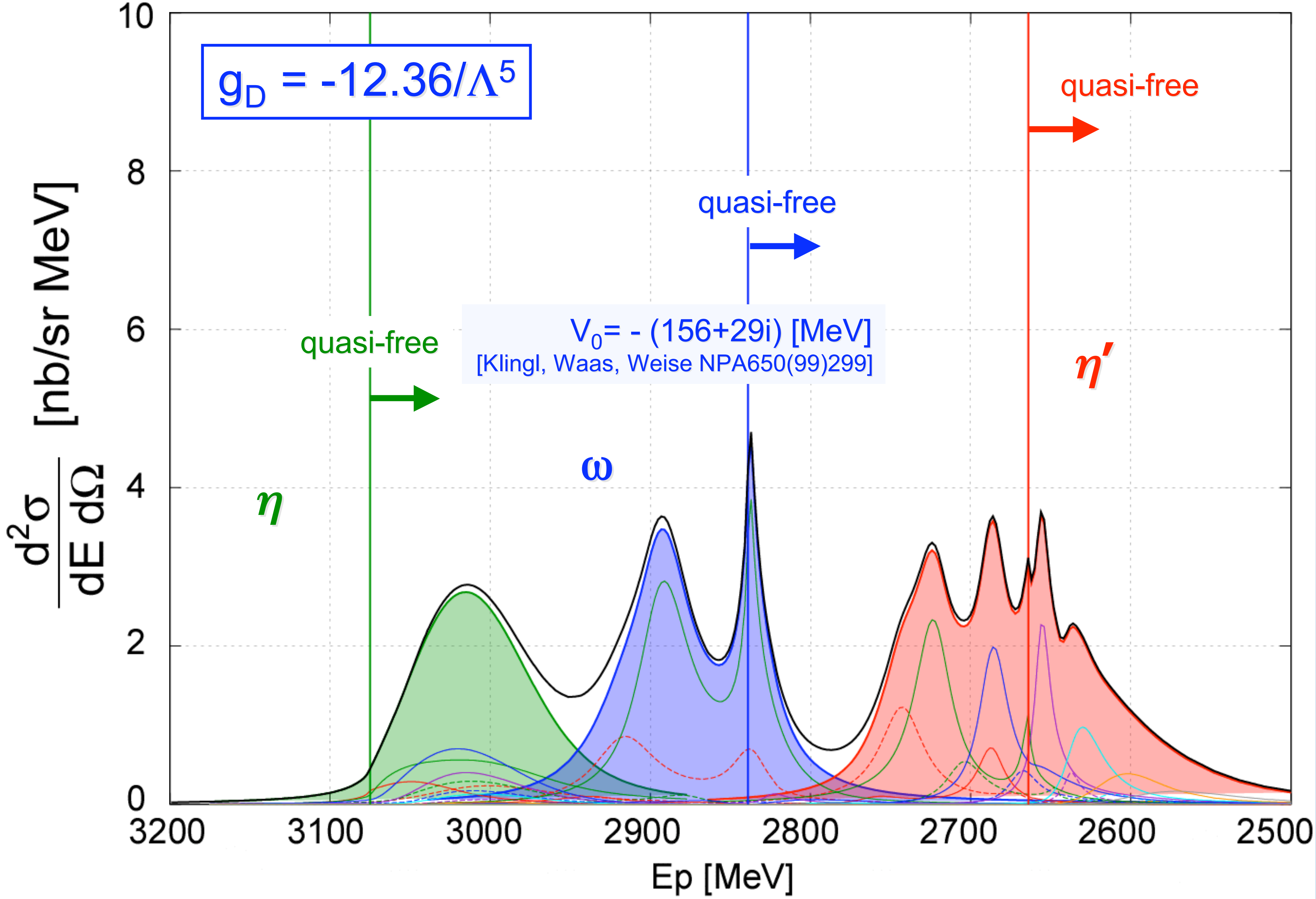
Momentum transfer



Numerical Results : $^{12}C(\gamma,p)^{11}B_{\eta'}$



Numerical results : $^{12}C(\gamma,p)^{11}B_{\eta,\omega,\eta'}$



3-3. Omega Mesic Nuclei

- nucl-th/0610085

Study of possible ω bound states in nuclei with the (γ, p) reaction

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[b]Research Center for Nuclear Physics, Osaka University, Ibaraki, Osaka 567-0047 Japan

[c]Department of Physics, Nara Women's University, Nara 630-8506 Japan

October 21, 2006

- Momentum transfer at 0 deg. and 10 deg.

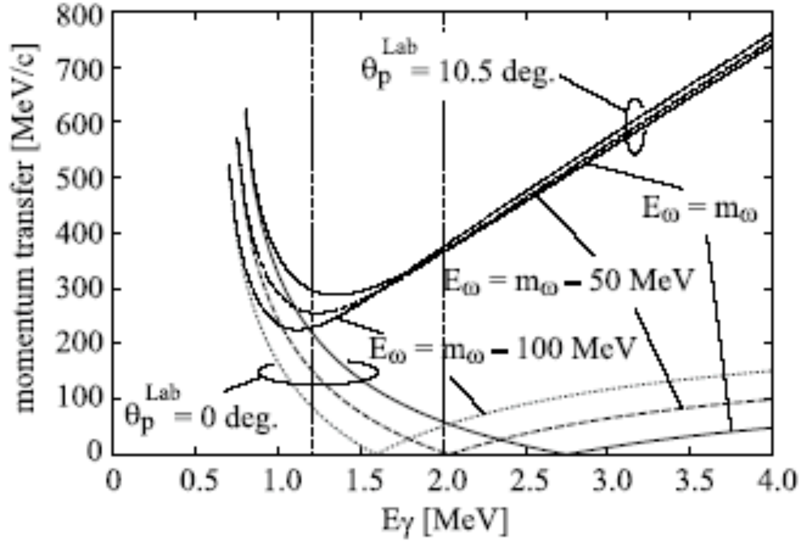

Figure 1: Momentum transfers are shown as a function of the incident photon energy E_γ in the (γ,p) reaction. The solid, dashed and dotted lines show the momentum transfers at ω energy $E_\omega = m_\omega$, $E_\omega = m_\omega - 50$ MeV and $E_\omega = m_\omega - 100$ MeV, respectively. The thick lines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

- E=2.0 GeV、0 deg & 10 deg、3 potentials

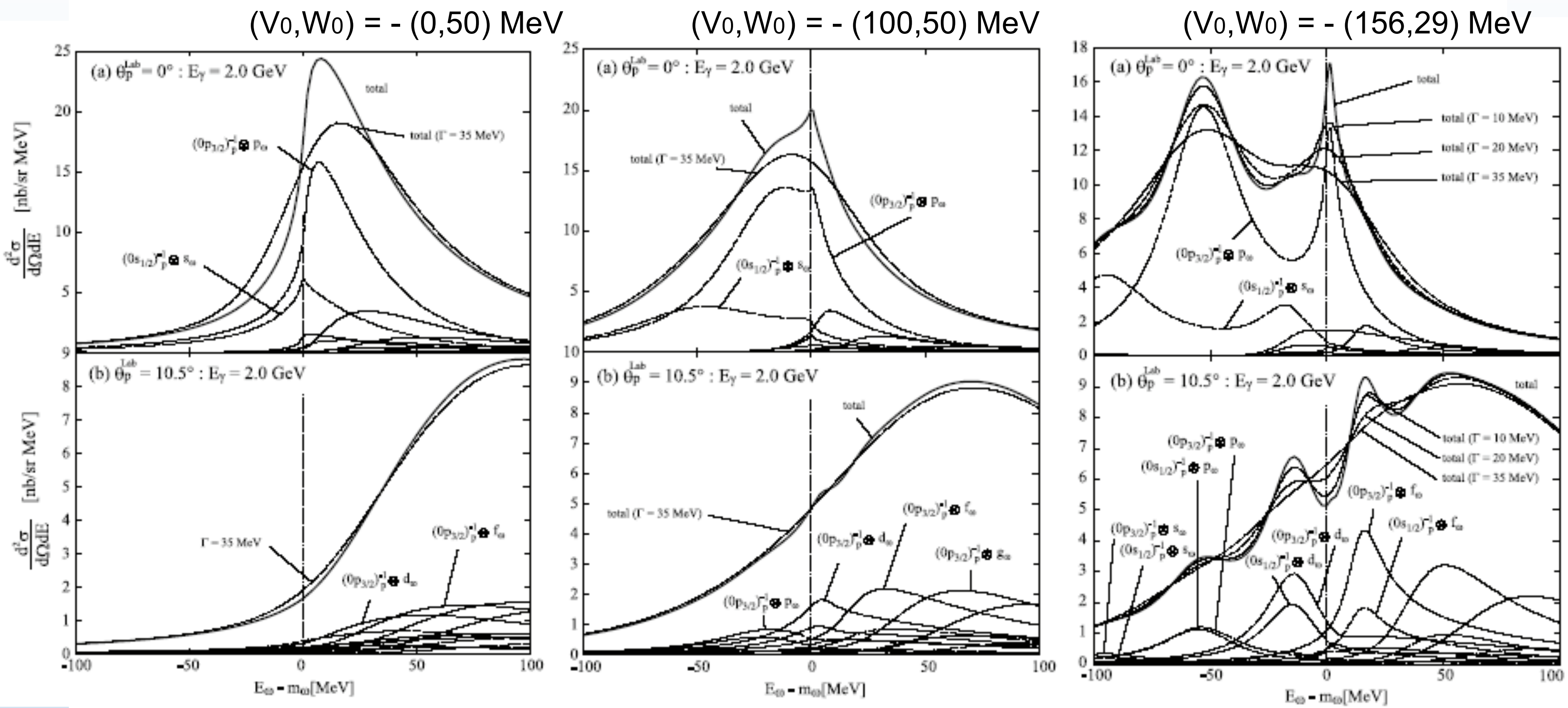

Figure 2: Formation spectra of the ω mesic nucleus in $^{12}C(\gamma,p)$ reaction at emitted proton angle (a) $\theta_p^{\rm Lab} = 0$ degree and (b) $\theta_p^{\rm Lab} = 10.5$ degree calculated with the potential depth $(V_0, W_0) = -(156, 29)$ MeV as in Eq. (2c). The incident photon energy is $E_\gamma = 2.0$ 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.

E=1.2 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

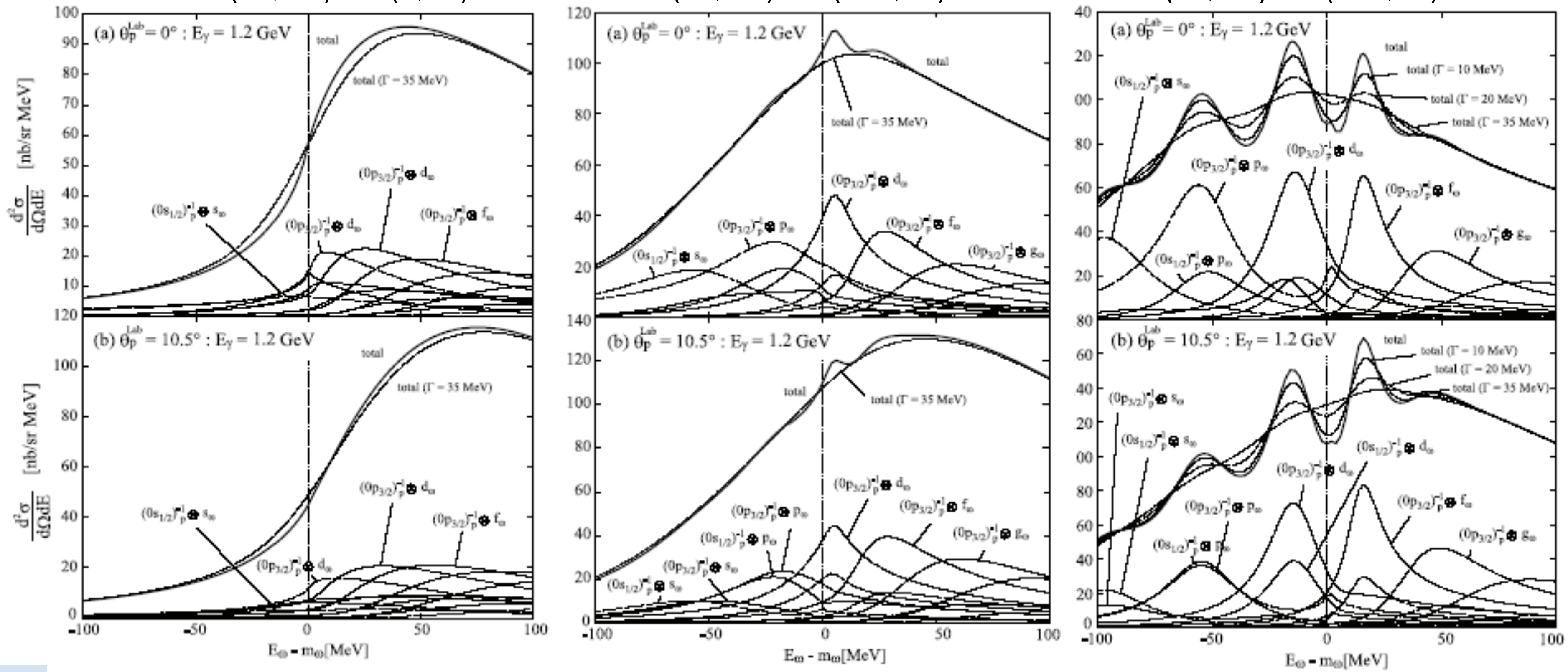

Figure 5: Formation spectra of the ω mesic nucleus in ^{12}C(γ,p) reaction at emitted proton angle (a) $\theta_p^{\rm Lab}$ = 0 degrees and (b) $\theta_p^{\rm Lab}$ = 10.5 degrees calculated with the potential depth $(V_0, W_0) = -(156, 29)$ MeV as in Eq. (2c). The incident photon energy is E_γ = 1.2 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.

(3.4 Penta hypernuclei formation)

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Production of Θ^+ hypernuclei with the (K^+, π^+) reaction

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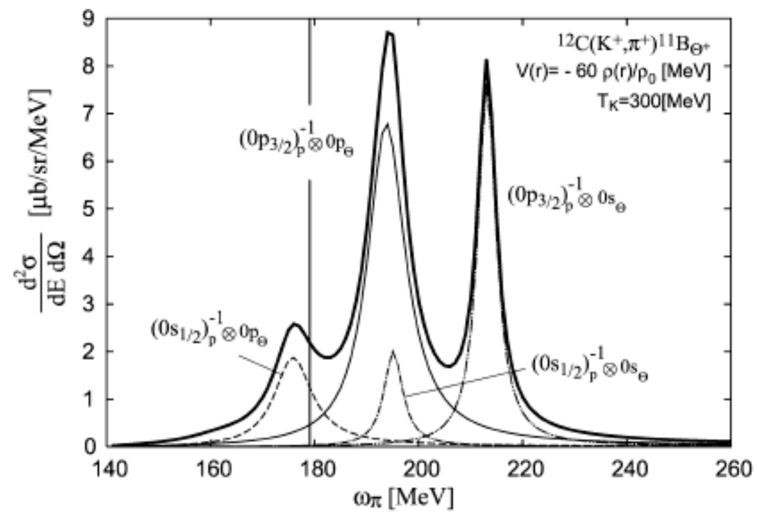

Fig. 2. Calculated Θ bound states formation cross section shown as a function of the emitted pion energy ω_π at forward angles for a ^{12}C target. The incident kaon kinetic energy, T_K, is 300 MeV, and the shallow Θ nuclear potential $V(r) = -60\rho(r)/\rho_0$ MeV is used. The total spectrum is shown 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.

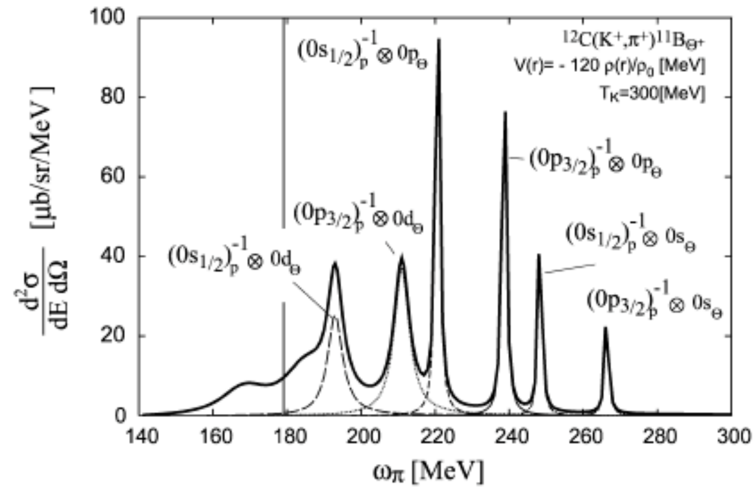

Fig. 3. Calculated Θ bound states formation cross section shown as a function of the emitted pion energy ω_π at forward angles for a ^{12}C target. The incident kaon kinetic energy, T_K, is 300 MeV, and the deep Θ nuclear potential $V(r) = -120\rho(r)/\rho_0$ MeV is used. The total spectrum is shown 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