原子核中の中間子の性質と
中間子原子、中間子原子核

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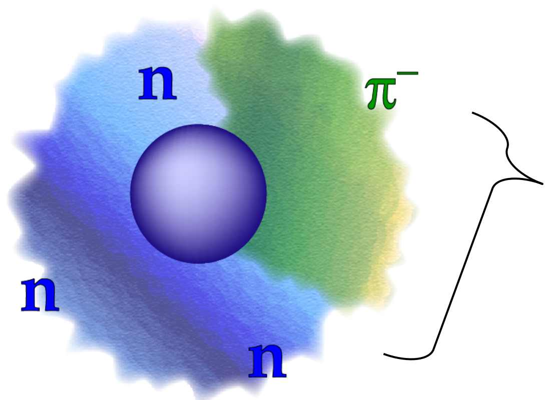
エキゾチック原子核実践講座 Aug.09@理研

1. Introduction and Motivation
今何がおもしろい？・・・J-PARC(永江さん)

- 1. Exotic Many Body Physics
- 理研での不安定核研究
  （Neutron Rich , Proton Rich,元素合成）
- Strangeness を含む3次元核図表
  （⇒田村さん）

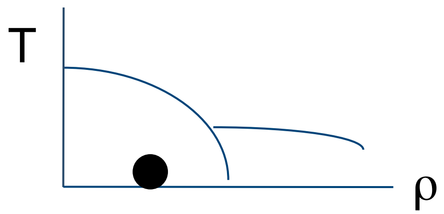
Ex.)



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

➢ 2. Hadron Physics at finite density

- High T, High ρ ,QGP ･･････ Heavy Ion Collision(RHIC)
- Low T, $\rho \sim \rho_0$, ･･････ Hadron in Nucleus



Fundamental theory (QCD)

⟷ Effective theory

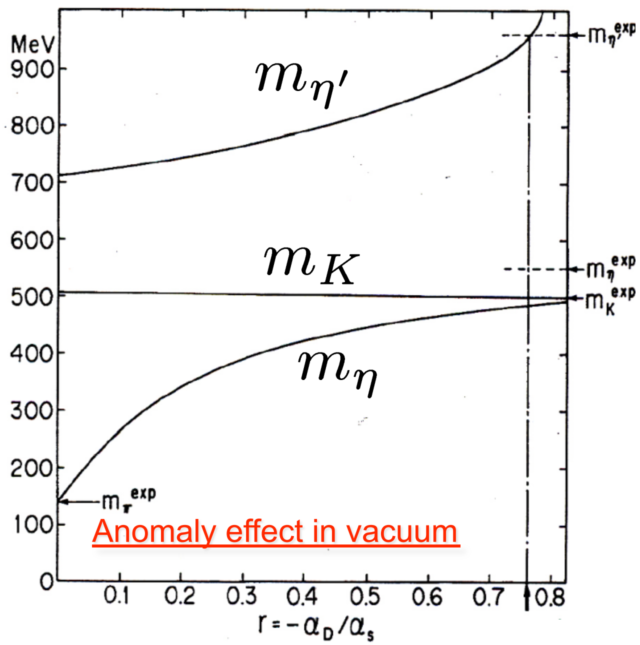
⟷ Hadron property at finite ρ

⟷ Infinite System ⟺ Finite System

⟷ Mesic Atoms and Mesic Nuclei

($\bar{K}$NN ･･･ 池田さん)

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



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

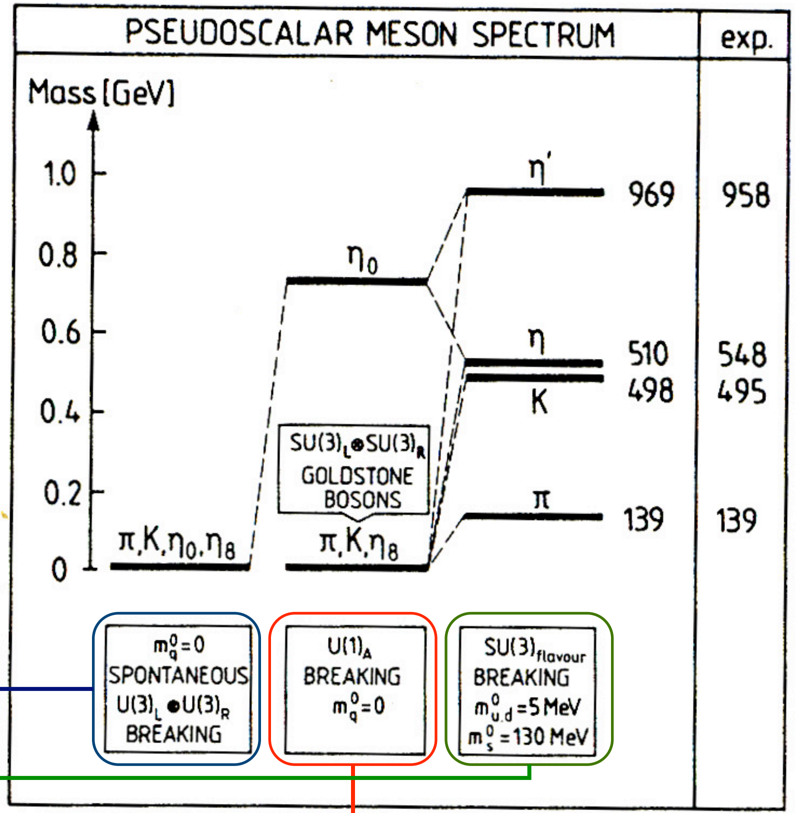


Fig. 10. *Pseudoscalar meson spectrum from the NJL model (Klimt et al. 1990), showing the chiral and flavour symmetry breaking pattern. Calculated and experimental masses are given in MeV.*

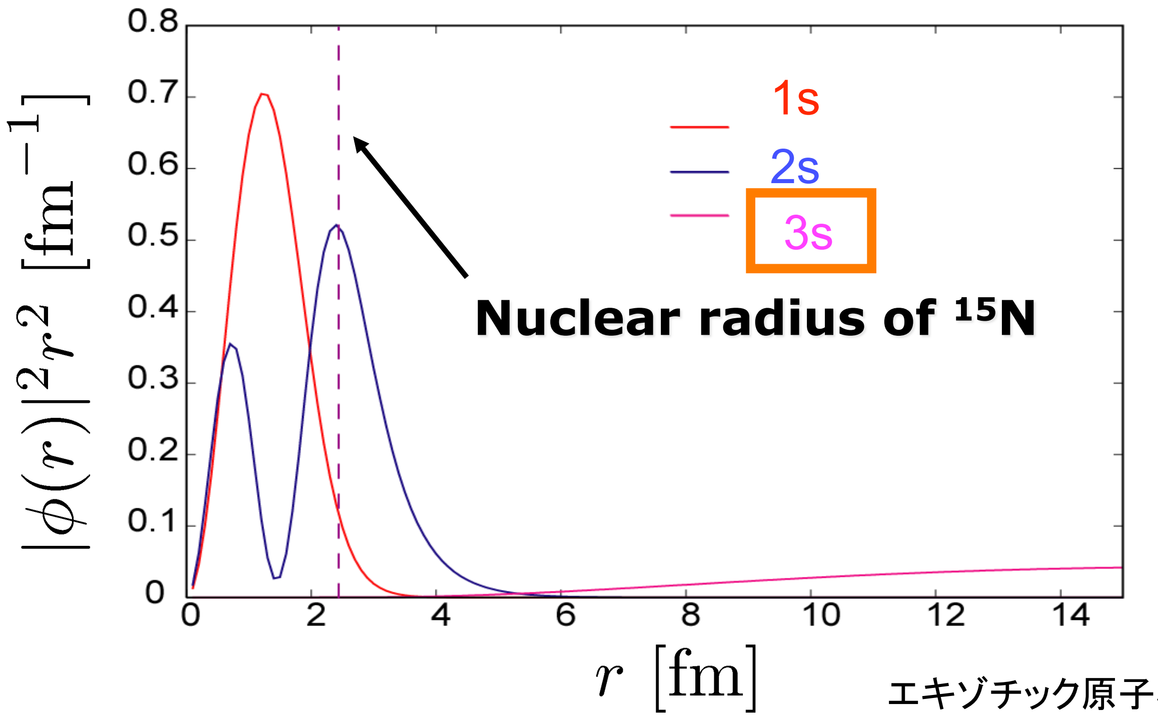
- Higgs mechanism
- Spontaneous Chiral Symmetry Breaking
- $U_A(1)$ Anomaly Effect

(⇒佐久間さん)

- 3. 他にもおもしろい事がいろいろある
- Hadron Physics (兵藤さん)
  - Hadron in Vacuum
  - Exotic Hadrons
  - Excited Hadrons
- Numerical Field Theory (Lattice) (石井さん)
  - Hadron間相互作用from QCD

2.Mesic Atoms and Mesic Nuclei

- Object :考える対象「原子」と「原子核」
  - Hadron – Nucleus bound systems.
    - Coulomb + Strong ・・・ Exotic Atoms
      (Deeply Bound) π atom, Kaonic Atom, $\bar{p}$ atom …
    - Strong ・・・ Exotic Nuclei
      Mesic Nuclei ($\bar{K}$, η, η(958), ω, Φ…), Hypernuclei, …



ex.)

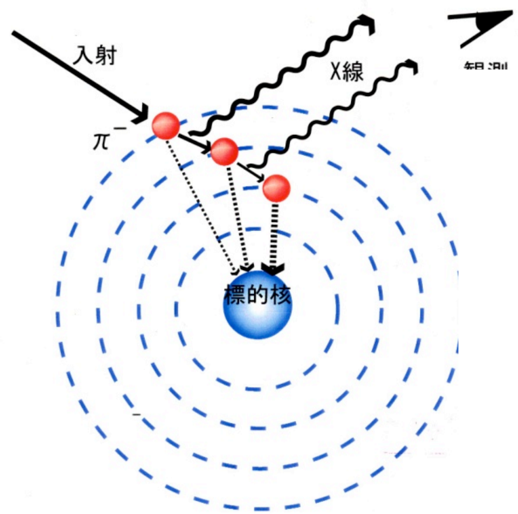
Kaonic Atoms

And

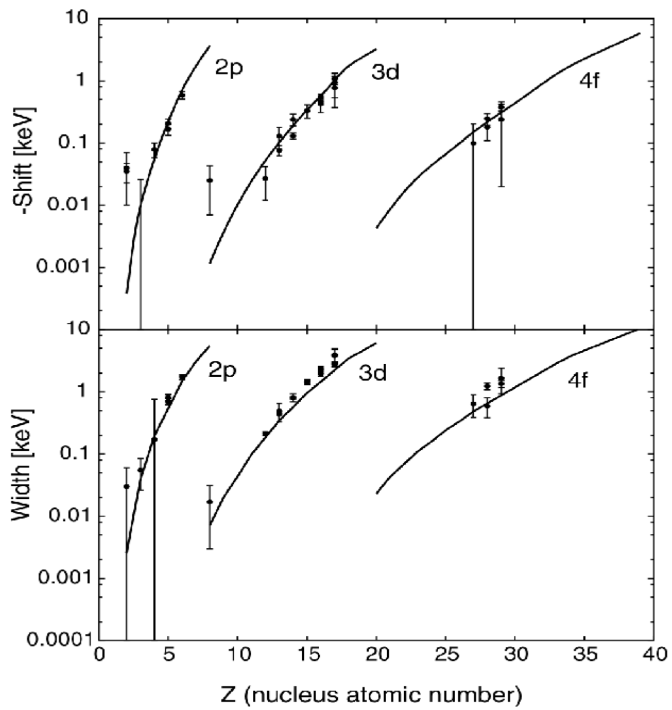
Kaonic Nuclei

By J. Yamagata

2 Mesic Atoms and Mesic Nuclei
X-ray Observation of Mesic Atoms



Kaonic Atom data



S. Hirenzaki, Y. Okumura, H. Toki, E. Oset, A. Ramos, Phys.Rev.C61:055205,2000.

Pionic X-ray data

(^{209}Bi)

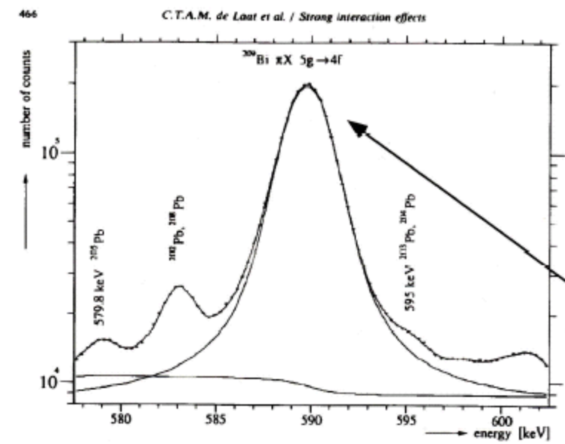


Fig. 5. Part of the pionic X-ray spectrum shown in fig. 4, showing the energy region of the pionic 5g→4f hyperfine complex from pions stopped in a ^{209}Bi target. The fit to the experimental data points is represented by the solid line. The background including the step function is also displayed by a solid line in the figure.

4f

(^{209}Bi)

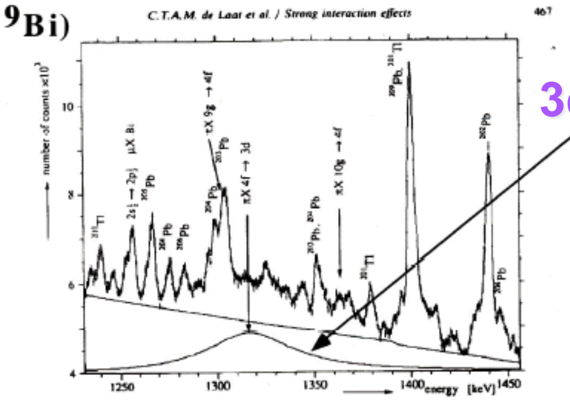
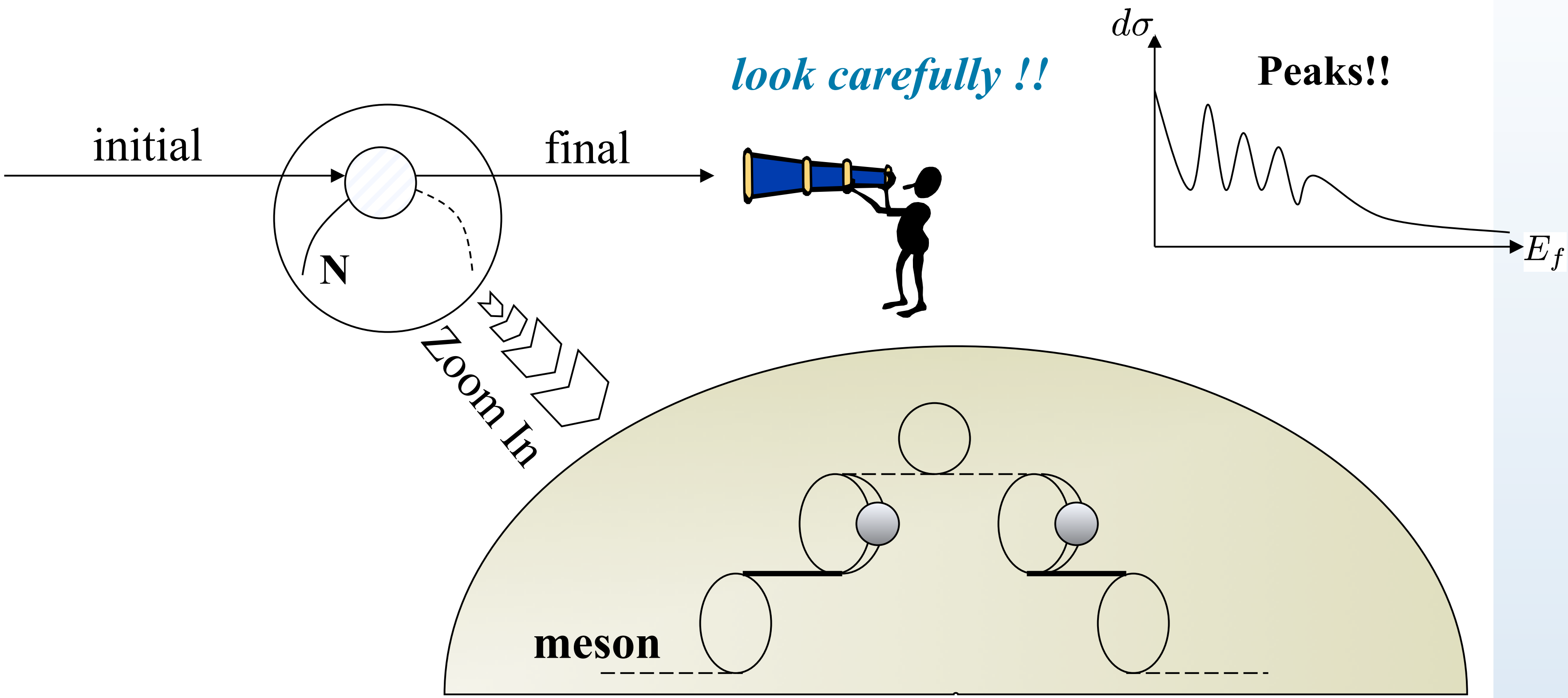


Fig. 6. This figure displays the 4f→3d hyperfine complex of the prompt pionic ^{209}Bi X-ray spectrum. The solid line represents the fit to the experimental data points. Also shown are the background (see text) and the resulting 4f→3d line. The various γ-rays also included in the fitting procedure have been identified as transitions mainly in Pb isotopes in the mass region A ≈ 200–208 as a result of pion and muon capture.

3d

C.T.A.M. De Laat, et al., Nucl.Phys.A523:453-487,1991.

Missing Mass Spectroscopy

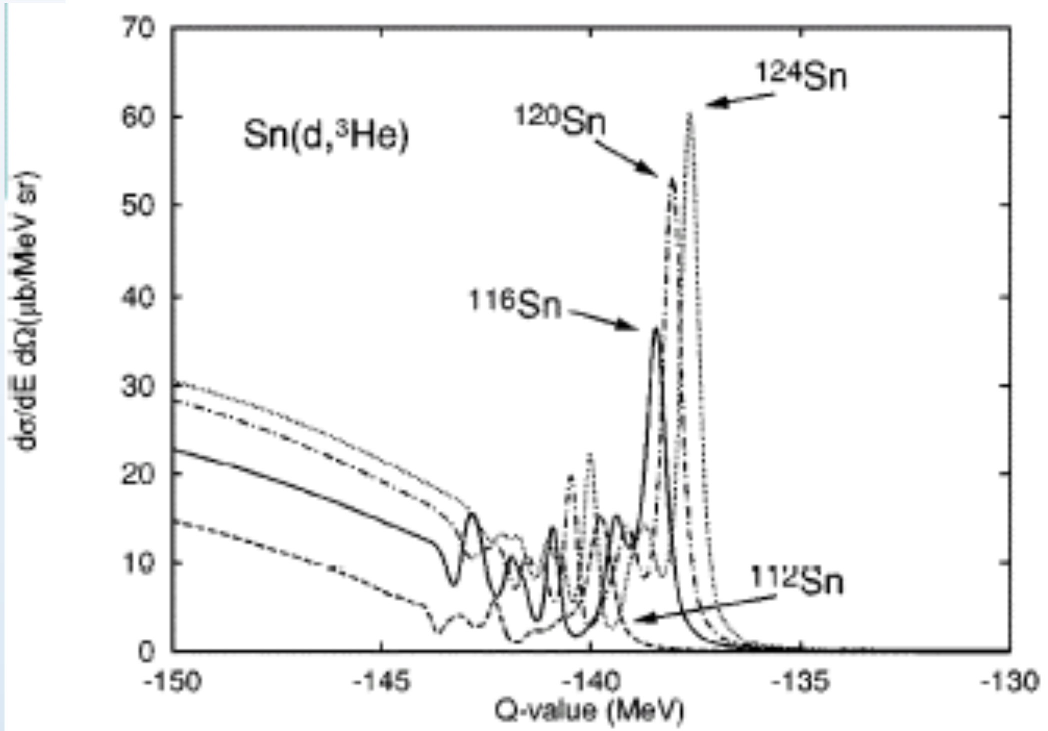


In-Medium Dispersion Relation

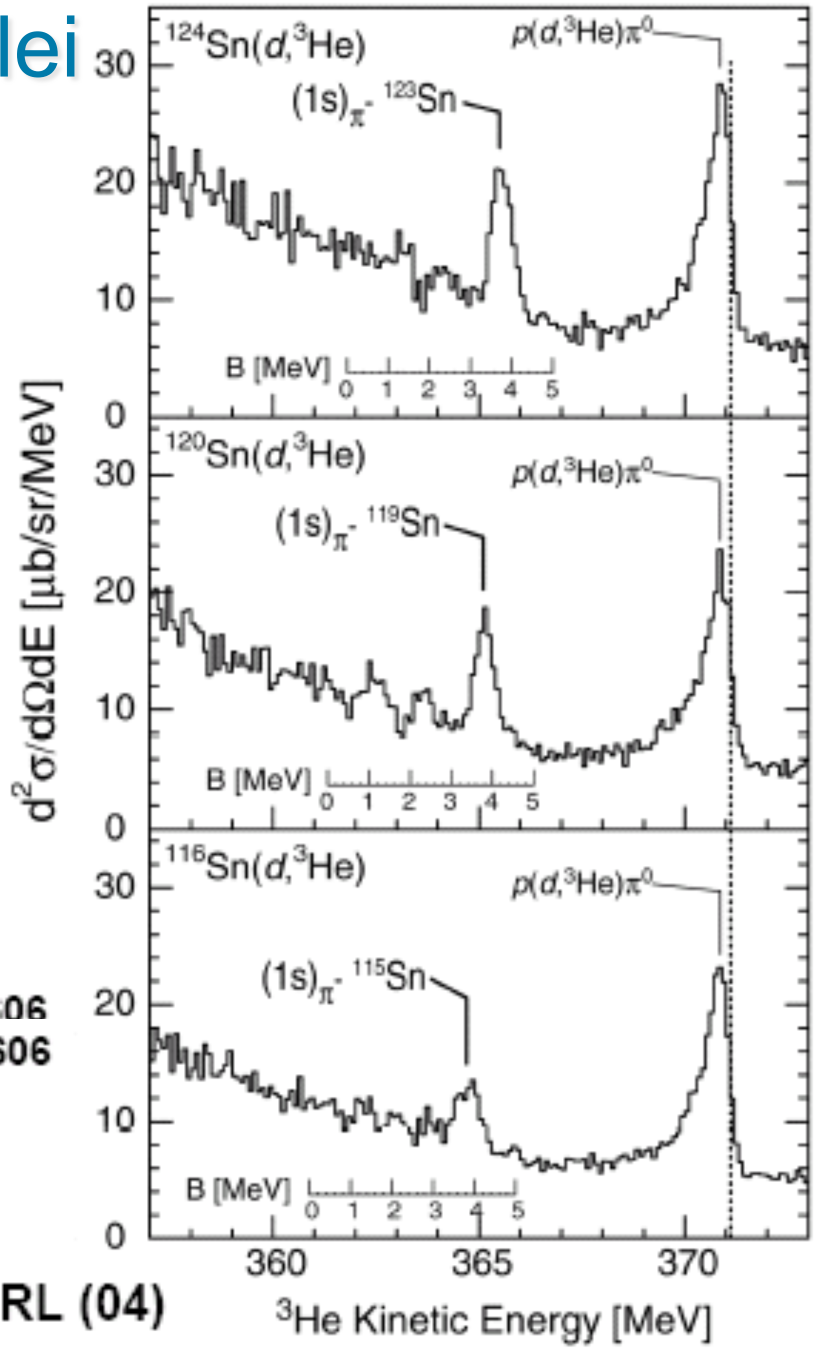
Medium Effects

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

Pionic 1s states of Sn nuclei

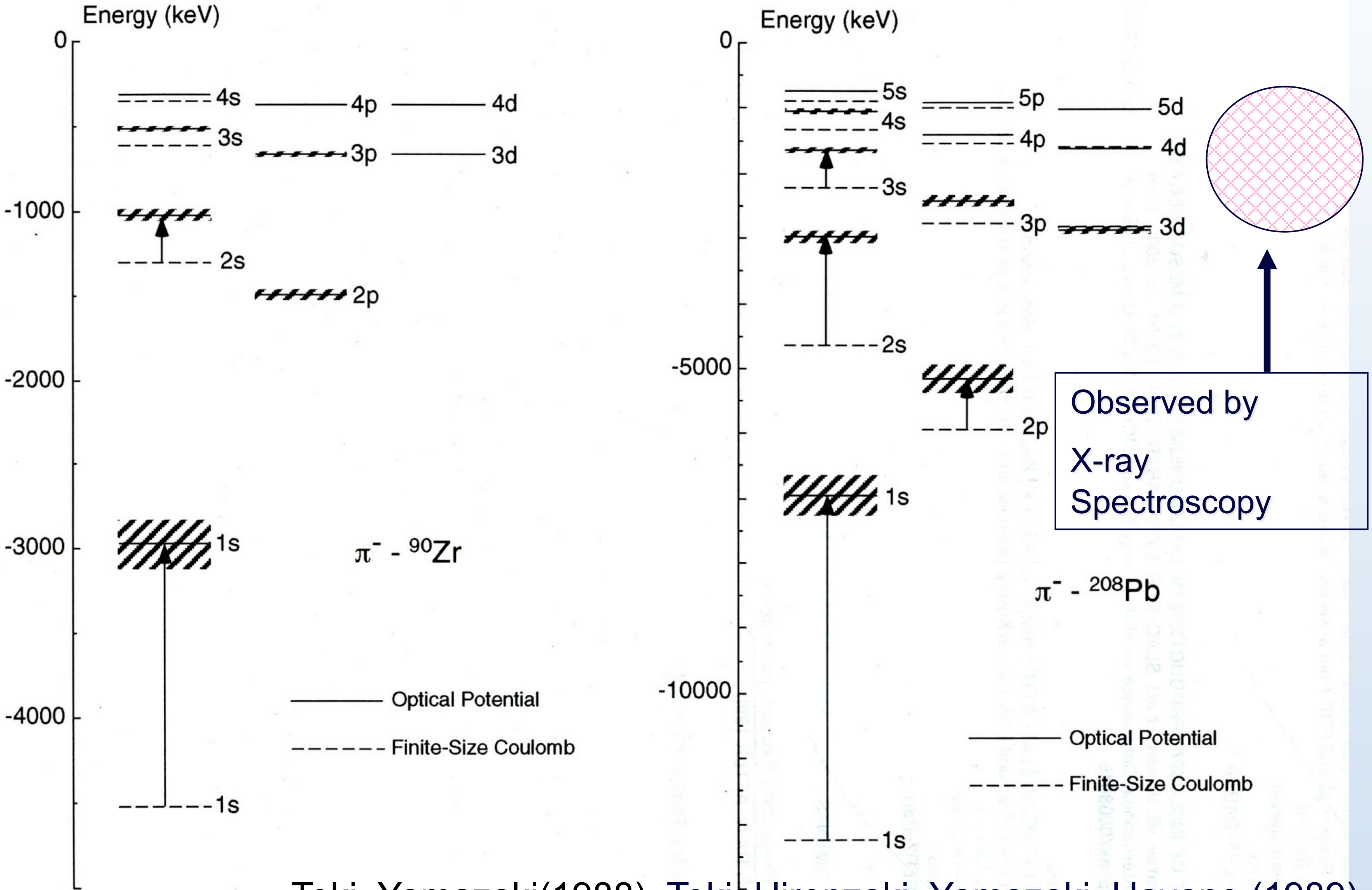


Umemoto, Hirenzaki, Kume, Toki PRC62(00)024606



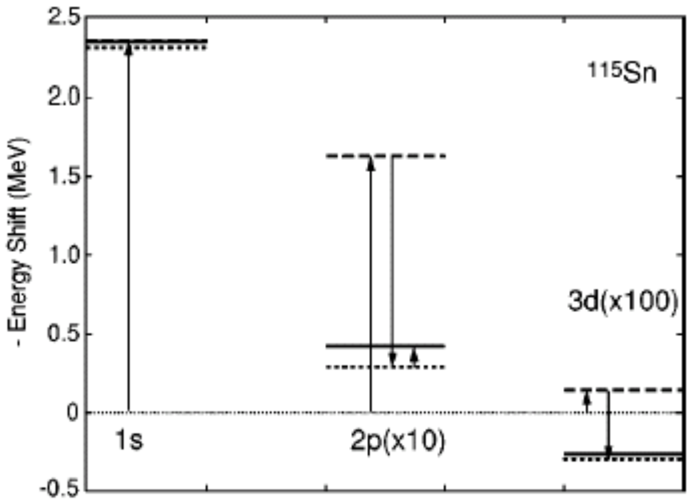
K. Suzuki *et al.* PRL (04)

Theoretical Level Structure



Toki, Yamazaki(1988), Toki, Hirenzaki, Yamazaki, Hayano (1989)

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



Umemoto et al., PRC62 (2000)

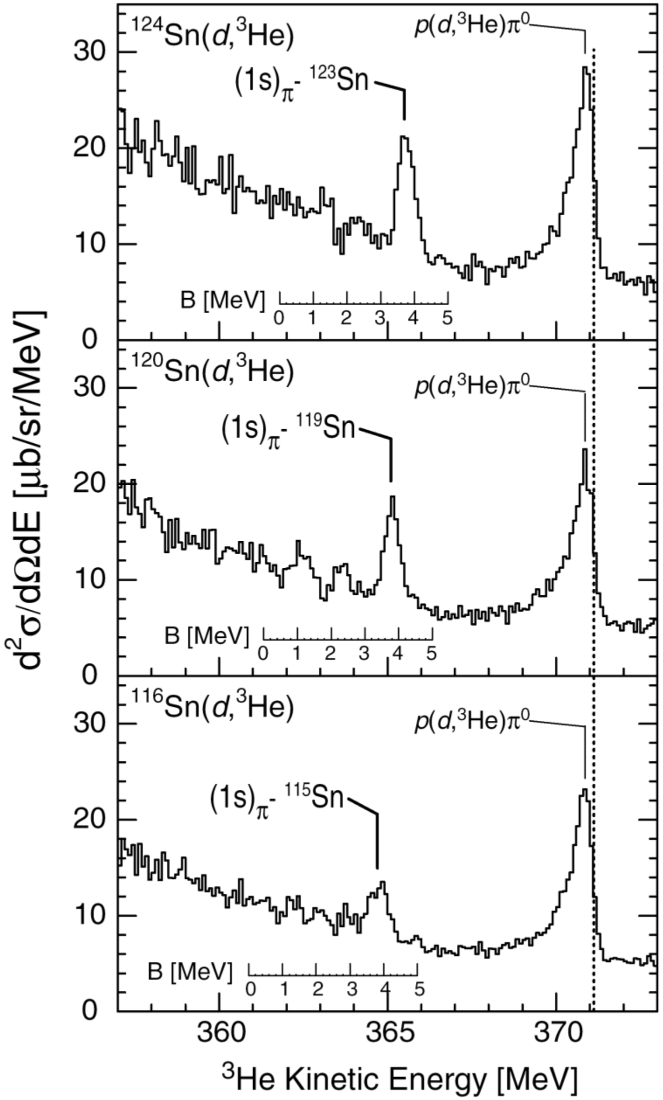
FIG. 1. The binding energies with finite-size Coulomb potential only $B_{\rm Coul}$ and Coulomb plus optical potential $B_{\rm full}$, are calculated. The energy shifts $B_{\rm Coul}$-$B_{\rm full}$ are shown as the solid bars for pionic $1s$, $2p$, and $3d$ states for ^{115}Sn and ^{207}Pb. The shifts 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.

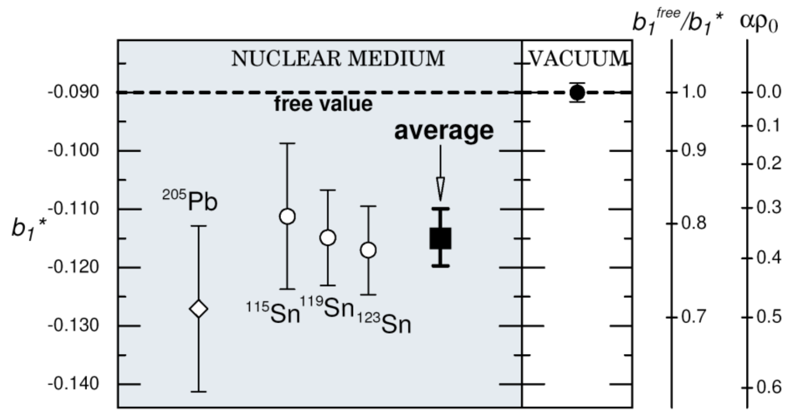
Ericson-Ericson, Ann. Phys. **36** (66) 323
Seki-Masutani, Phys. Rev. **C27**(83)2799

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

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

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





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

GOR relation + Tomozawa-Weinberg Relation

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

⇩

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

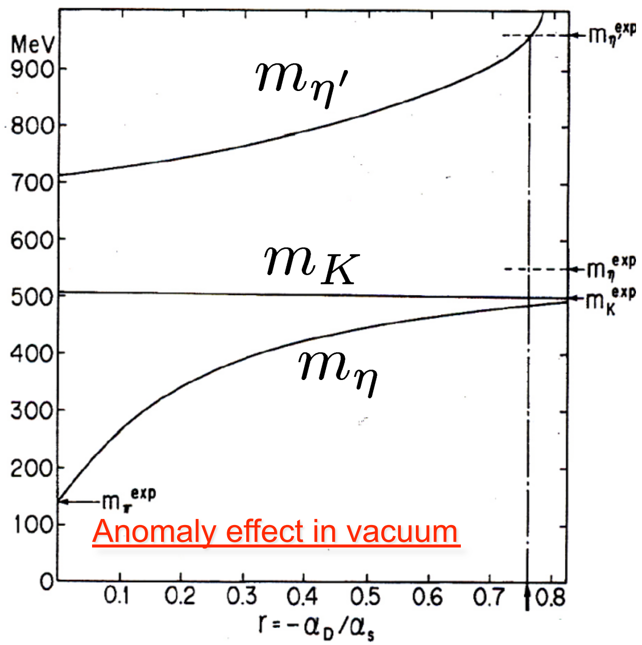
3. Some Recent Topics

- Pseudo Scalar Mesons
- π･･･RIBF ･･･異なるρをprobe? (non yrast state)
- K･･･J-PARC ･･･Kaonic nucleus + Kaonic Atom, Λ(1405)
- η･･･J-PARC ･･･ηNN*(1535)coupling, nucleon chiral partner
- η'･･･ ? ･･･$U_A(1)$ anomaly effect in nucleus

- Vector Mesons
- ρ･･･ J-PARC,KEK
- ω･･･ J-PARC,KEK
- Φ･･･ J-PARC,KEK

} mass, width shift (Spectral function)

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



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

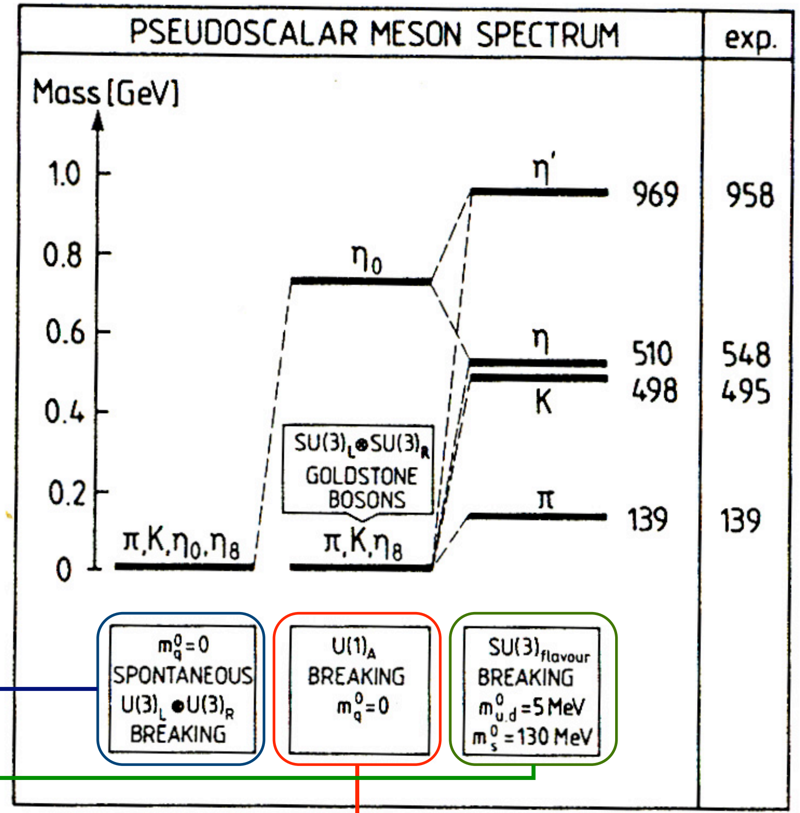
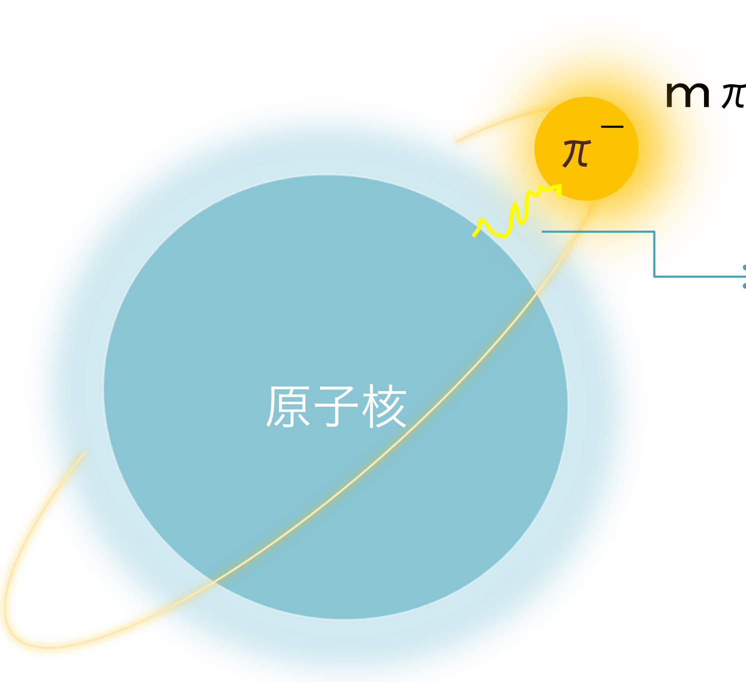


Fig. 10. *Pseudoscalar meson spectrum from the NJL model (Klimt et al. 1990), showing the chiral and flavour symmetry breaking pattern. Calculated and experimental masses are given in MeV.*

- Higgs mechanism
- Spontaneous Chiral Symmetry Breaking
- U$_A$(1) Anomaly Effect (⇒佐久間さん)

3-1. π中間子原子(木村梨恵、比連崎悟，山縣淳子，Li Sheng Geng)



mπ～140[MeV]

クーロン相互作用ー引力
強い相互作用　　ー斥力

ポテンシャル
ポケット形成

π中間子ー原子核間の
相互作用の理解

π中間子原子の束縛エネルギー
や崩壊幅の観測

- π中間子原子の観測(1950年代～)
  - X線分光

    ex) C. Batty, E. Friedman, and A. Gal, Phys. Rep. 287(1997)385
  - (d,^{3}He)反応　重い核の深く束縛された状態を観測

    H. Toki, T. Yamazaki, Phys. Lett. B213(1988)129

    H. Toki, S. Hirenzaki, T. Yamazaki, R. S. Hayano,　Nucl. Phys. A501(1989)653

<u>1996年　Pb標的(2p state)</u>

S. Hirenzaki, H. Toki, T. Yamazaki, Phys. Rev. C44(1991)2472

K. Itahashi, et al. , Phys. Rev. C62(2000)025201

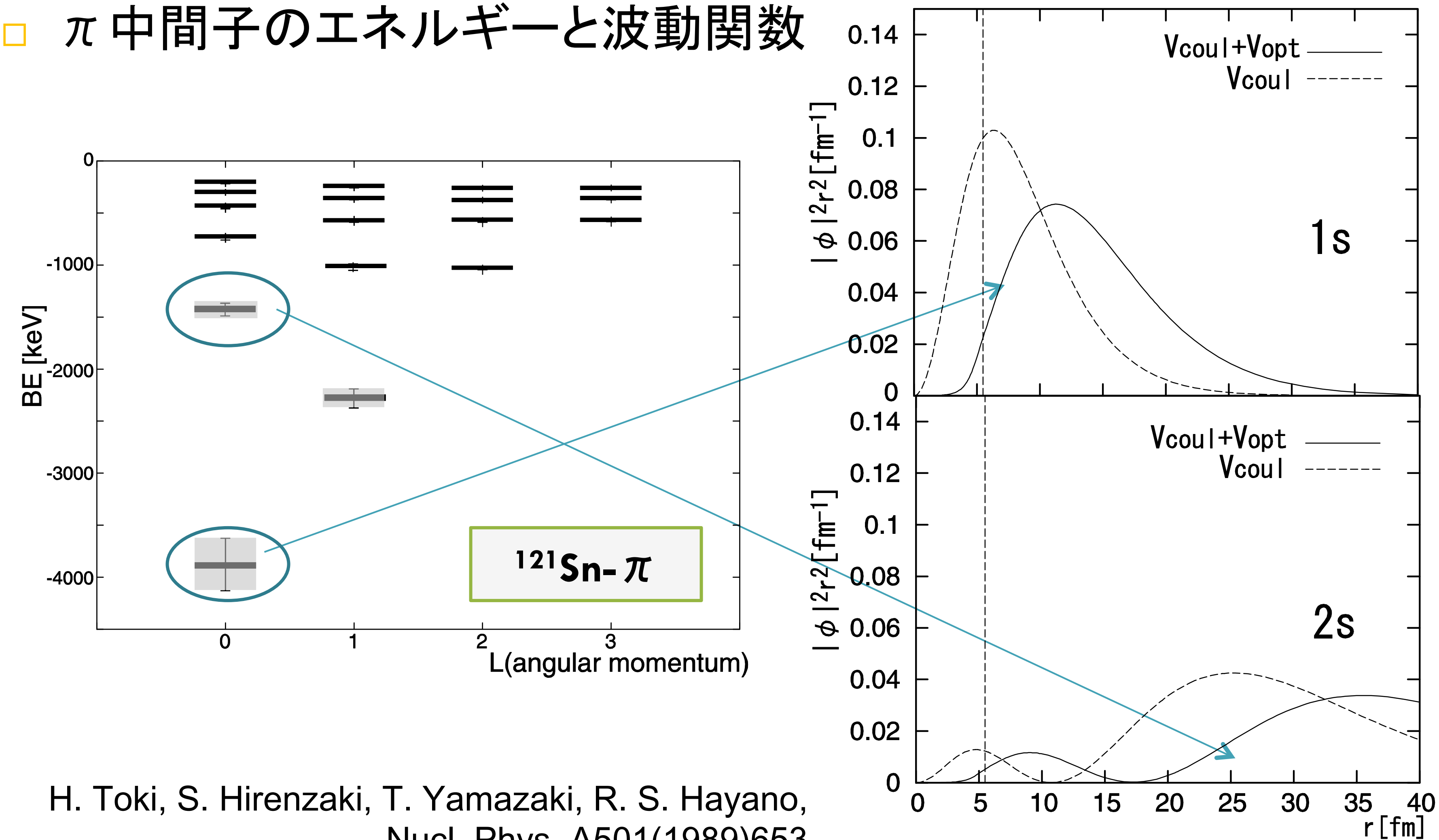
<u>2001年　Sn標的(1s state)</u>

Y. Umemoto, S. Hirenzaki, K. Kume and H. Toki, Phys. Rev C62(2000) 024606

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

@ドイツGSI

□ π 中間子のエネルギーと波動関数



H. Toki, S. Hirenzaki, T. Yamazaki, R. S. Hayano, Nucl. Phys. A501(1989)653

There have been active discussions

- **K. Suzuki et al.**, Phys. Rev. Lett. 92(2004)072302 $< \bar{q}q >_\rho$ observation
- **Daisuke Jido, Tetsuo Hatsuda, Teiji Kunihro, Phys.Lett. B670 109-113, 2008**
  'In-medium Pions and Partial Restoration of Chiral Symmetry'
- **Kolomeitsev, Kaiser, Weise**, Phys. Rev. Lett. 90(2003)092501
  in two-loop chiral perturbation
  - Energy dependent of Π
  - Gauge coupling of V_c
  - Phenomenological pieces ($B\rho^2$, p-wave terms)
- **Garcia-Recio, Nieves, Oset,** Phys. Lett. B 541(2002)64
  - Discussion on ρ^n (n>1) ?
- **M. Doring, E. Oset**, arXiv:0705.3027 [nucl-th]
  - s-wave pion-nucleus optical potential in chiral unitary model
- **E. Friedman and A. Gal**, Phys. Lett. B578 (2004)85
- **G. Chanfray, M. Ericson, M. Oertel**, Phys. Lett. B563(2003)61

π中間子原子の高分解能実験@理研RIBF

RIBF-027 K. Itahashi, et al,

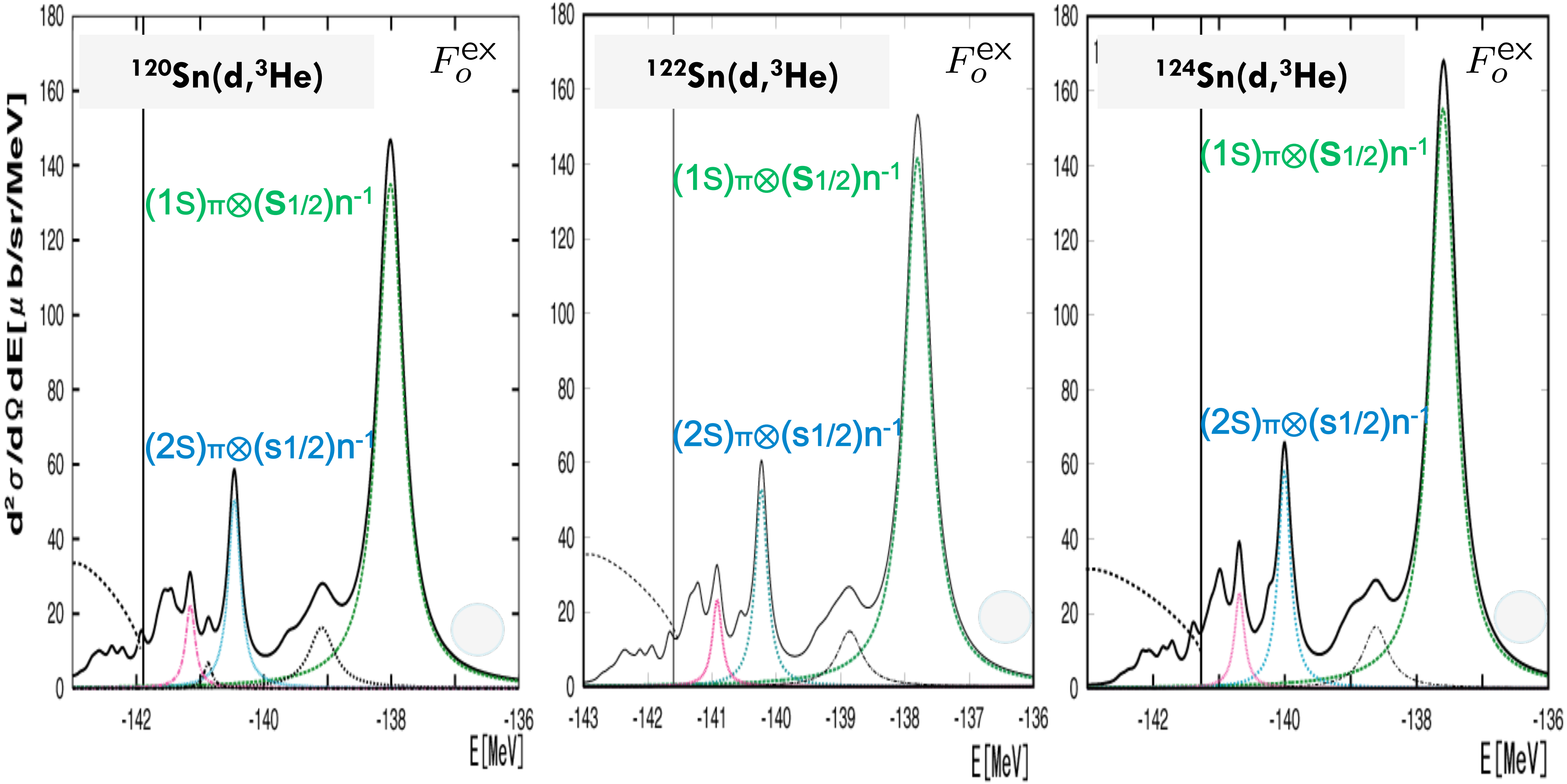
- (d,^{3}He)反応
- T_d=500[MeV] Recoilless
- 標的核　^{119}Sn, ^{120}Sn, ^{122}Sn, ^{124}Sn
  ^{121}Sb, ^{123}Sb,
  ^{122}Te, ^{124}Te, ^{126}Te
- 分解能　～150[keV]（以前の3倍近く改善された分解能）
  →1つの標的核に対していくつかの状態が観測可能

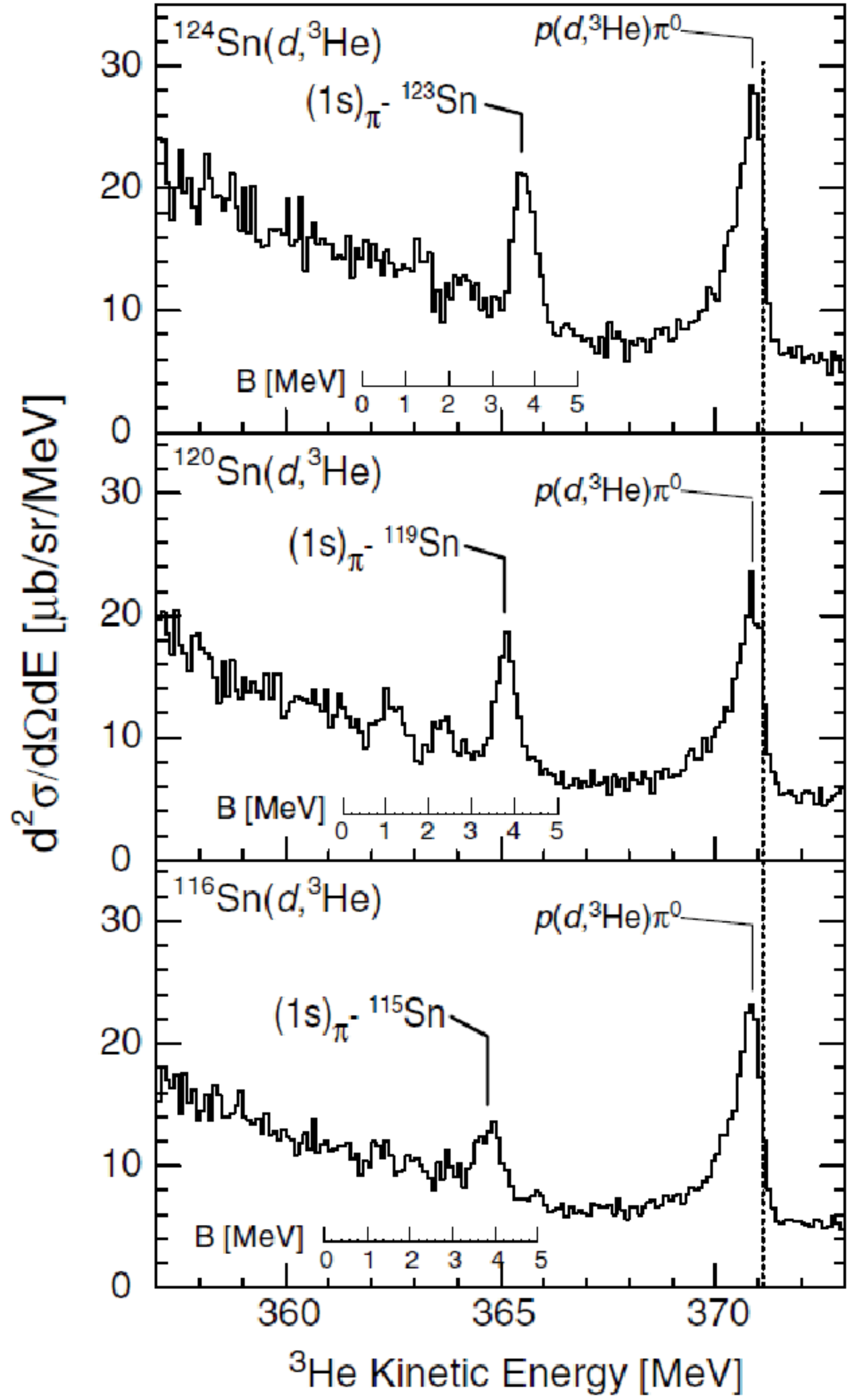
⇒ 異なるρをProbe する可能性

Cf. Seki-Masutani Relation

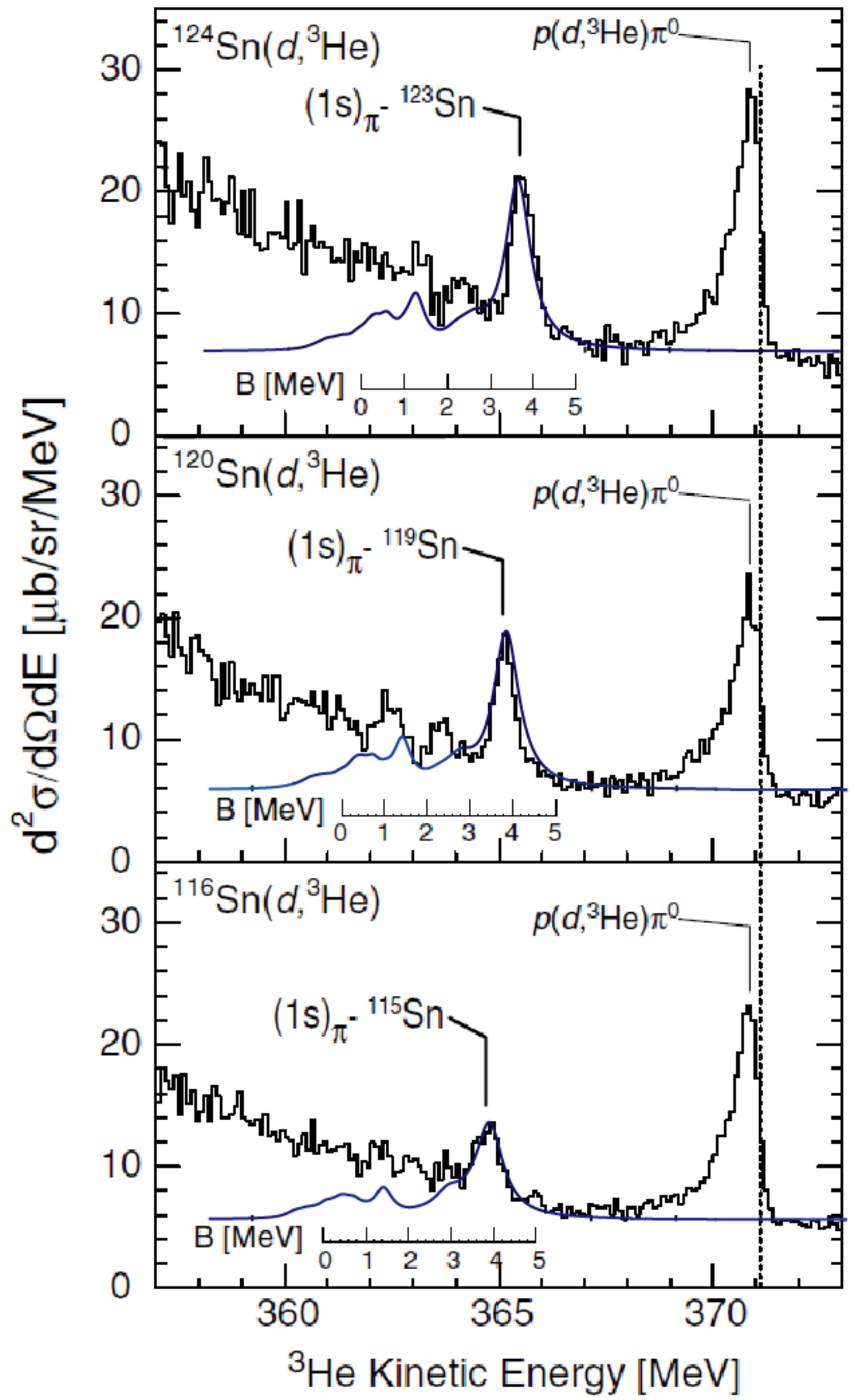
$$\rho_{\text{effective}} \sim \frac{1}{2}\rho_0, \text{ for yrast states}$$

π中間子原子の生成断面積　～標的核Sn～



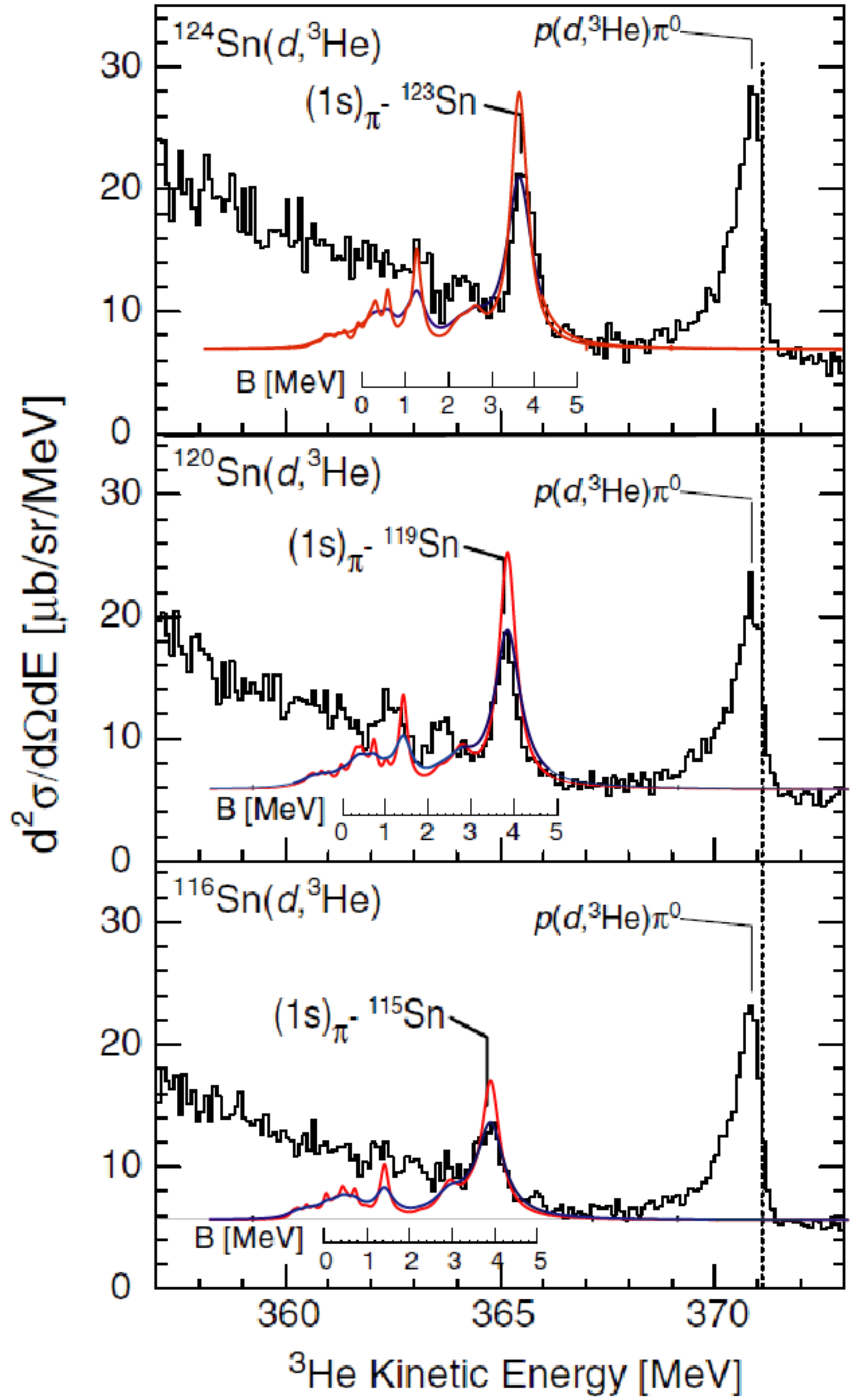


EXPERIENCE at GSI
FWHM394kev



EXPERIENCE at GSI
FWHM394kev

THEORY
FWHM394kev



EXPERIENCE at GSI
FWHM394kev

THEORY
FWHM394kev

THEORY
FWHM150kev！

２ｓのピークも見えるでしょう。

π atom at RIBF

- Exp. plan by Ito, Itahashi (RIBF-027)
- 2 ~ 3 times better energy resolution
- better determination of π-A interactions
- Various ρ probe?

- In future, pionic atom in unstable nuclei

  - Hirenzaki, Kajino, Kubo, Toki, Tanihata, PLB(87)
  - Umemoto, Hirenzaki, Kume, Toki, Tanihata, NPA(01)
  - Fujita, Hirenzaki, Kume, PRC(03)
  - Kienle, Yamazaki, Toki, ‘ Inverse kinematics idea’ 91~92

3–2. η – Nucleus system : Introduction

H. Nagahiro and D. Jido

works for 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)**
* Hayano, Hirenzaki, Gilltzer, Eur.Phys.J.A6(1999)99
* D. Jido, H.Nagahiro, S.Hirenzaki PRC66(2002)045202
* Exp. at GSI (2005?) (Yamazaki, Hayano group)

properties of eta meson

η meson

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

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

η-N system

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

» $\Gamma_{\pi N} \sim \Gamma_{\eta N} \sim 75$[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)**

Our Motivation

η-Nucleus potential is sensitive to the in-medium properties of N*

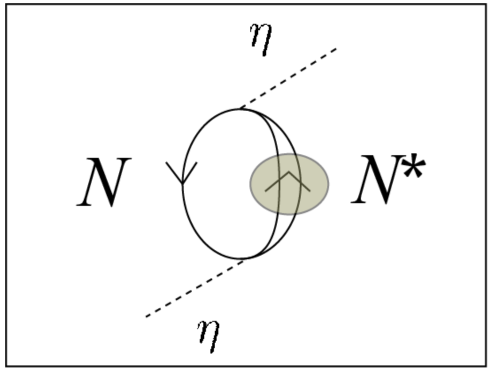
η mesic nuclei as a probe of the in-medium modification of N*(1535)

N*(1535) in-medium

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

* Chiral Doublet Model
* Chiral Unitary Model

η-Nucleus Interaction
~ N* dominance model ~



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

optical potential

energy dependence

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

density-dependence

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

potential nature

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

$$\omega + m_N - m_{N^*} < 0$$ ➡ attractive

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

General feature

medium effect

m_N & m_{N^*} change ??

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

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

Chiral model 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

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**

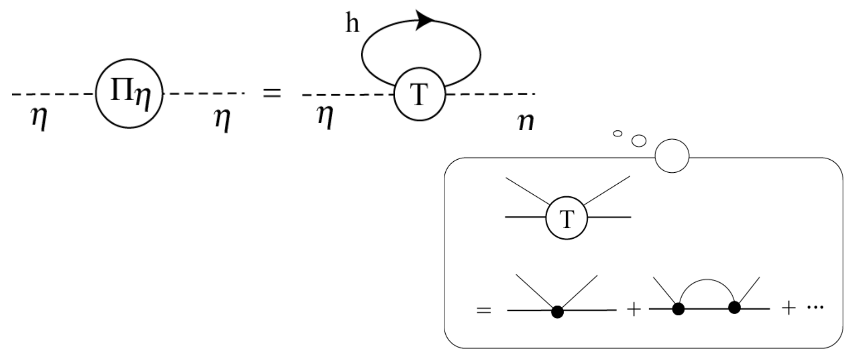
Chiral unitary model

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.

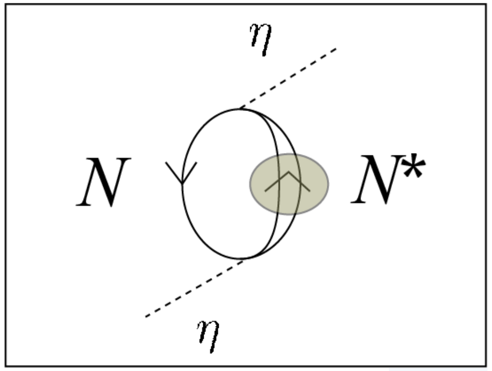
$$\{\pi^- p, \pi^0 n, \eta n, K^0\Lambda, K^+\Sigma^-, K^0\Sigma^0, \pi^0\pi^- p, \pi^+\pi^- n\}$$



* 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

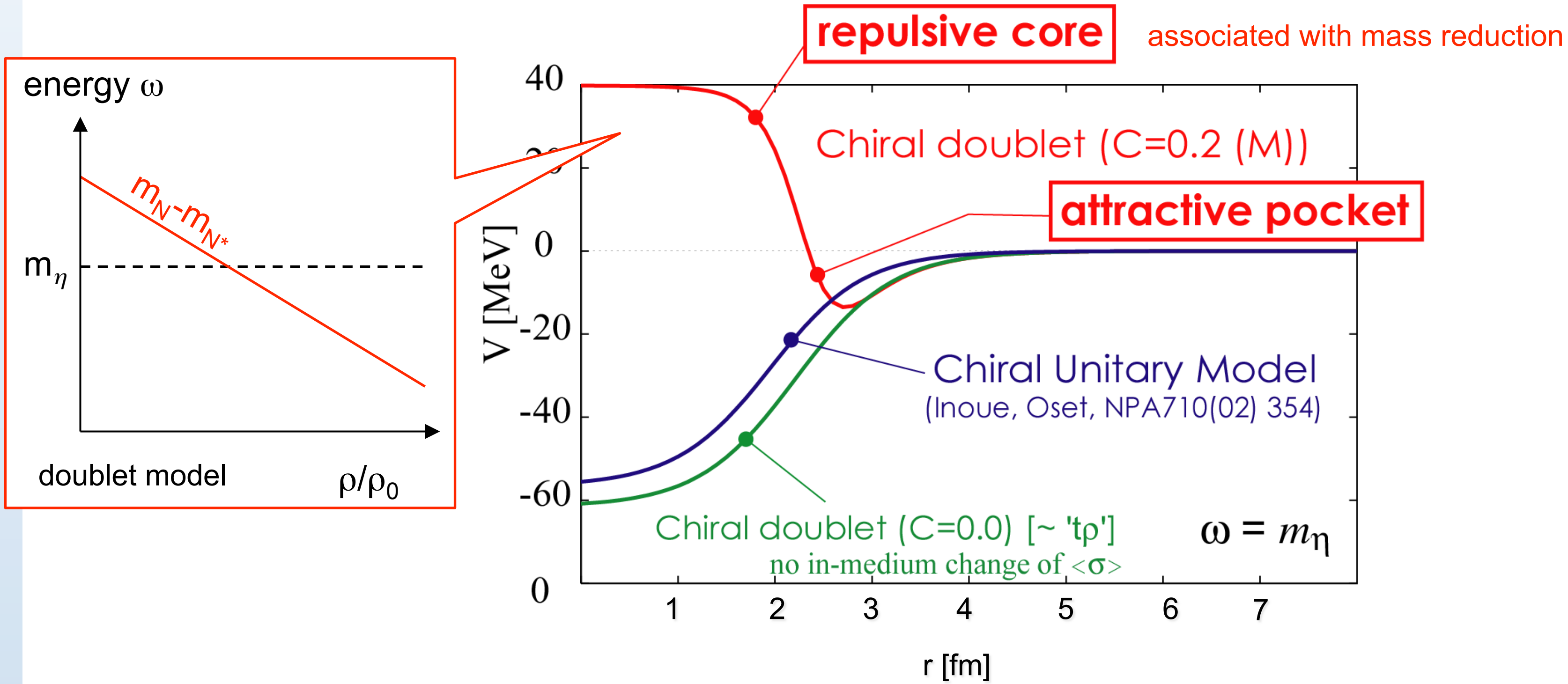


optical potential

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

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



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

理研

What should we observe ?

Bound State

* Chiral Doublet model with C=0.0

	^{11}B	(B.E., Γ) [MeV]	^{39}K
0s	(13.7, 41.5)		(30.3, 42.5)
0p	—		(14.6, 50.7)

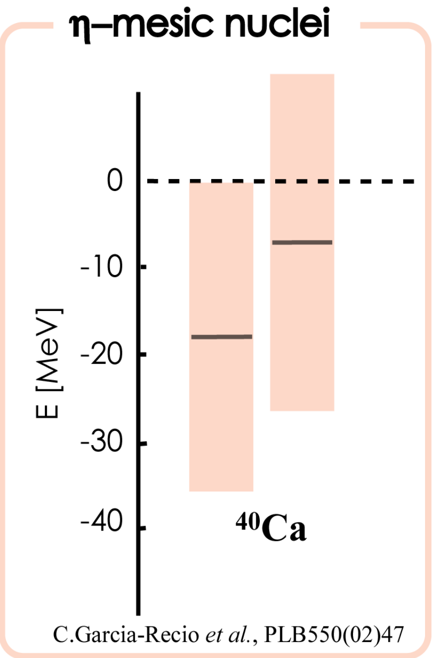
* Chiral Doublet model with C=0.2

no bound state

* Chiral Unitary model

	^{12}C	(B.E., Γ) [MeV]	^{40}Ca
0s	(9.71, 35.0)		(17.88, 34.38)
0p	—		(7.04, 38.6)

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



NOT Discrete

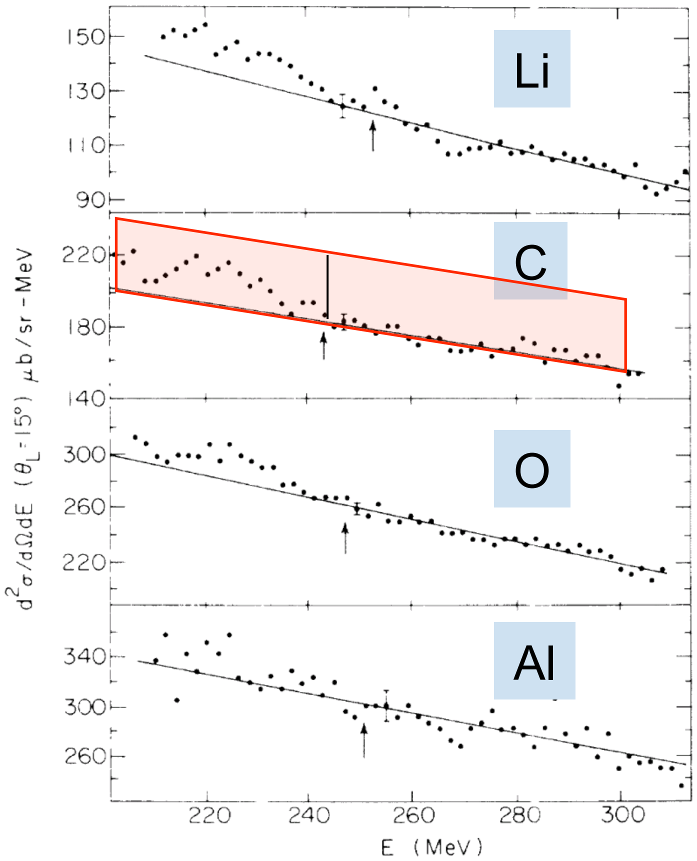
We need to observe
* whole spectral shape
* a few peaks

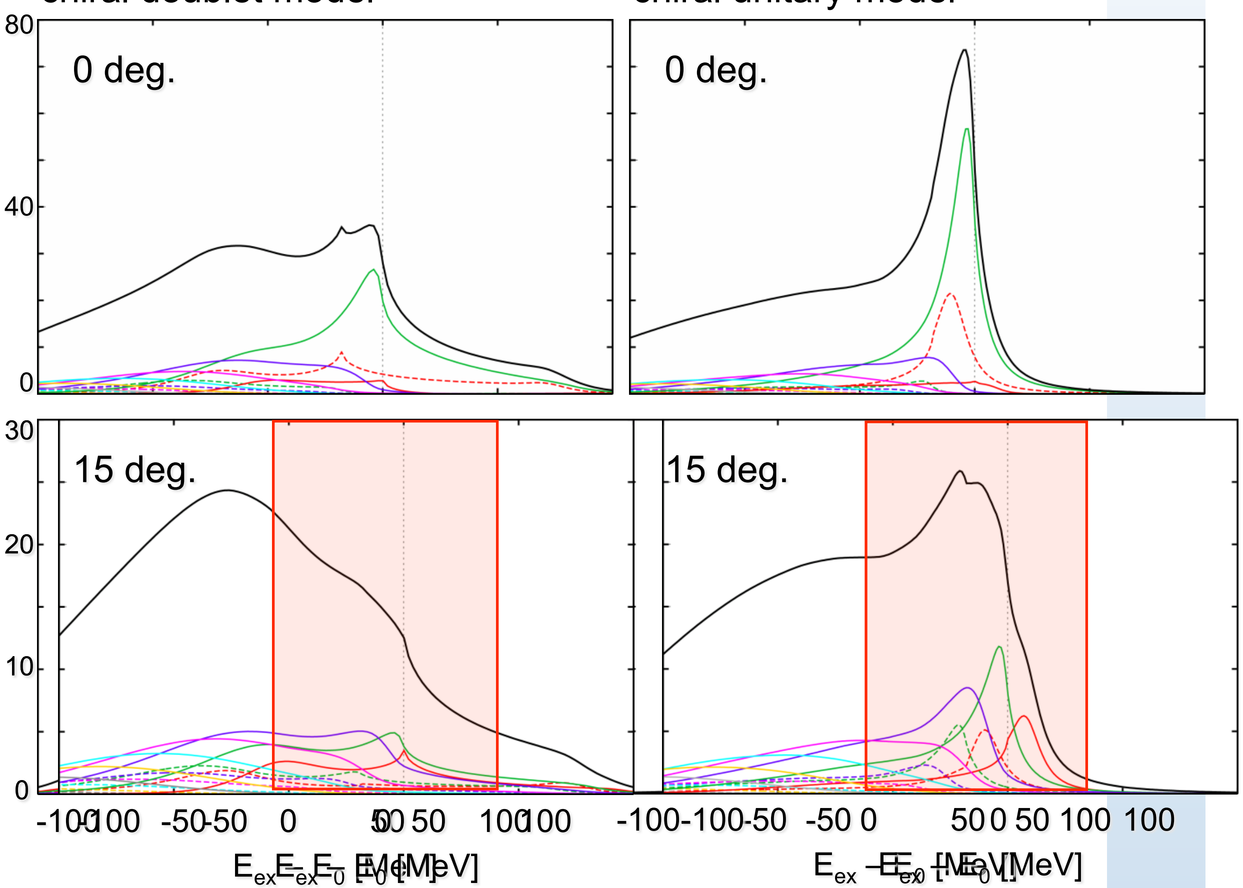
(π^+,p) spectra : at J-PARC ?

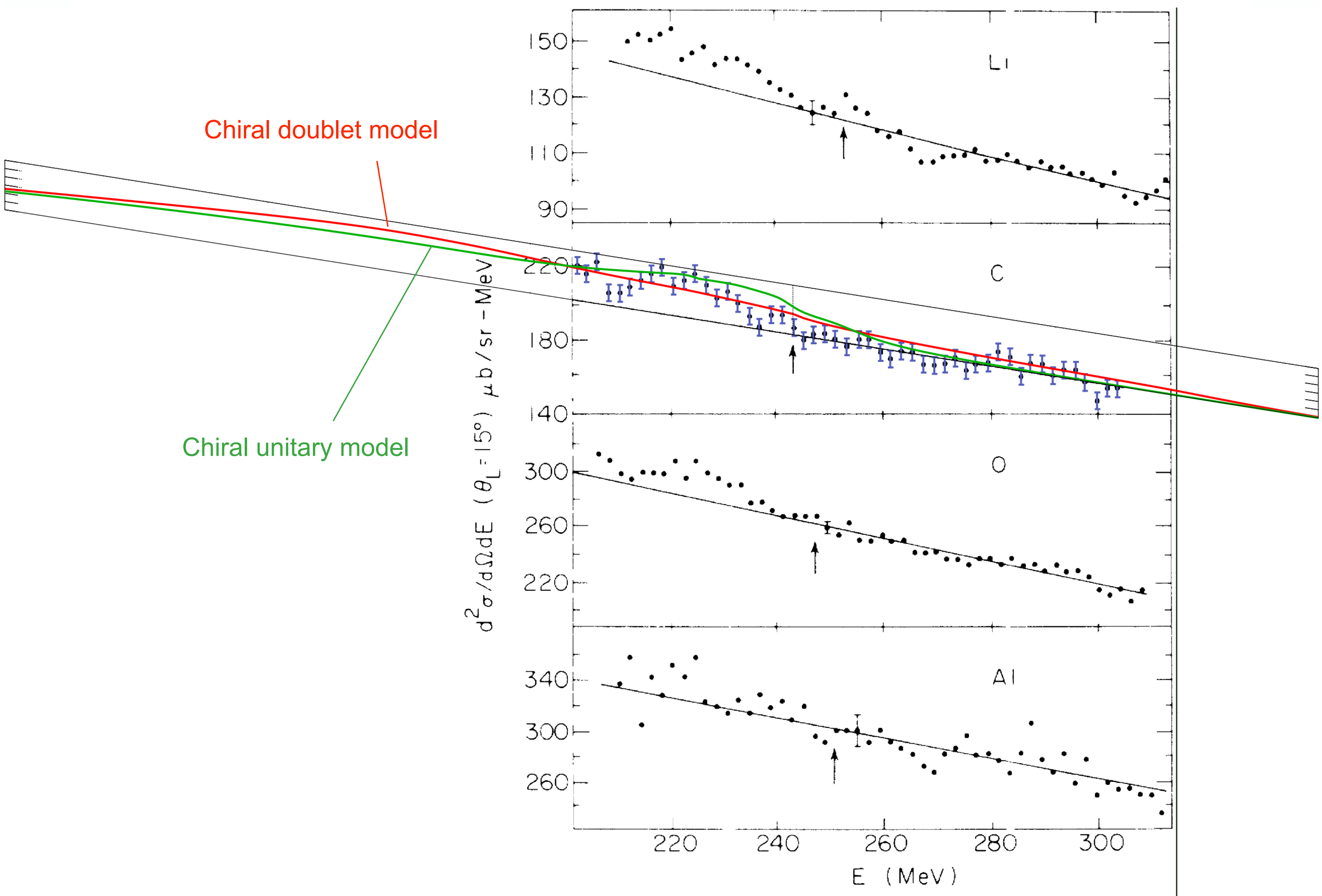
- Chrien et al., PRL60(1988)2595
  - p_π = 800 MeV/c
  - proton angle : 15 deg. (Lab.) --- cf ω case : Kaskulov, Nagahiro, Hirenzaki, Oset

nucl-th/0610085

Chrien at al., PRL60(88)2595, Fig.1







Chiral doublet model
Chiral unitary model
Li
C
O
Al
$d^2\sigma/d\Omega dE$ ($\theta_L = 15°$) μb/sr − MeV
E (MeV)

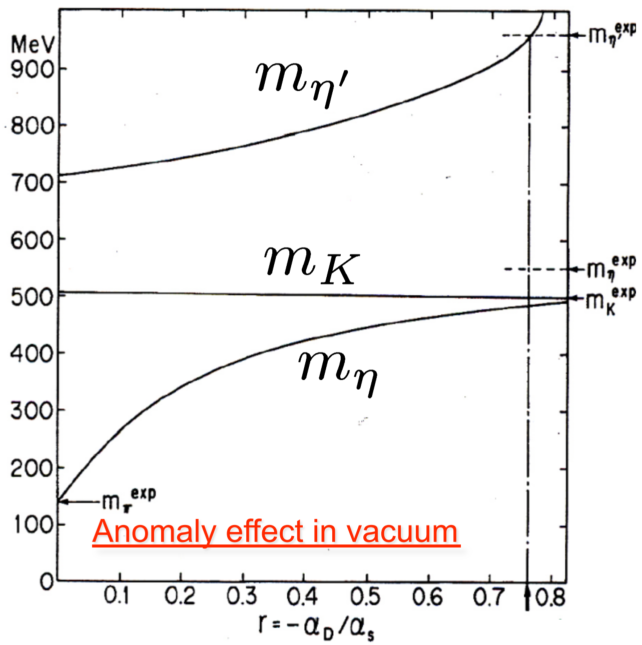
η mesic Nucleus

- η mesic nuclei as a probe of N*(1535) in nuclear medium
  - N* properties in-medium
    - Chiral Doublet Model
      - N* mass reduction … repulsive η-nucleus potential
    - Chiral Unitary Model
      - No mass shift of N* … attractive η-nucleus potential
- Formation cross section with (π,N) reactions (J-PARC)

  Theory: Nagahiro, Jido, Kolomeitsev

  Exp: K.Itahashi, H.Fujioka (J-PARC LOI)

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



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

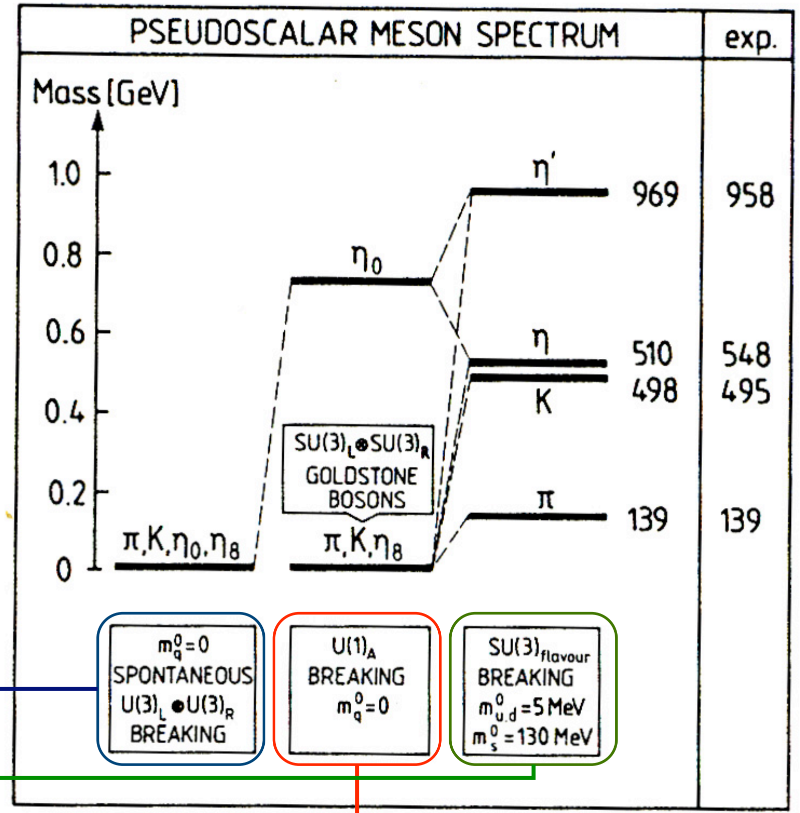


Fig. 10. *Pseudoscalar meson spectrum from the NJL model (Klimt et al. 1990), showing the chiral and flavour symmetry breaking pattern. Calculated and experimental masses are given in MeV.*

- Higgs mechanism
- Spontaneous Chiral Symmetry Breaking
- $U_A(1)$ Anomaly Effect (⇒佐久間さん)

3-3. η- and η'(958)-mesic nuclei (Hideko Nagahiro, Makoto Takizawa, Satoru Hirenzaki)

- 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
      - Y. Kohyama, K.Kubodera and M.Takizawa, PLB208(1988)165
      - 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 η' at $\rho \neq 0$**
  - a poor experimental information on the $U_A(1)$ anomaly at finite density
- proposal for the formation reaction of the η'-mesic nuclei using the **(γ,p) reactions**
  - $U_A(1)$ anomaly in medium from the viewpoint of "mesic nuclei"
  - the η' properties, especially mass shift, at finite density

Model for η and η' meson in medium

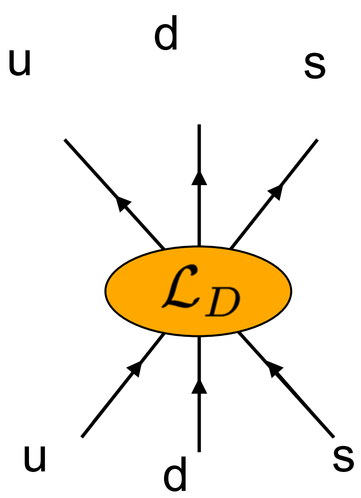
- **Nambu-Jona-Lasinio model** with the **KMT interaction**
  - » unified treatment of the η and η' meson

$$\mathcal{L} = \bar{q}(i\not\partial - m)q + \frac{g_s}{2}\sum_{a=0}^{8}\left[(\bar{q}\lambda_a q)^2 + (i\bar{q}\lambda_a\gamma_5 q)^2\right]$$

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

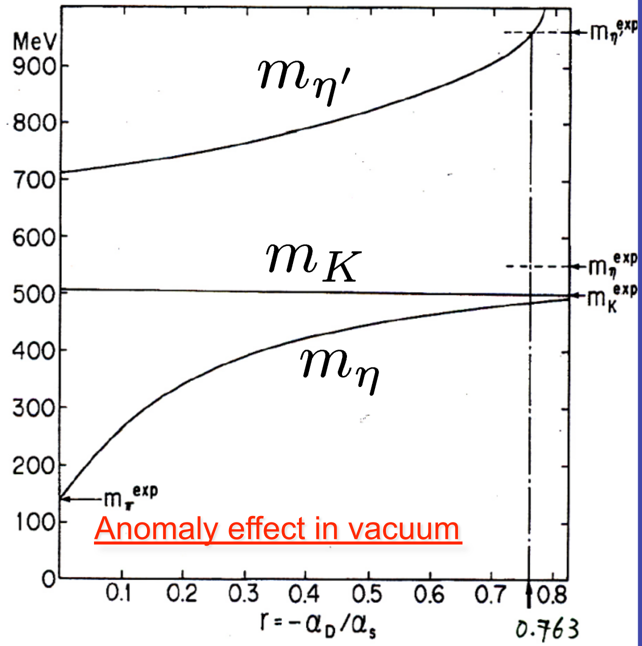
explicit breaking the $U_A(1)$ sym.

Kobayashi, Maskawa Prog.Theor.Phys.44, 1422 (70)
G. 't Hooft, Phys.Rev.D14,3432 (76)



One can reproduce the heavy η' mass

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

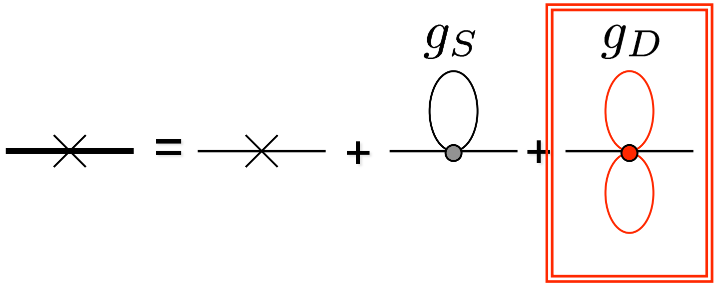


Masses in finite T/ρ with NJL

T. Kunihiro, PLB219(89)363
P. Costa *et al.*,PLB560(03)171 etc…

Gap equations for quarks

$$\begin{cases} M^u = m^u - 2g_S\langle\bar{u}u\rangle - 2g_D\langle\bar{d}d\rangle\langle\bar{s}s\rangle \\ M^d = m^d - 2g_S\langle\bar{d}d\rangle - 2g_D\langle\bar{s}s\rangle\langle\bar{u}u\rangle \\ M^s = m^s - 2g_S\langle\bar{s}s\rangle - 2g_D\langle\bar{u}u\rangle\langle\bar{d}d\rangle \end{cases}$$



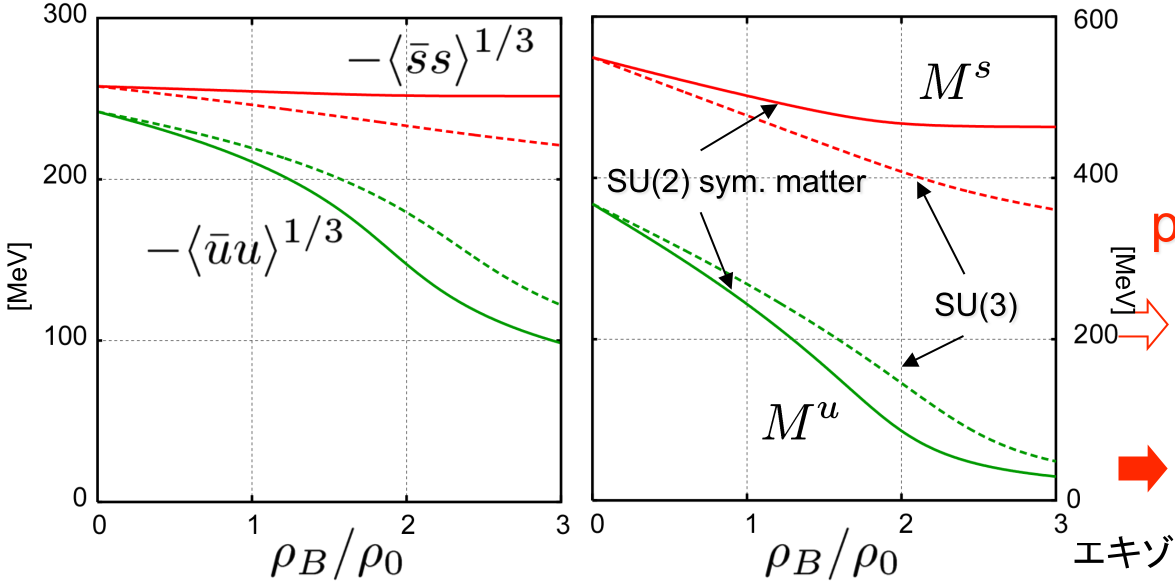
flavor mixing terms

condensate in finite T/ρ

$$\langle\bar{q}q\rangle = -2N_C\int\frac{d^3p}{(2\pi)^3}\frac{M}{E_p}(1-n_p(T,\mu)-\bar{n}_p(T,\mu))$$

$$n(T,\mu) = \frac{1}{e^{(E_p-\mu)/T}+1}$$

Fermi distribution function

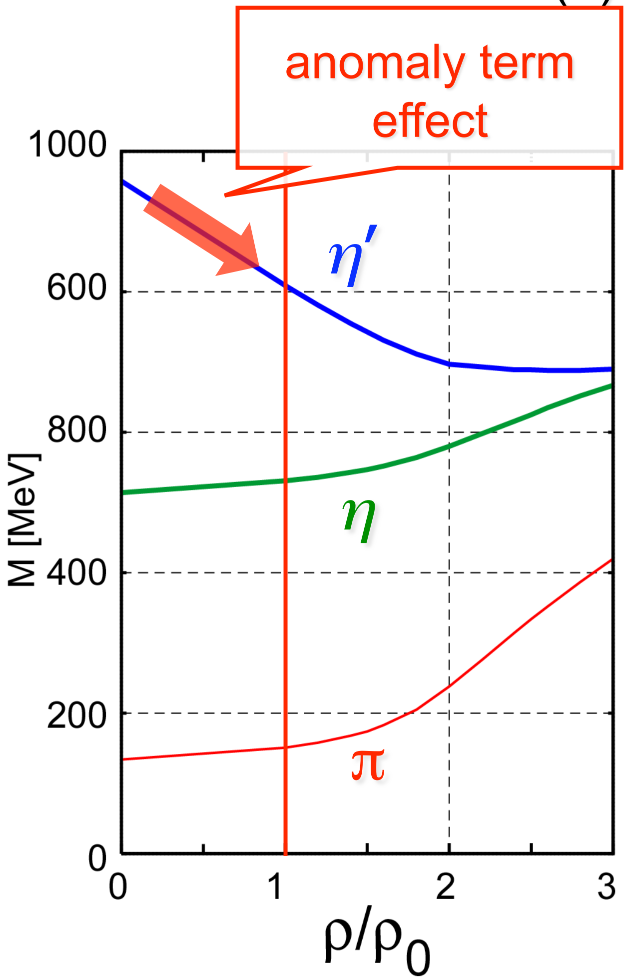


partial restoration in medium

meson properties (mass)

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

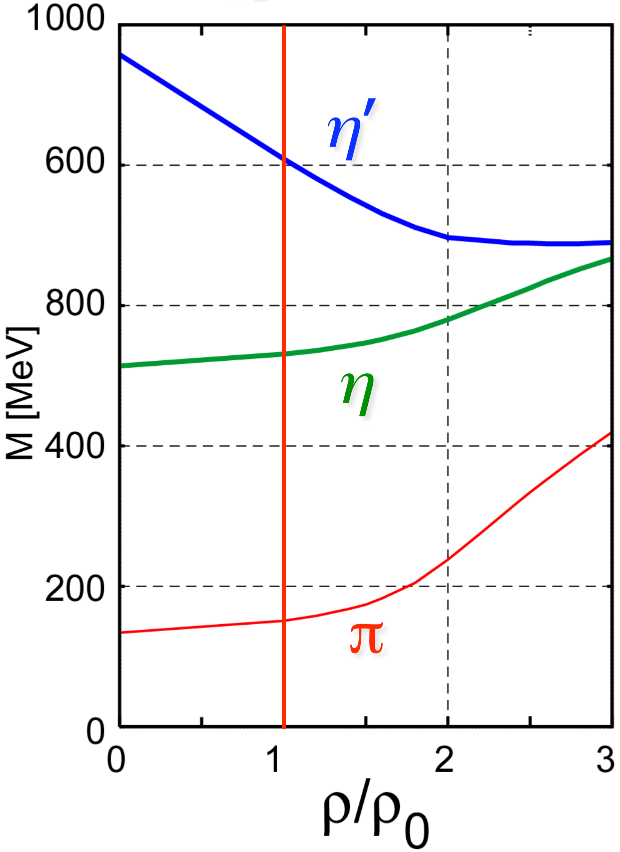
$$\Delta m_{\eta'} \sim -150 \text{ MeV @ } \rho_0$$
$$\Delta m_{\eta} \sim +20 \text{ MeV @ } \rho_0$$

We can see the large medium effect even at normal nuclear density.

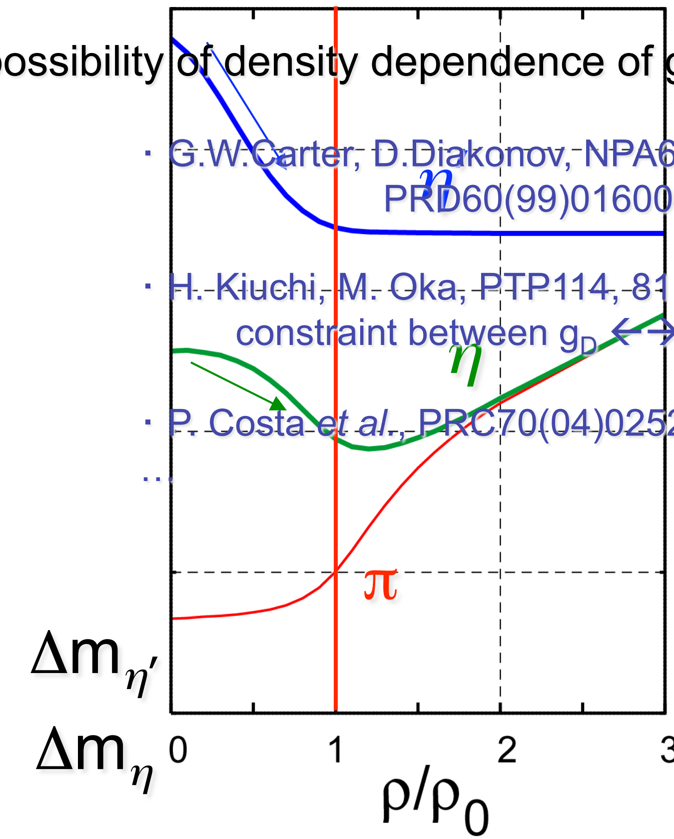
anomaly effect in the finite density

- We simulate an extreme case.

g_D : constant



$g_D = g_D(\rho=0)\ \exp(-(\rho/\rho_0)^2)$



possibility of density dependence of g_D

- G.W.Carter, D.Diakonov, NPA642(98)78
  PRD60(99)016004.
- H. Kiuchi, M. Oka, PTP114, 813, (2005)
  constraint between g_D ←→ Mq
- P. Costa *et al.*, PRC70(04)025204
- …

$\Delta m_{\eta'} \sim$ -250 MeV @ ρ_0

$\Delta m_{\eta} \sim$ -100 MeV @ ρ_0

η- & η'-Nucleus optical potential

~ potential description

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

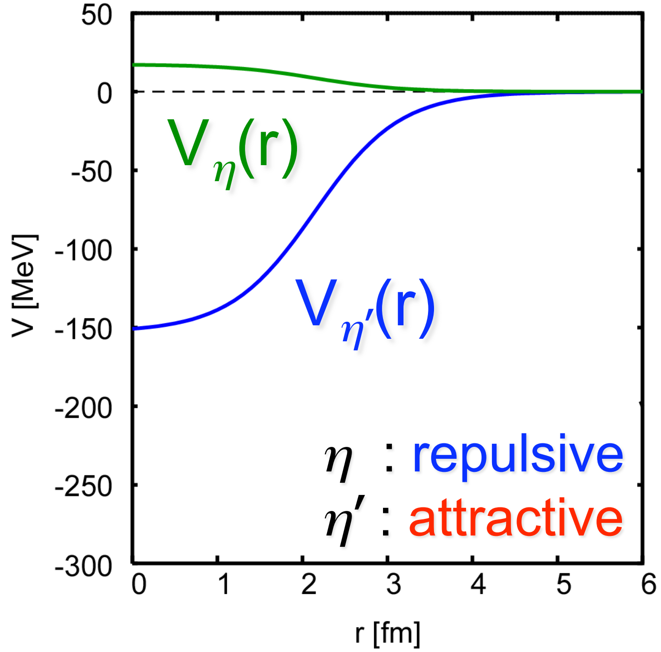
Real Part V_0

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

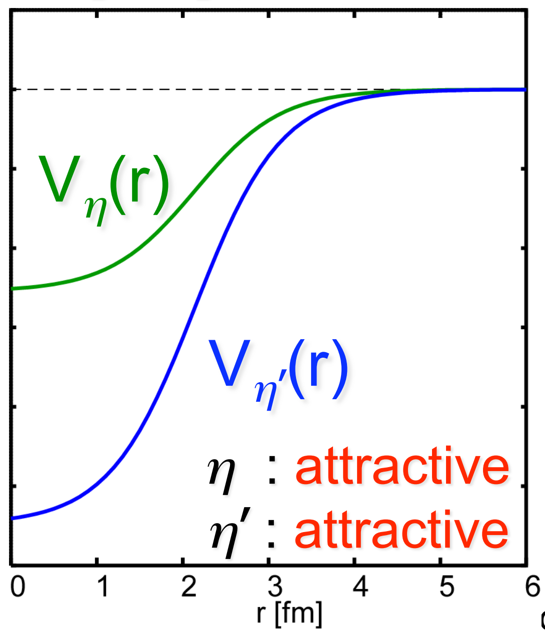
$$m_{\eta'}^2 \to m_{\eta'}^2(\rho) = (m_{\eta'} + \Delta m_{\eta'}(\rho))^2 \sim m_0^2 + 2m_0\Delta m(\rho)$$

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

g_D : constant



$g_D = g_D(\rho=0)\, e^{-(\rho/\rho_0)^2}$



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

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

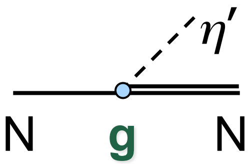
$$\Delta m(\rho) \to V(\rho(r)) = V_0 \frac{\rho(r)}{\rho_0}$$

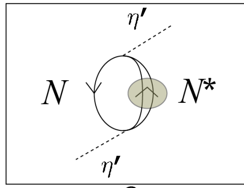
Imaginary Part W_0 for η' ~ phenomenological estimation

» estimated from AIP Conf.Proc.717(04) 837 (A.Sibirtsev,Ch.Elster, S.Krewald, J.Speth)
analysis of $\gamma p \to \eta' p$ data

(only one resonance included)

⟶ fix a coupling g





› in analogy with Δ-hole model for the π-nucleus system

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

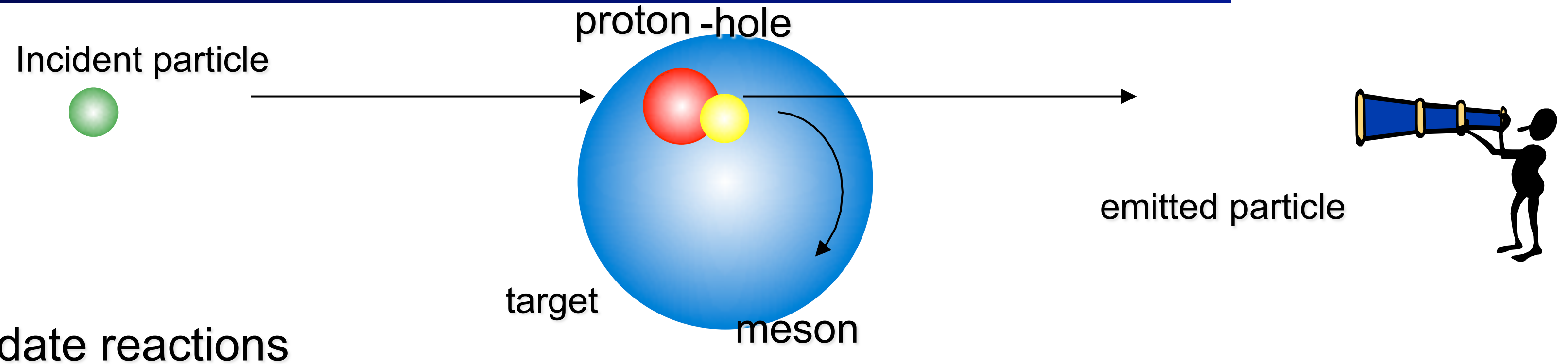
$$W_0 = -5,\ -20\ \mathrm{MeV}\ (\mathrm{parameter})$$

Imaginary Part for η

$W_0 = -40$ MeV

D.Jido,H.N.,S.Hirenzaki, PRC66(02)045202,
H.N.,D.Jido,S.Hirenzaki, PRC68(03)035205,

Missing mass spectroscopy / reaction parameters



candidate reactions

ex.) (d,^{3}He) reaction … π atom formation, η-mesic nuclei @ GSI

(γ,p) reaction … smaller distortion effect, nearly recoilless for heavy η'

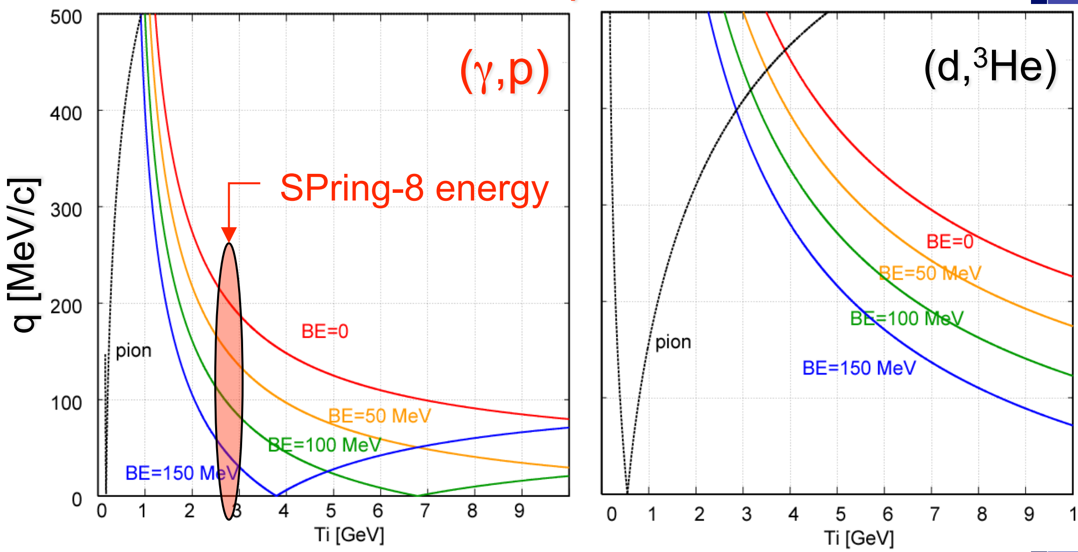
Reaction parameters

- (γ,p) reaction Eγ=2.7 GeV
- target : ^{12}C
- forward : θ_p = 0 deg.
- elementary cross section for γ+p → η'+p

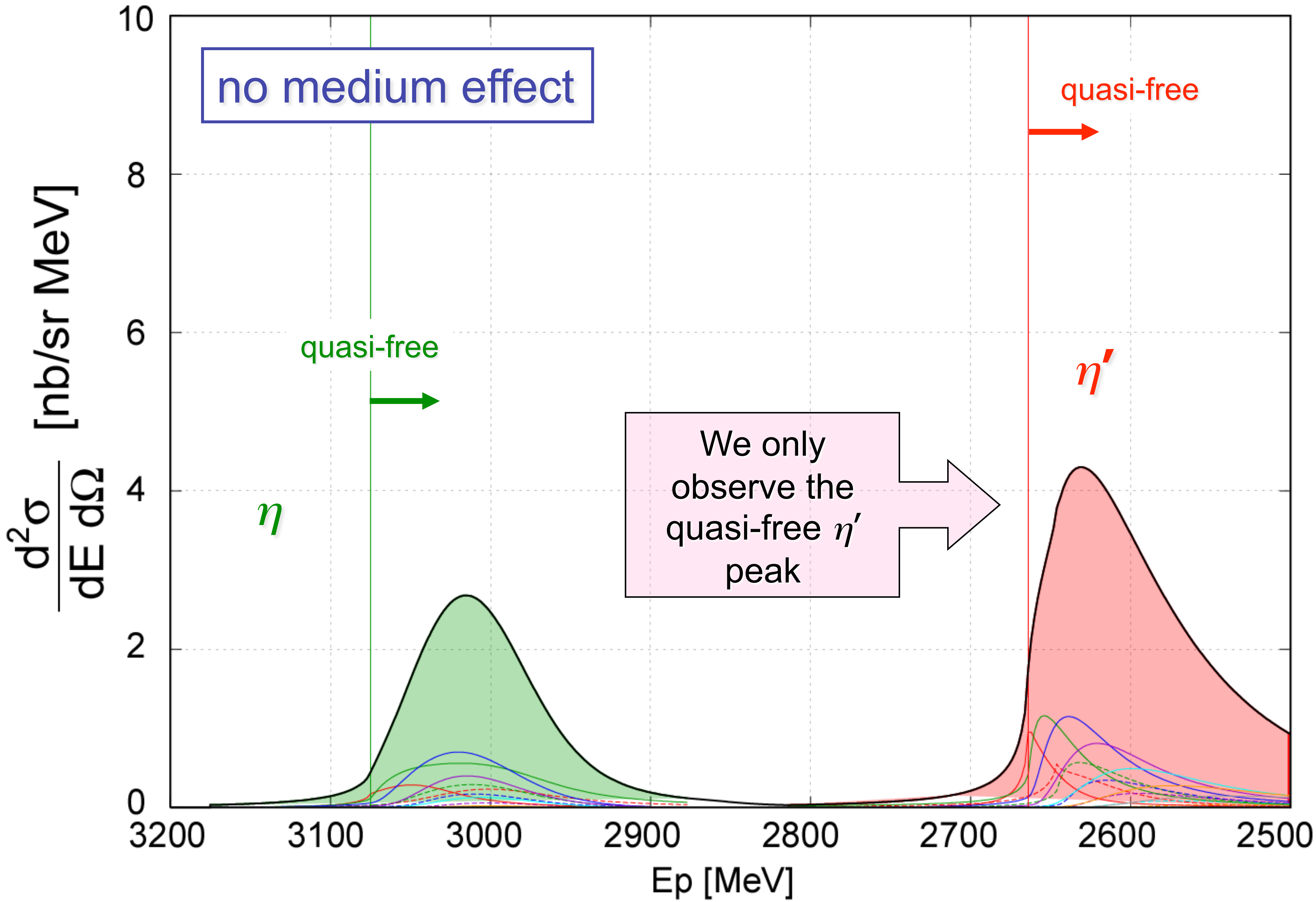
$$\left(\frac{d\sigma}{d\Omega}\right)^{Lab}_{0^\circ} \sim 150\ \mathrm{nb/sr}$$

[SAPHIR collaboration, PLB444(98)555-562
Chiang, Yang, PRC68(03)045202]

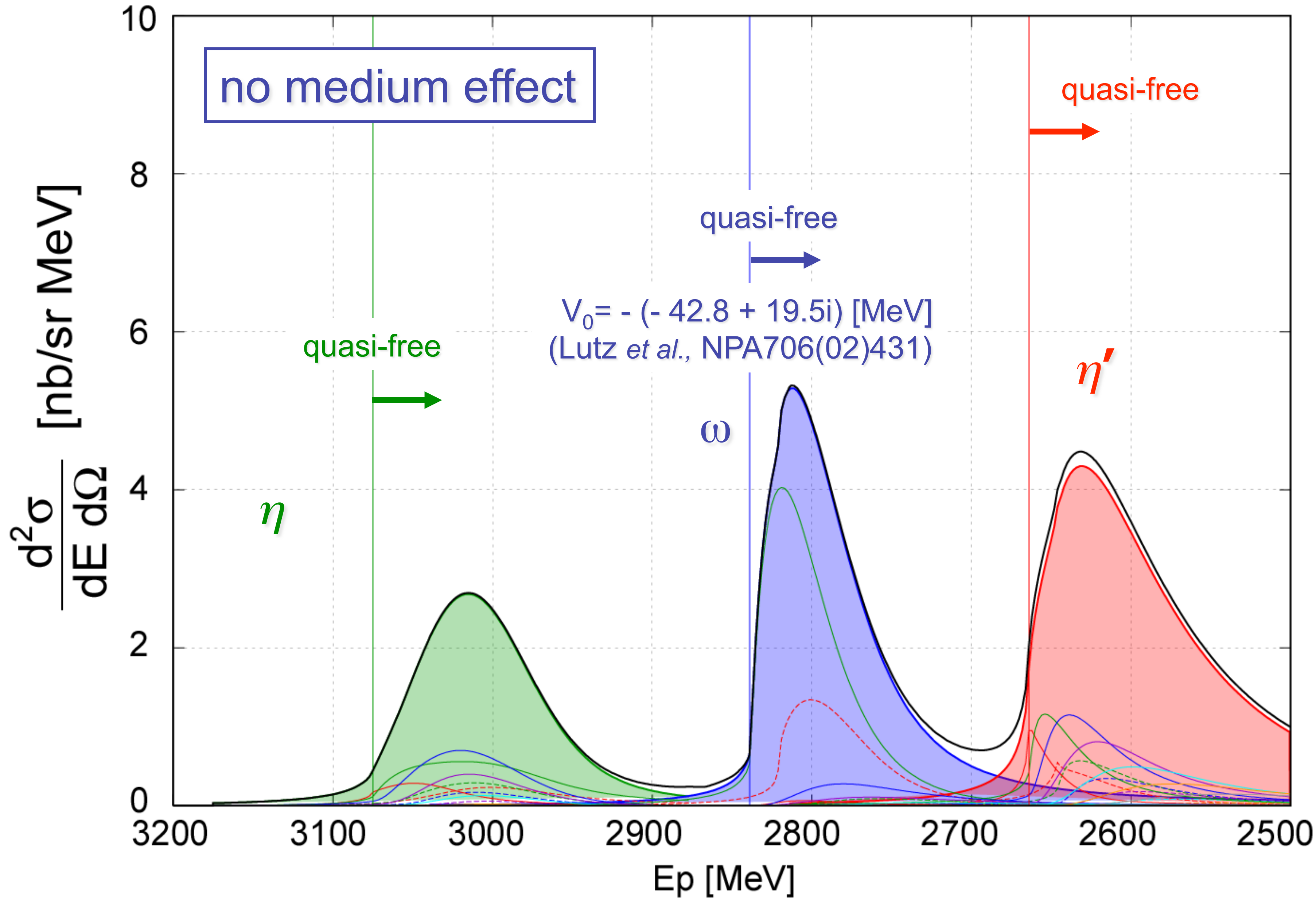
Momentum transfers for η'-mesic nuclei formation



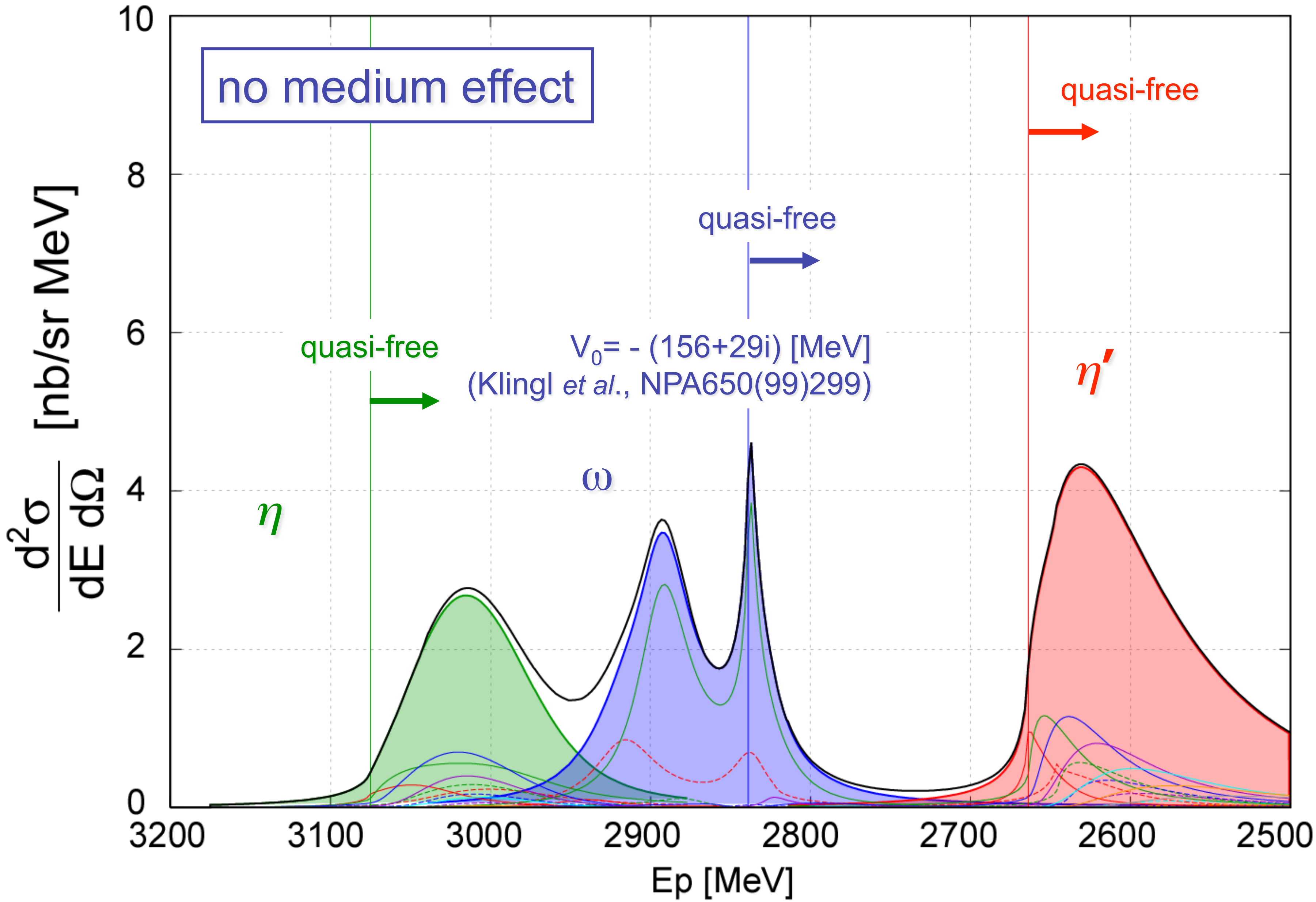
Numerical results : $^{12}C(\gamma,p)^{11}B_{\eta,\omega,\eta'}$



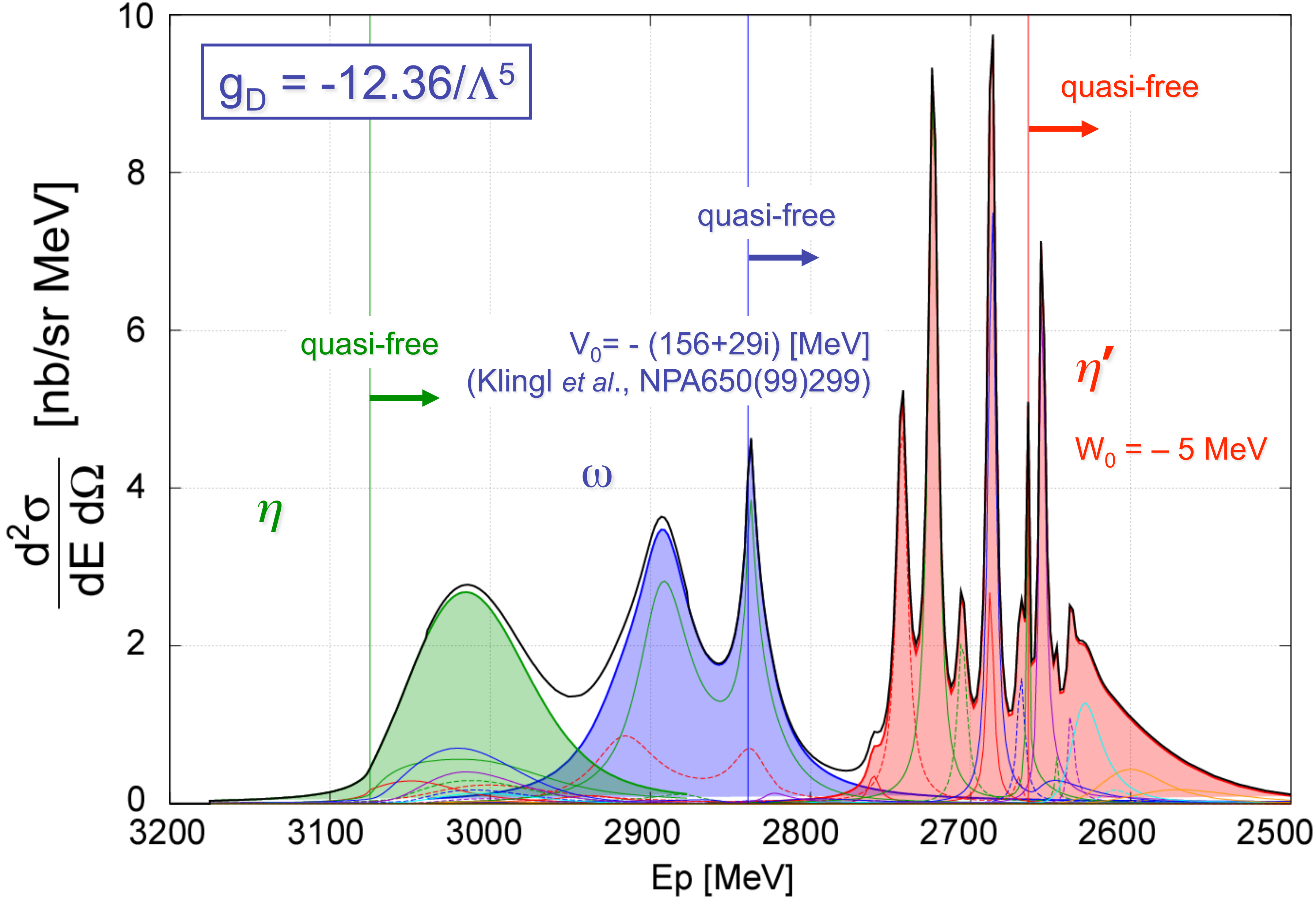
Numerical results : $^{12}C(\gamma,p)^{11}B_{\eta,\omega,\eta'}$



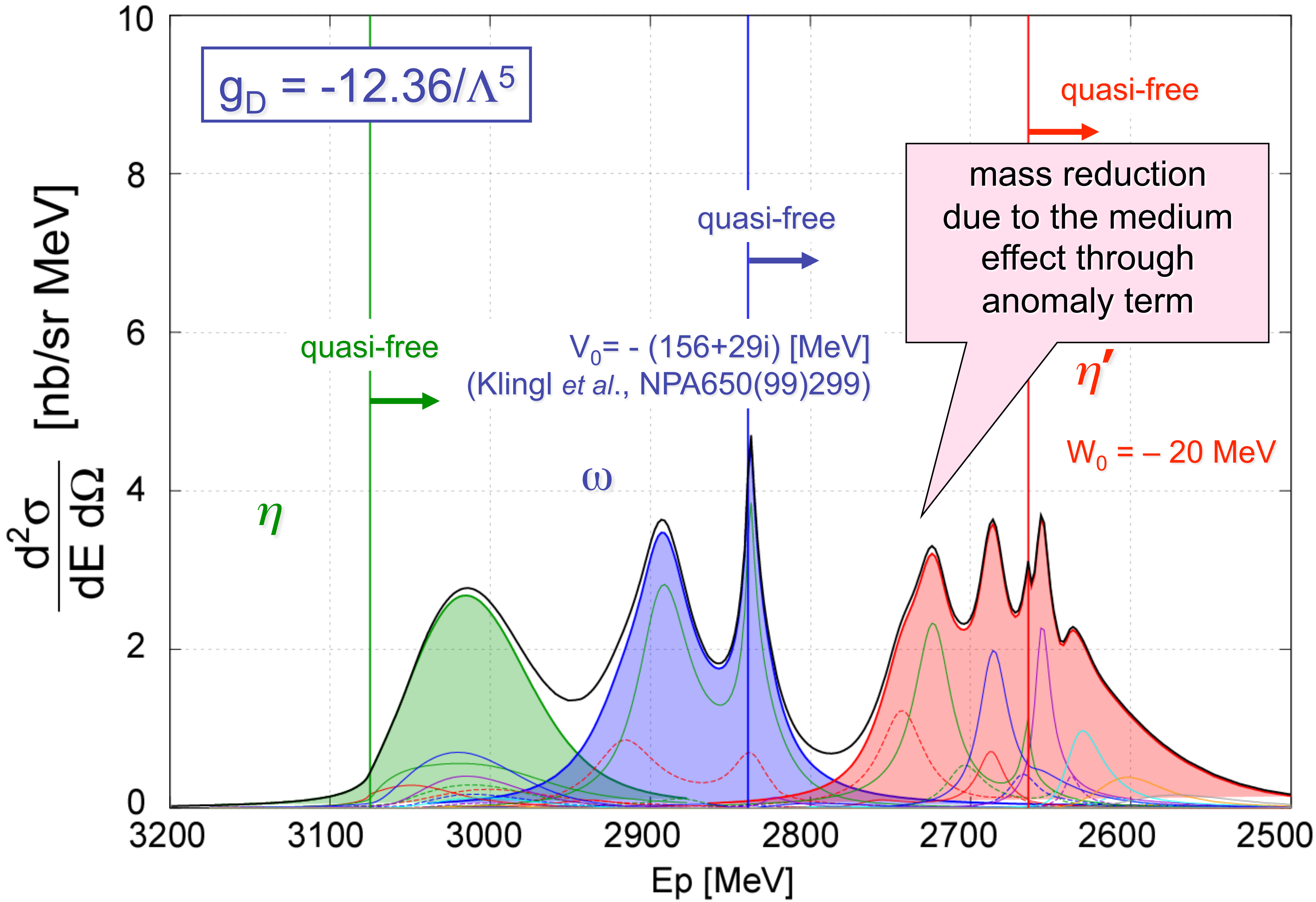
Numerical results : $^{12}C(\gamma,p)^{11}B_{\eta,\omega,\eta'}$



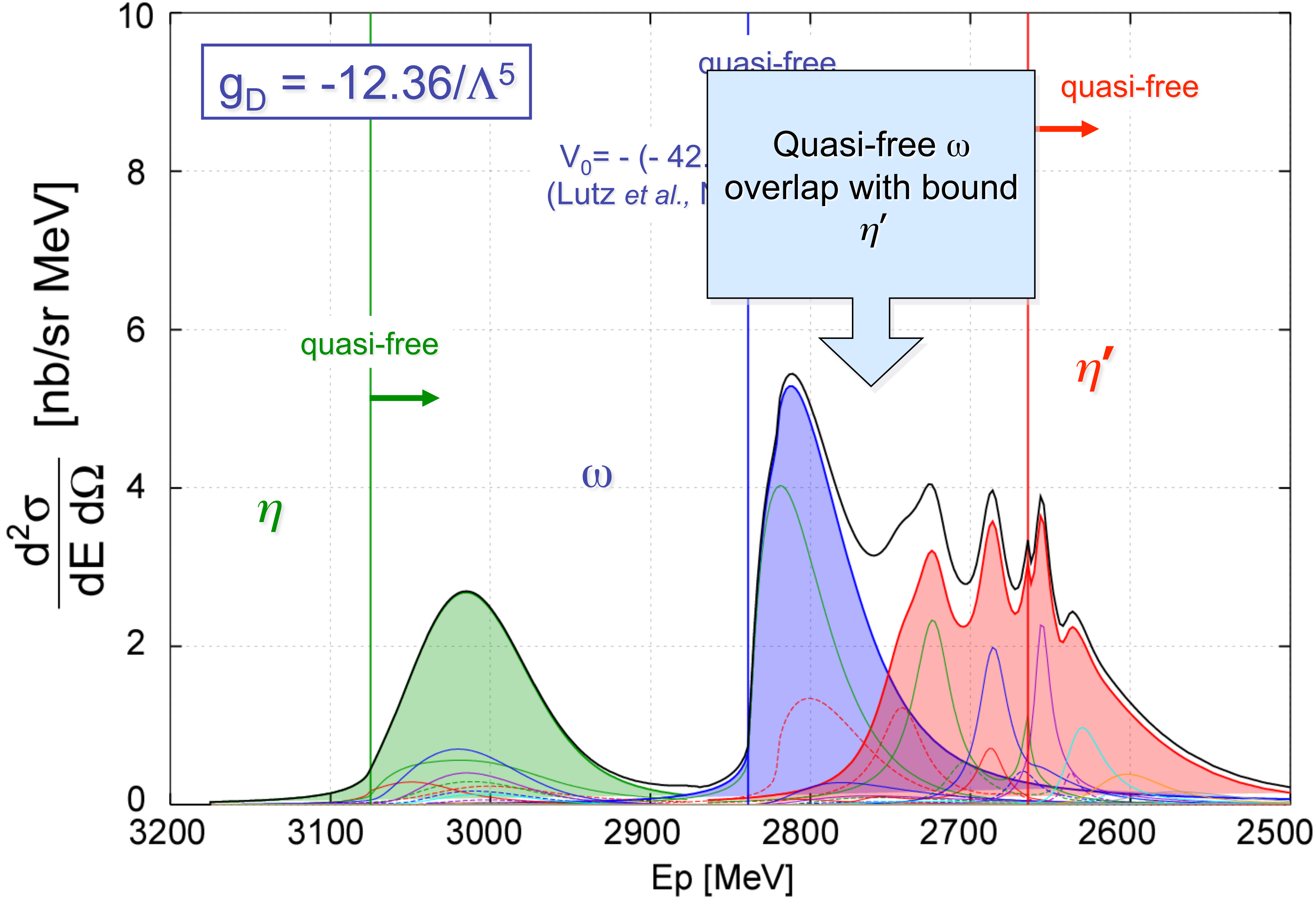
Numerical results : $^{12}C(\gamma,p)^{11}B_{\eta,\omega,\eta'}$



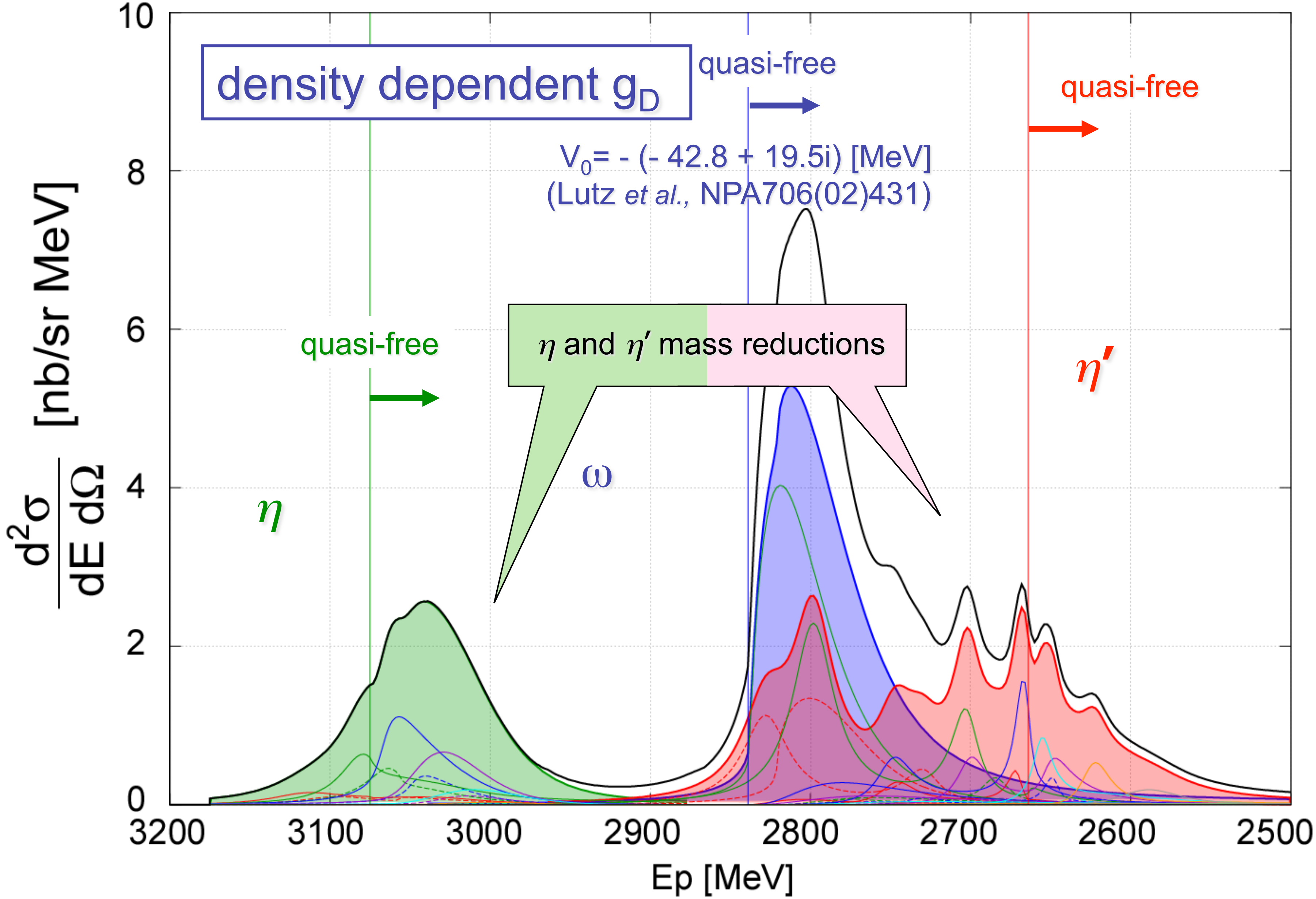
Numerical results : $^{12}C(\gamma,p)^{11}B_{\eta,\omega,\eta'}$



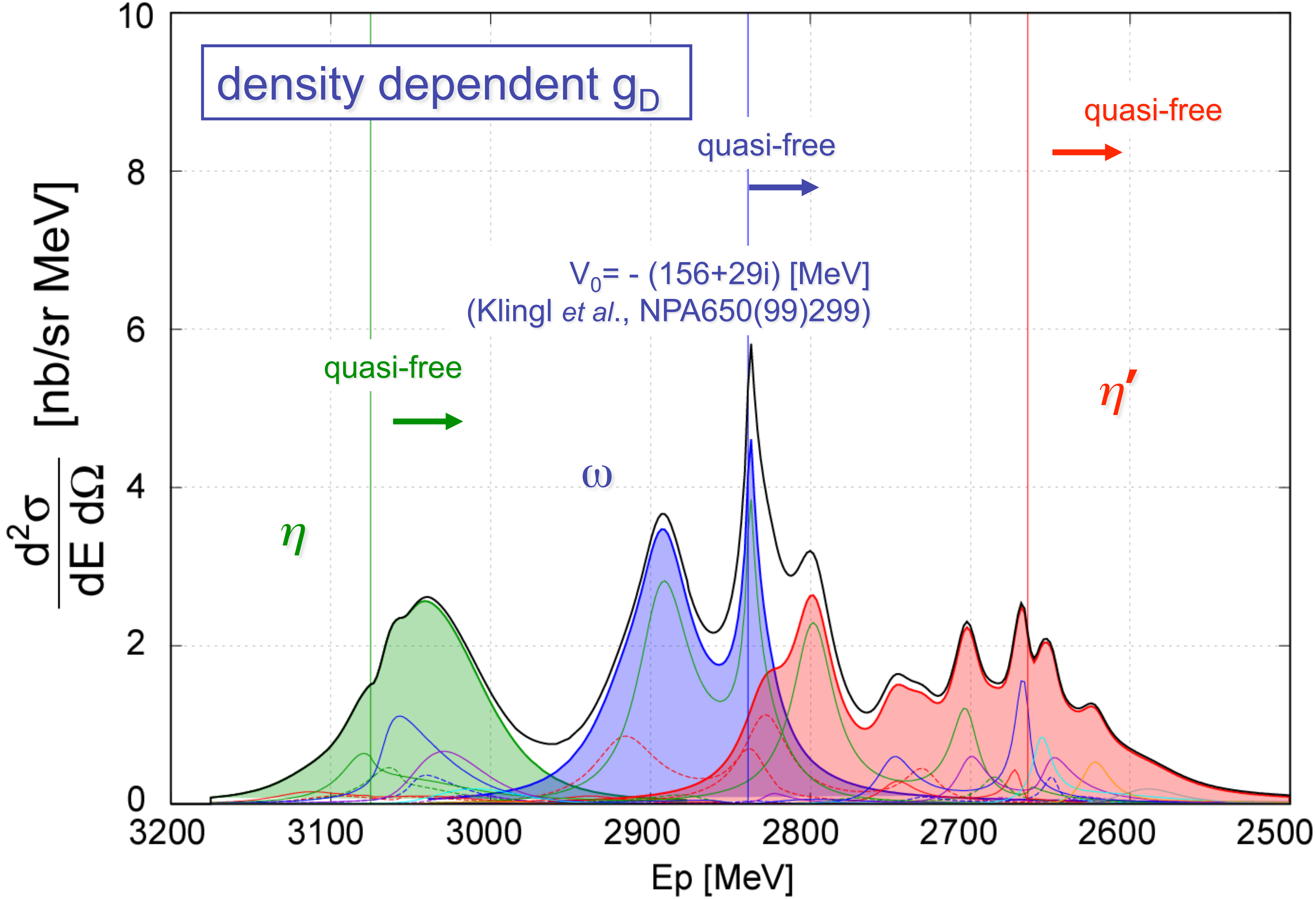
Numerical results : $^{12}C(\gamma,p)^{11}B_{\eta,\omega,\eta'}$



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



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



η and η' mesic nuclei

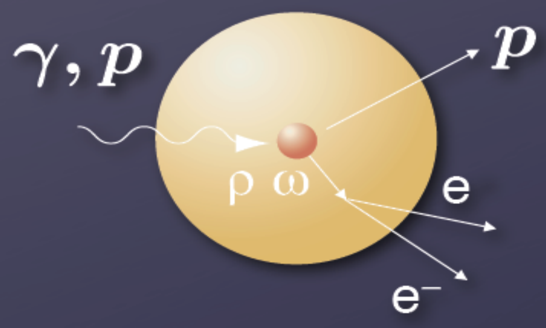
- $U_A(1)$ anomaly effect in finite density
  through the view point of **"mesic nuclei"**
    - possibility of observation of anomaly effects in-medium
    - η and η' mesic nuclei with NJL model
    - response to the environment change

- (γ,p) reaction for the mesic nuclei formation
  - Reasonably large cross sections predicted
    - S/N ~ 1/10 … N.Muramatsu, private communication
    - the experiment for the formation of ω-mesic nuclei
      @ SPring-8
    - (π,N) experiment for η mesic nuclei formation @ J-PARC
- Future
    - density dependence of g_D ?
    - Other treatment ? – beyond the NJL model
    - relation with other models for η & η'
      - chiral doublet model & chiral unitary approach for the η-mesic nuclei

3-4 Vector Mesons in Nuclei

By Hayano@INPC07

M_{e+e-}



KEK E325 p+A → V + X
J-LAB g7 γ+A → V + X

$$m_{\rho,\omega} = \sqrt{(p_{e+} + p_{e-})^2}$$

- small FSI
- rare decay
- fast ω, ϕ decay outside

	$BR(e^+e^-)$	cτ
ρ (770)	4.7×10^{-5}	1.3 fm
ω (782)	7.2×10^{-5}	23 fm
ϕ (1020)	3×10^{-4}	44 fm

* Omega mesic nuclei

- Data @ TAPS
- Problems of background, energy resolution,

  and finite angle observation
- Possible ω bound state signals.

  Kaskulov, Nagahiro, Hirenzaki, Oset,

  Phys. Rev. C75 (2007) 064616
- Exp by K.Ozawa, J-PARC proposal

  $A(\pi^-, n)\,\omega + \omega \rightarrow \pi^0\,\gamma$ reaction
- m_{vector} shift VS chiral symmetry . Simple relation?

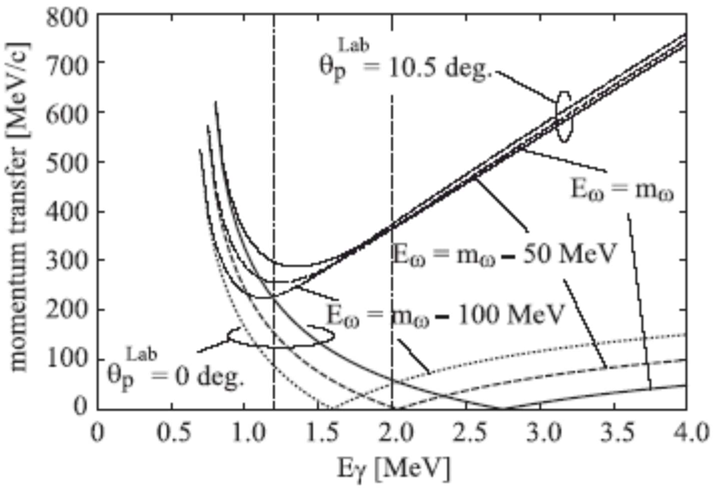


FIG. 1. Momentum transfers as a function of the incident photon energy E_γ in the (γ, p) reaction. The solid, dashed, and dotted lines show the momentum transfers at ω energy $E_\omega = m_\omega$, $E_\omega = m_\omega -$ 50 MeV, and $E_\omega = m_\omega - 100$ MeV, respectively. The thick lines indicate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

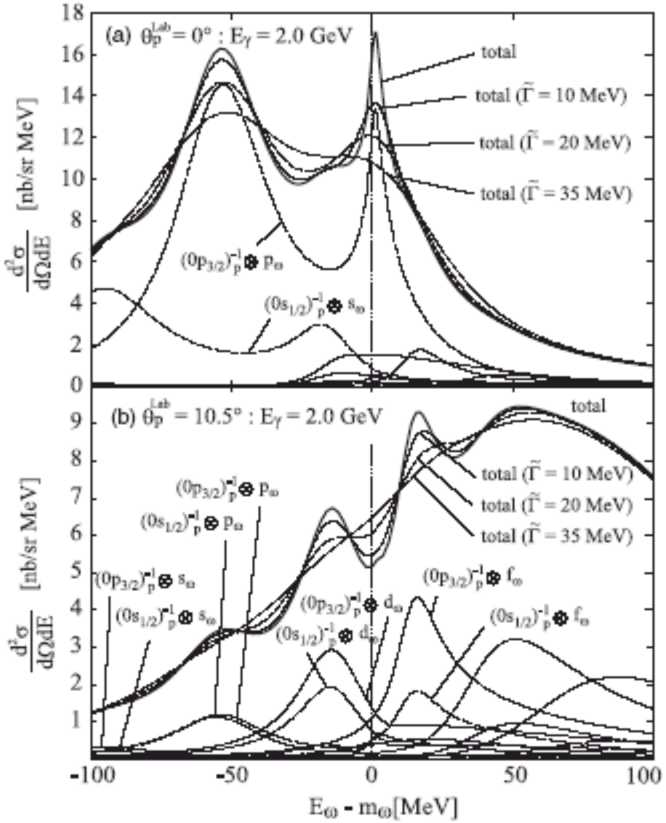


FIG. 2. Formation spectra of the ω mesic nucleus in ^{12}C(γ, p) reaction at emitted proton angle (a) $\theta_p^{\rm Lab} = 0°$ and (b) $\theta_p^{\rm Lab} = 10.5°$ calculated with the potential depth $(V_0, W_0) = -(156, 29)$ MeV as in Eq. (2c). The incident photon energy is $E_\gamma = 2.0$ GeV. The thick solid lines show the total spectra; the dashed lines, the subcomponents as indicated in the figures. The assumed experimental resolutions $\tilde{\Gamma}$ are also indicated.

ϕ mesic nuclei

J. Yamagata-Sekihara (YITP)
D. Cabrera (Complutense Univ., Madrid)
M. J. Vicente Vacas (Valencia Univ.)

- ϕN interaction …… s quark component
  - OZI rule violation
  - <N|s̄s|N>
  - Chiral symmtery restoration by s̄s
- Strong coupling to K̄K …. Relate to Kaon in nuclei
  - (asymmetric) medium effects from $\Pi_{\bar{K}}$ and Π_K

* ϕ meson - nucleus system

- ϕ meson mass shift in nucleus medium
  - QCD Sum Rule -- $m^*/m=1-0.03\rho/\rho_0$

    (Theor.) T. Hatsuda, S. H. Lee, Phys. Rev. C 46 (92) R34
  - 12GeV/c Proton induced $\phi \to e^+e^-$ -- mass shift 3.4 $\pm$0.6%

    (Exp.(KEK-PS E325 Collaboration)) R. Muto, et al., Phys. Rev. Lett. 98 (07) 042501

- ϕ meson photo - production
  - Pomeron Exchange Process
  - Anomalous p_γ dependence of $\left(\frac{d\sigma}{dt}\right)$

    (Theor.) A. I. Titov and T. -S. H. Lee, Phys. Rev. C 67 (03) 065205

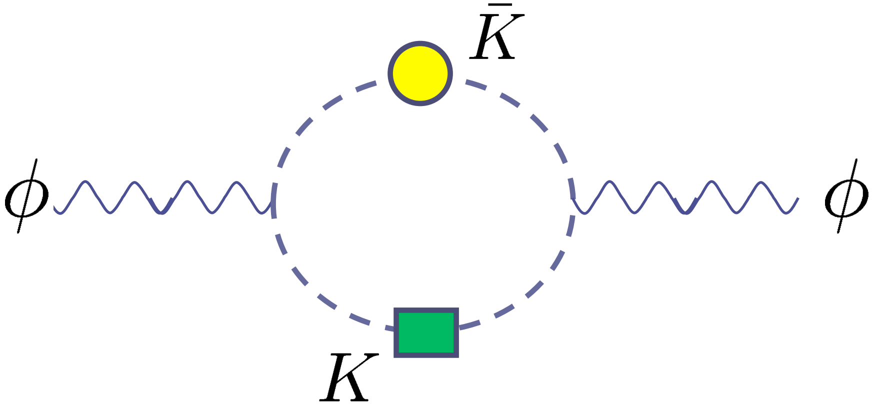
    (Exp.(LEPS Collaboration)) T. Mibe, et al., Phys. Rev. Lett. 95 (05) 182001

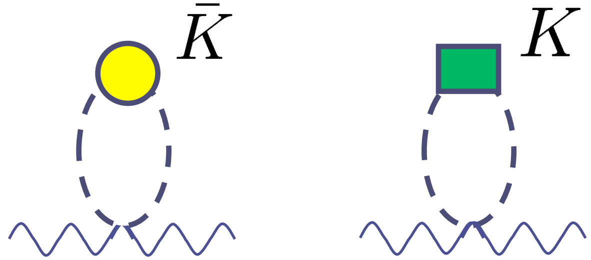
ϕ in Nucleus as Mesic Nucleus (Bound Satets)

* ϕ-Meson self-energy in Nuclear Matter $\Delta\Pi_{\phi}(E,\rho)$

Main diagrams

D. Cabrera, M. J. Vicente Vacas, PRC67(03)045203



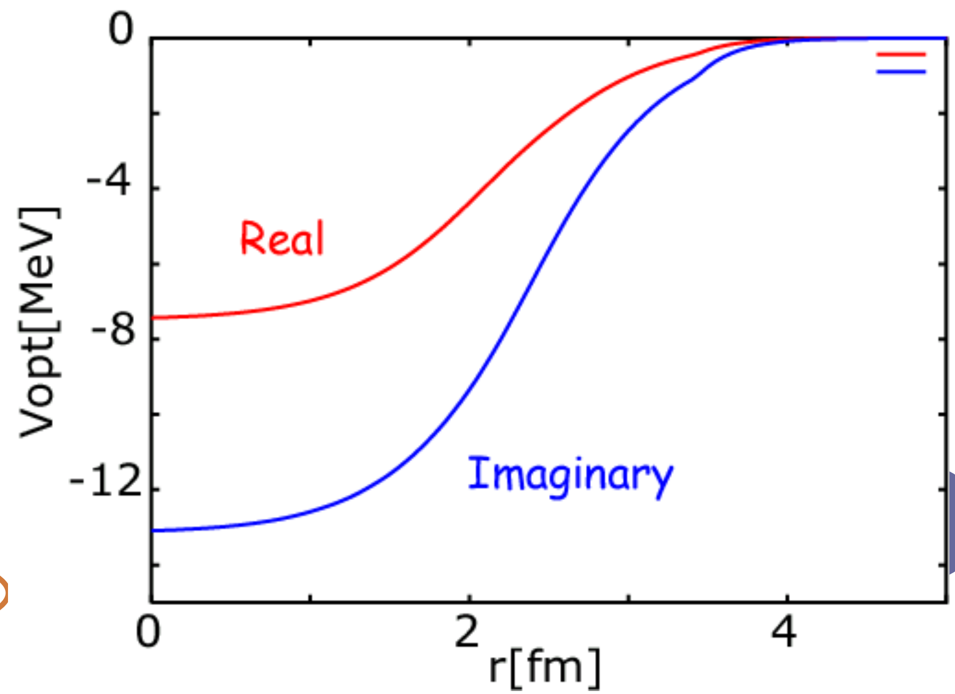


$$\Delta\Pi_{\phi} = \Pi_{\phi}^{med} - \Pi_{\phi}^{free}$$

- Optical potential

$$\Delta\Pi_{\phi}(E,\rho) = 2\mu V_{\rm opt}(E,r)$$

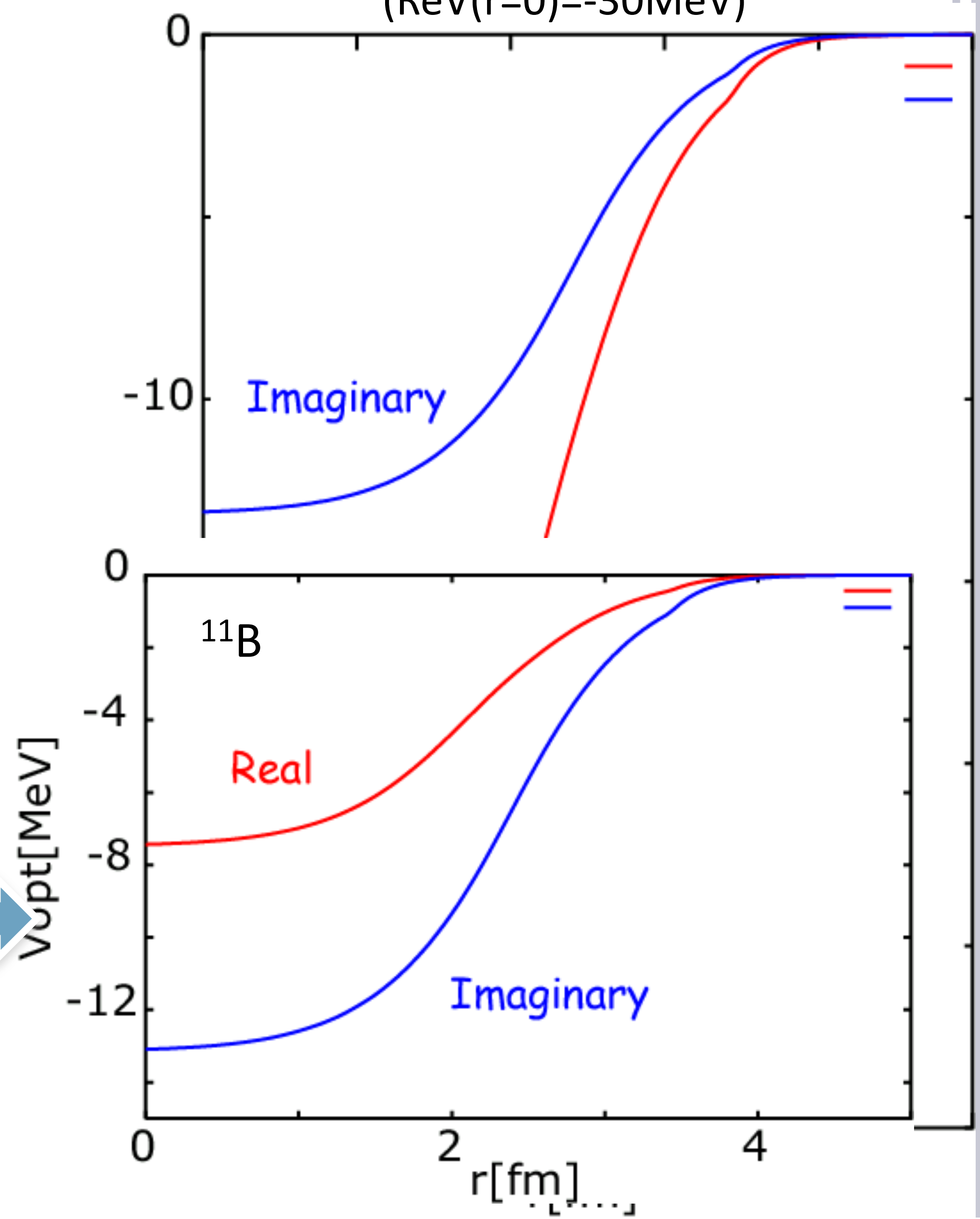
Very Shallow Real Part



ϕ in Nucleus

* Optical Potential of ϕ

<< Deep Φ potential>>
(ReV(r=0)=-30MeV)

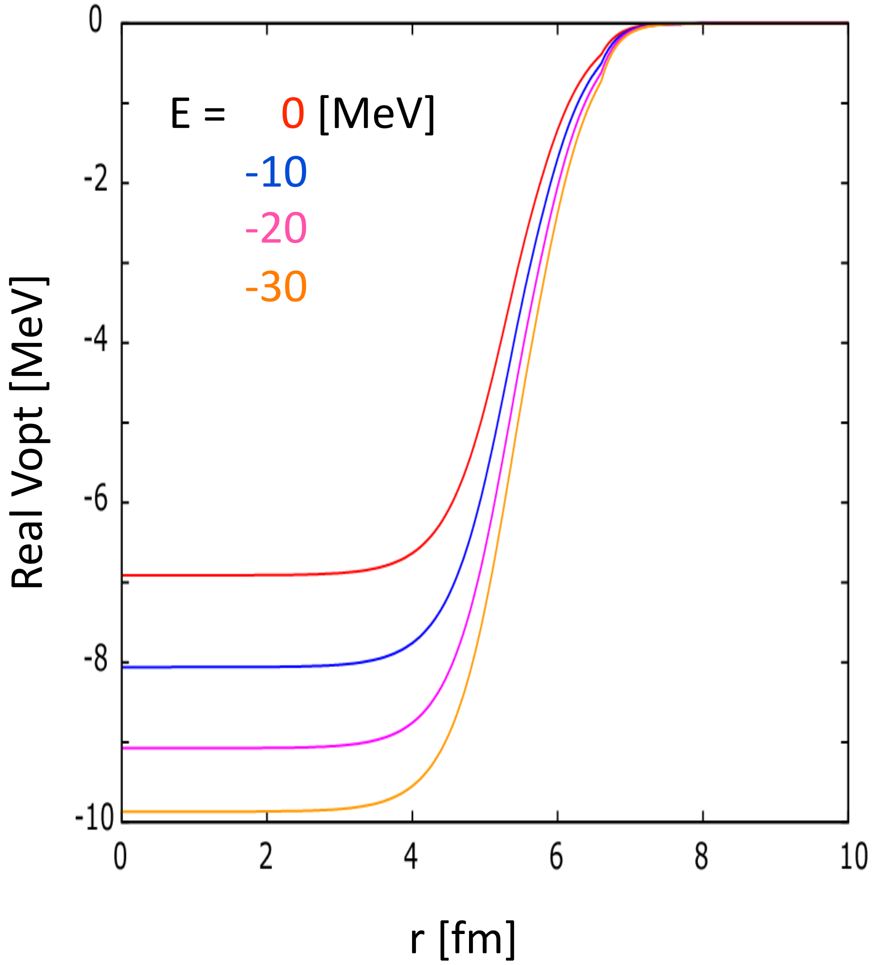


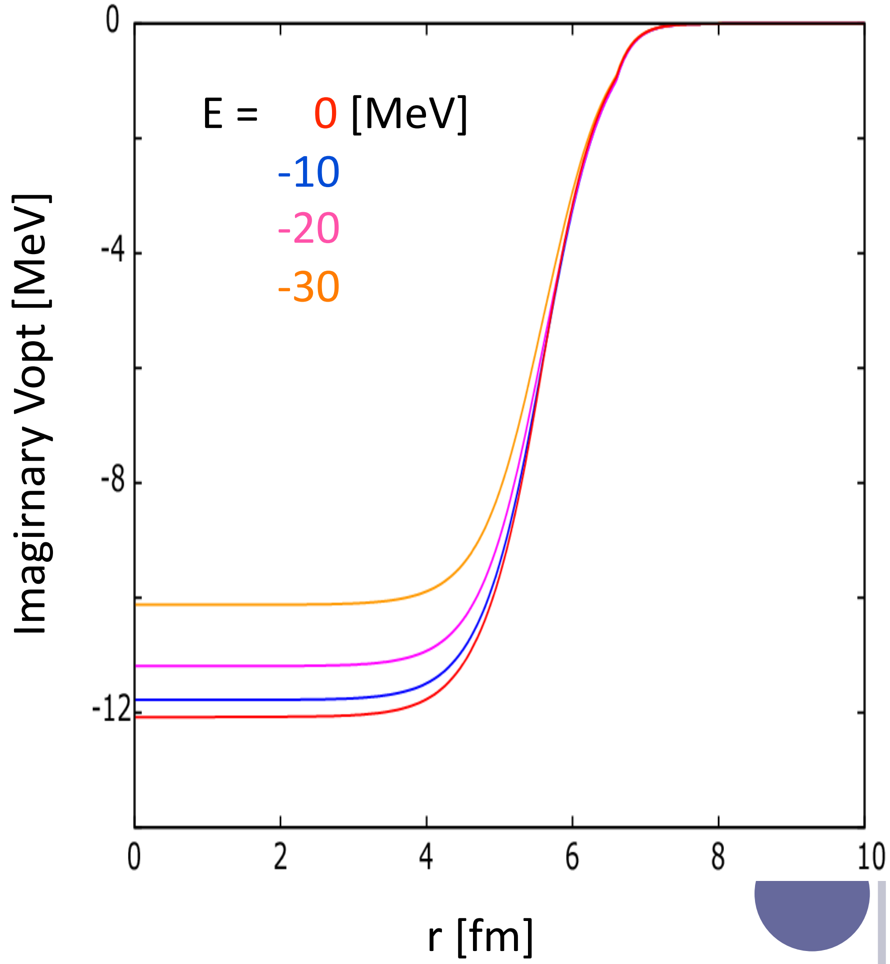
<< Shallow Φ potential >>
(ReV(r=0)=-7MeV)

* Real Part:-**30MeV**
(QCD Sum rule)
(KEK-PS E325)

φ in Nucleus

＊Energy dependence of φ optical potential (Sn case)





Structure of φ Mesic Nuclei

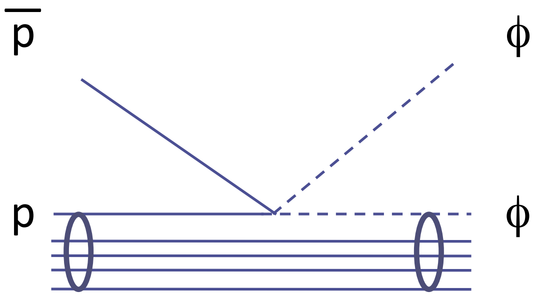
- Klein-Gordon equation $$[-\nabla^2 + \mu^2 + \Delta\Pi(r,E)]\phi(\vec{r}) = E\phi(\vec{r})$$
- φ bound states in Nucleus (Γ includes free φ width : Γ = 4.26 MeV)

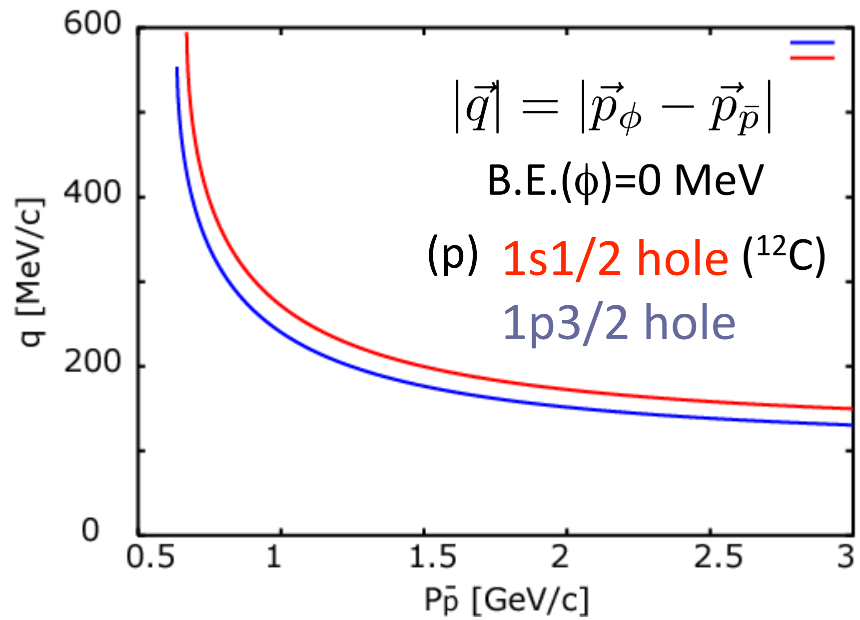
State--B.E. (Γ) [MeV]	Shallow Φ potential (ReV(r=0)=-7MeV)	Deep Φ potential (ReV(r=0)=-30MeV)
^{11}B (^{12}C)	None	1s -- 10.2(22.1)
^{39}K (^{40}Ca)	None	1s -- 28.5(24.2) 2p -- 11.8(24.1)
^{123}In (^{124}Sn)	1s -- 2.34(25.82)	1s -- 34.5(22.9) 2s -- 12.2(24.1) 2p -- 26.3(24.2)
^{207}Tl (^{208}Pb)	1s -- 3.73(26.71)	1s -- 40.1(21.8) 2s -- 24.4(24.4) 2p -- 27.1(22.2) 3p -- 13.1(24.7) 3d -- 27.5(24.0)

Formation reaction -- ($\bar{p}$,ϕ) reaction

Discussion with
Iwasaki and Ohnishi
LOI@JPARC

- Momentum transfer





$p_{\bar{p}}$ = 1.3 GeV/c

Relatively smaller momentum transfer
than (γ,p), (π^-,n).

- Green Function Method

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

$$\left(\frac{d^2\sigma}{d\Omega dE}\right) = \left(\frac{d\sigma}{d\Omega}\right)^{\rm ele} \sum_\alpha -\frac{1}{\pi}{\rm Im}\int d\vec{r}d\vec{r}'\, f^*_\alpha(\vec{r}')G(E;\vec{r},\vec{r}')f_\alpha(\vec{r})$$

$$\left(\frac{d\sigma}{d\Omega}\right)^{\rm ele} \quad -$$

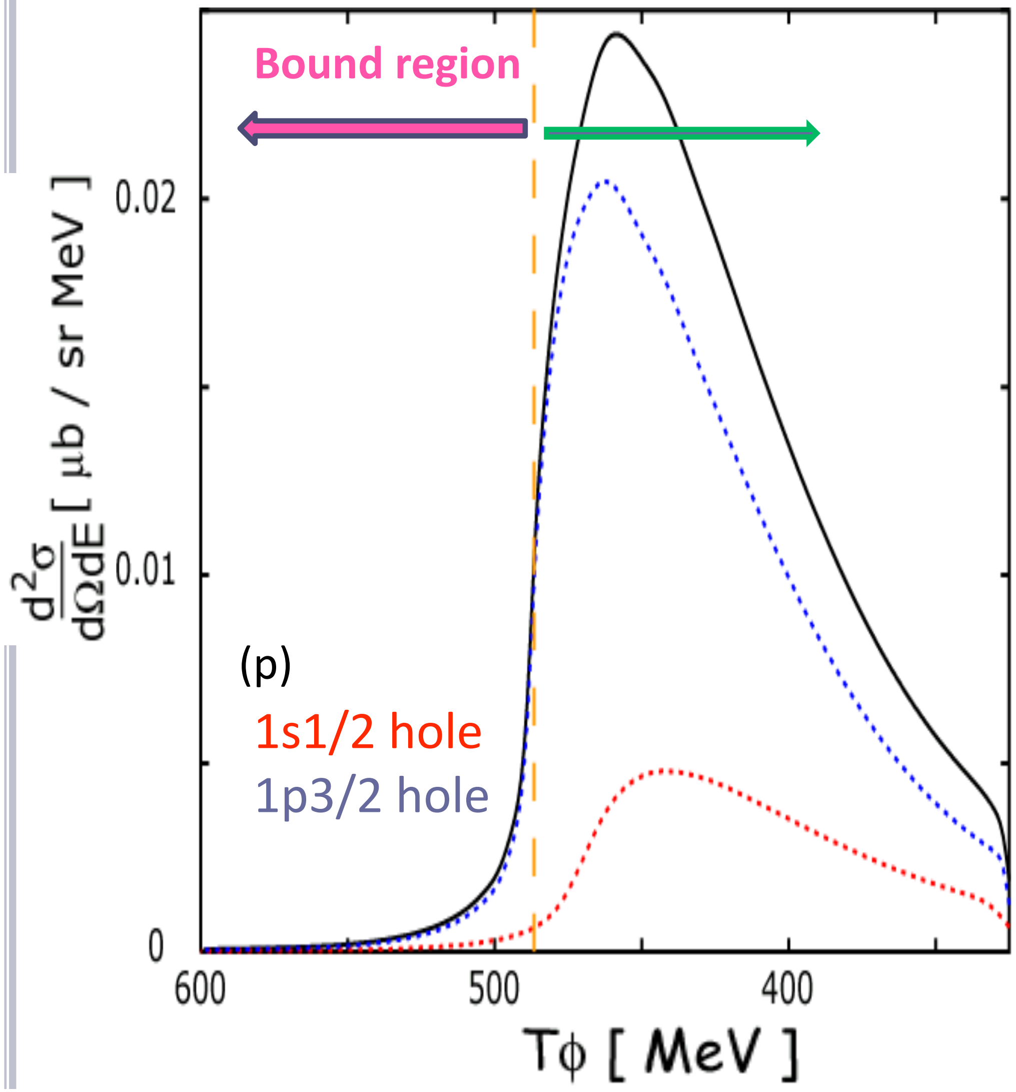
uniform in CM sys.)

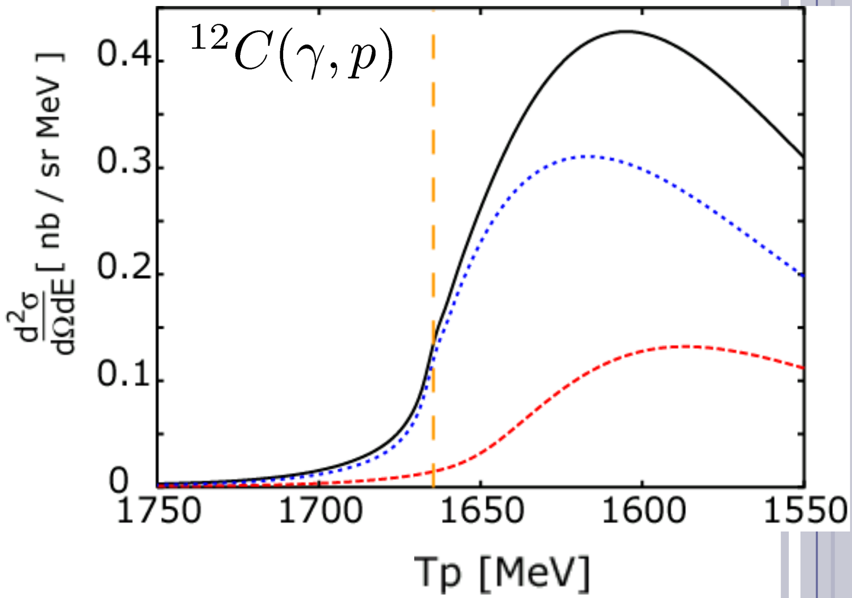
C. Evangelista et al., Phys. Rev. D 57(98)5370

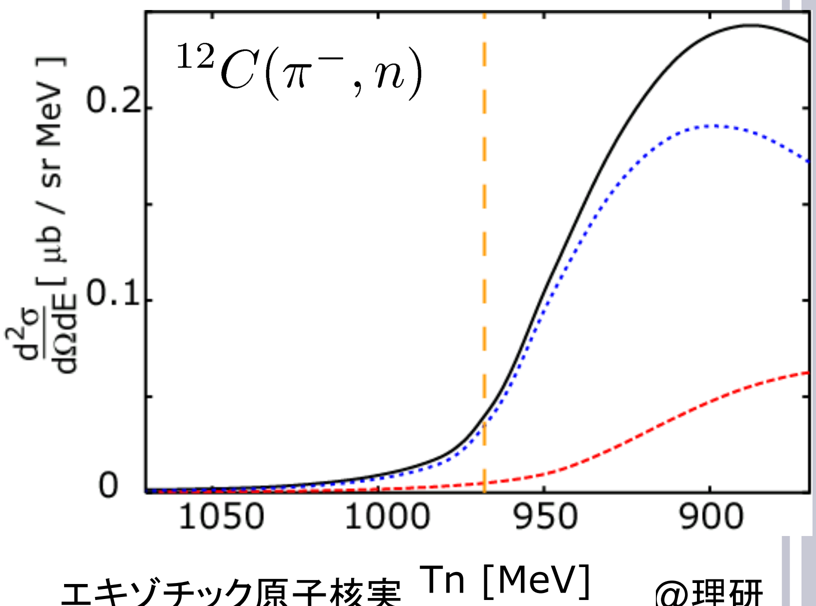
Formation Spectrum -- ^{12}C target case

<< Shallow Φ potential>>

- $p_{\bar{p}}$=1.3 GeV/c

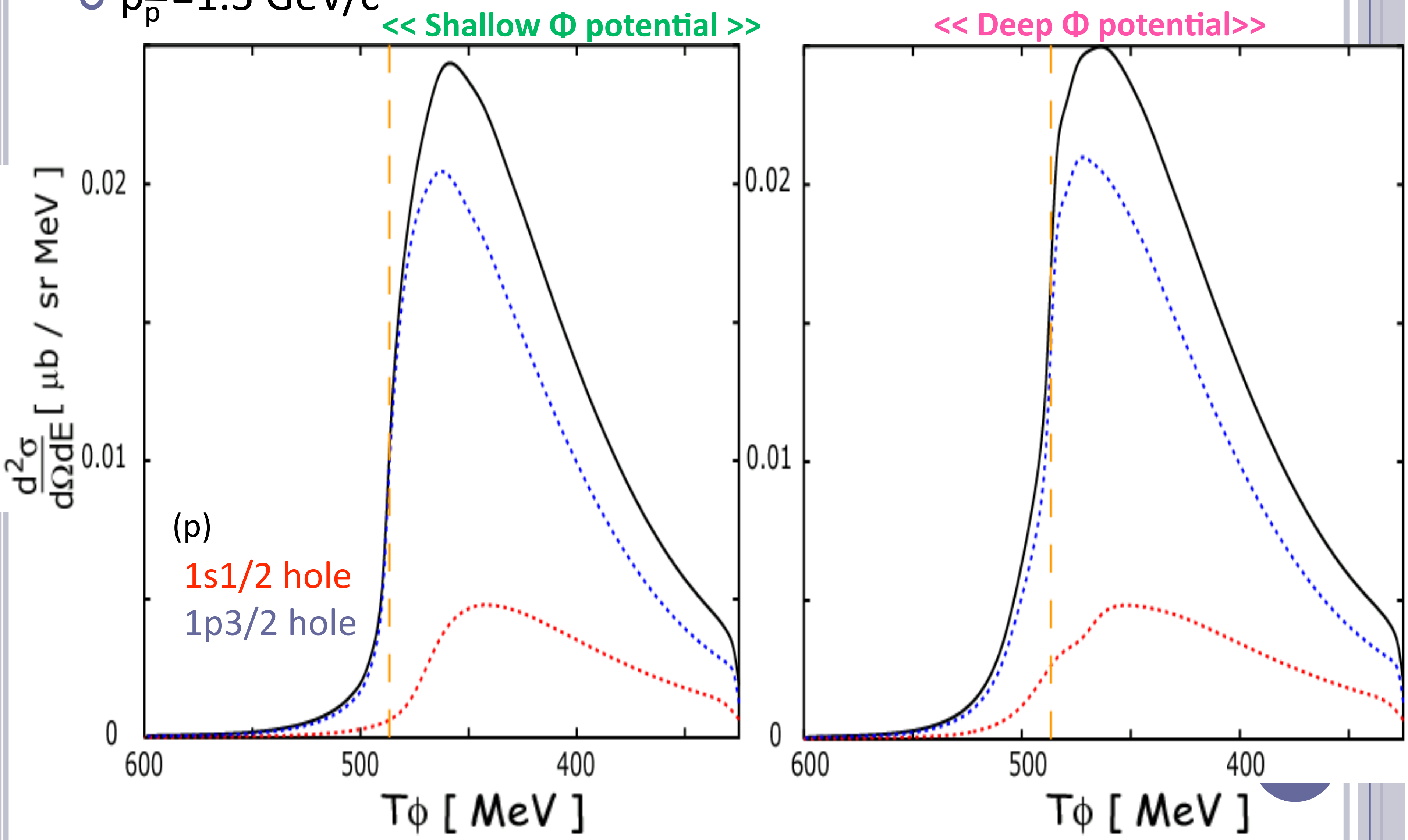






Formation Spectrum -- $^{12}C(\bar{p},\phi)$ reaction

- $p_{\bar{p}}$=1.3 GeV/c

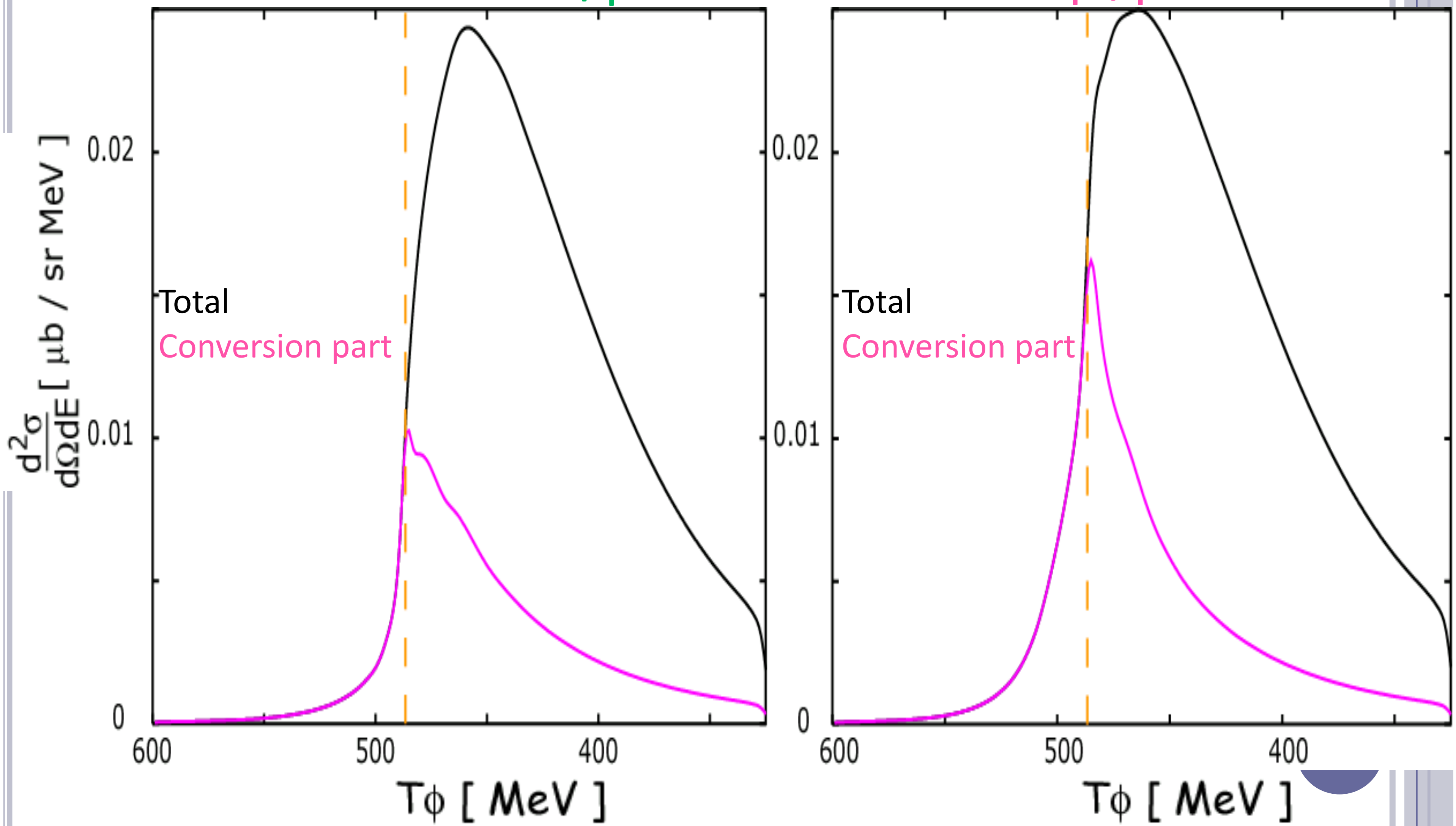


Formation Spectrum -- $^{12}C(\bar{p},\phi)$ reaction

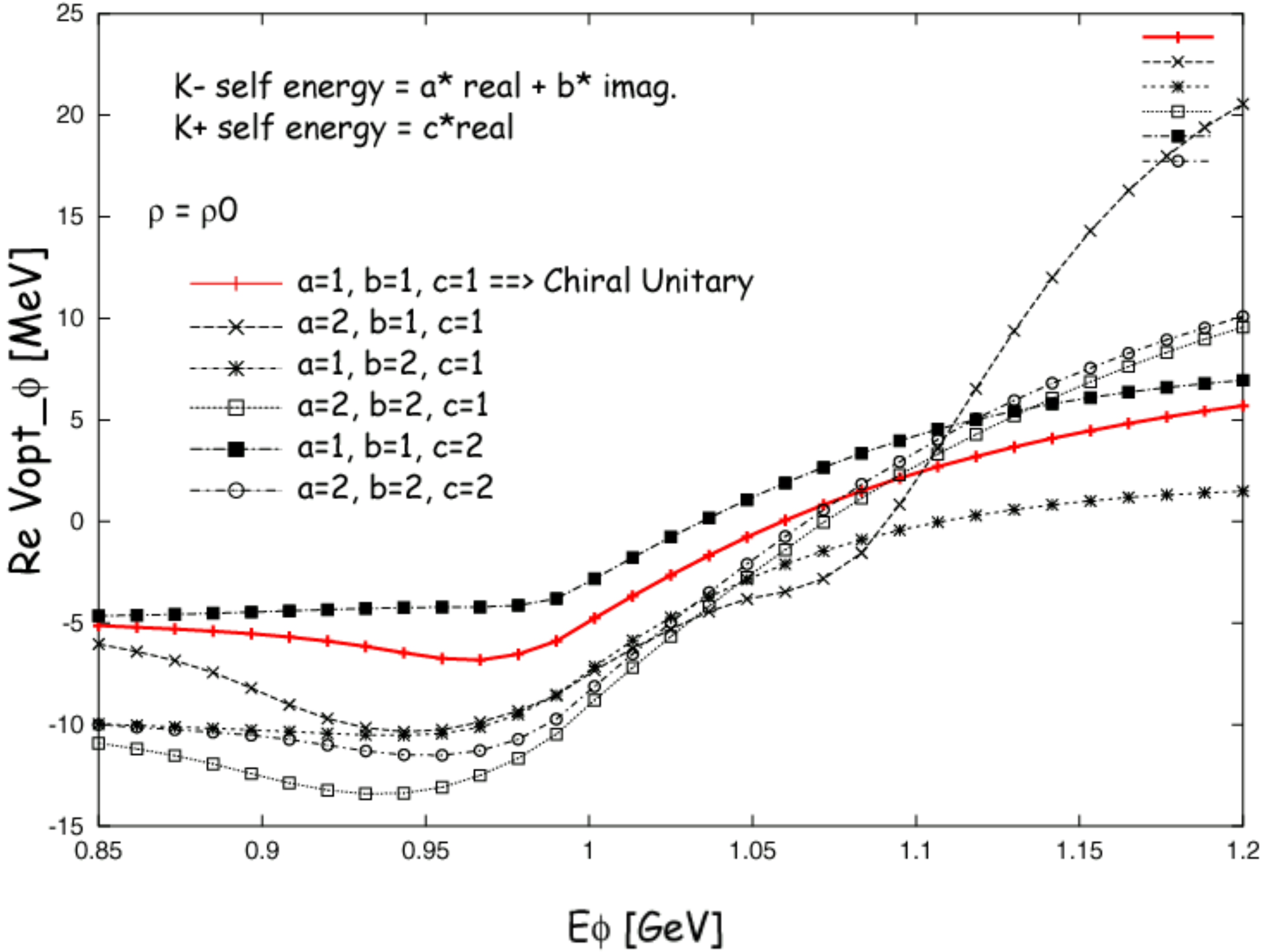
Conversion Part

Discussion with
Iwasaki and Ohnishi

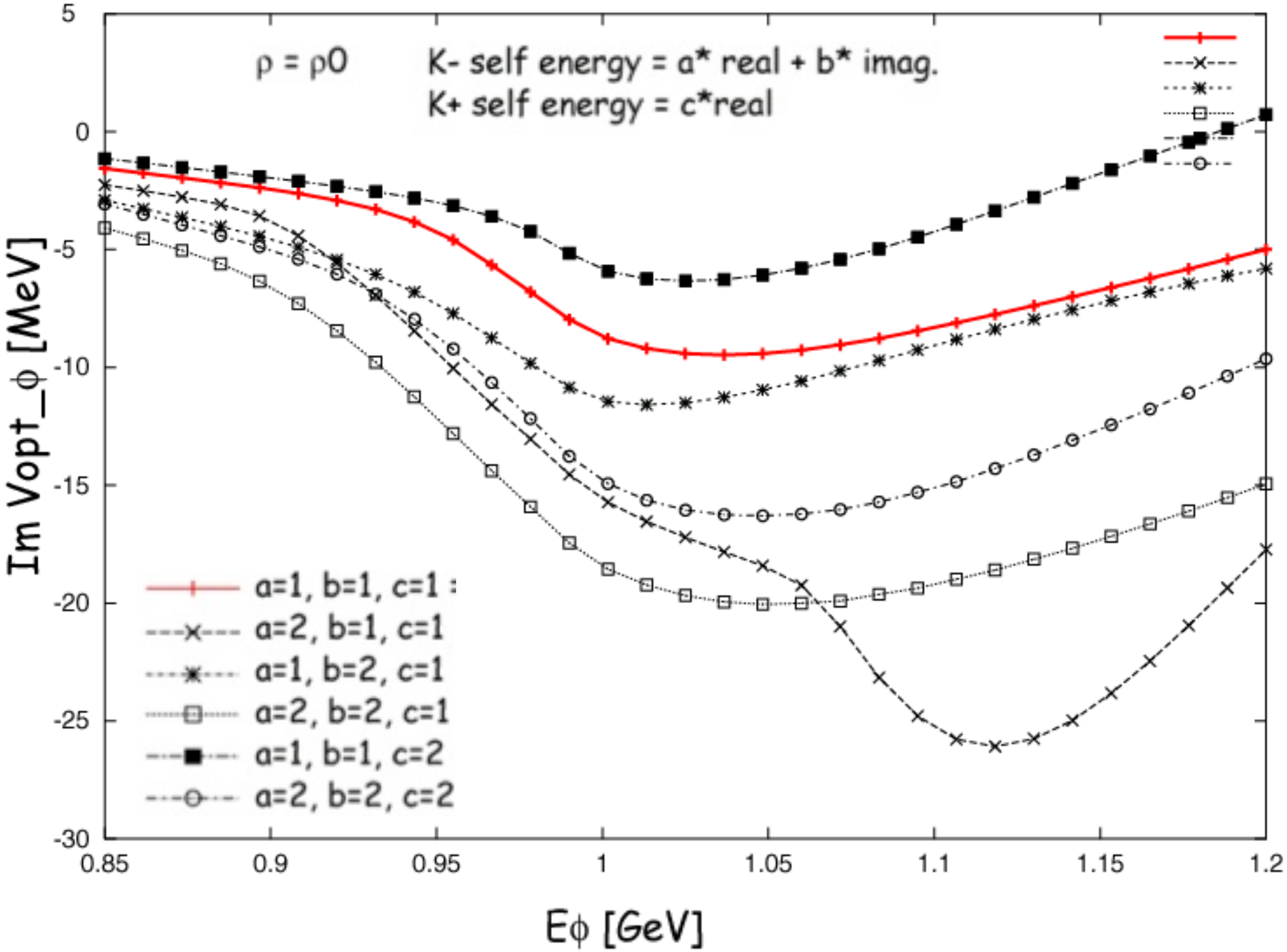
<< Shallow Φ potential >> **<< Deep Φ potential>>**



Kaon Self-energy dependence of ϕ potential (Real part)



Kaon Self-energy dependence of ϕ potential (Imag. Part)



ϕ in Nucleus

- Spectra <--> Depth of optical pot. <--> mass shift ?

  Comparison of Spectra * Shallow V(0) ～ -7 MeV

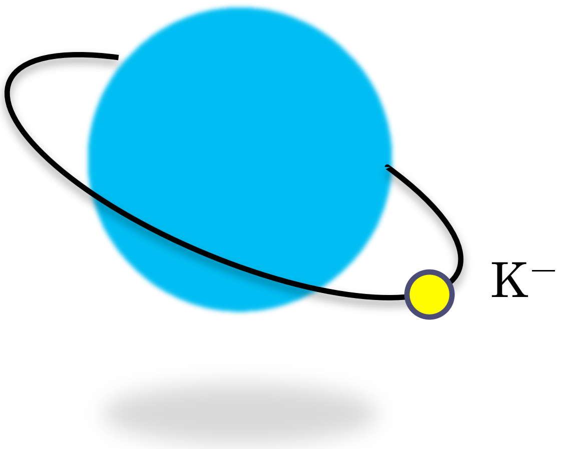
  * Deep V(0) ～ -30 MeV

- Large width <--> Smooth Spectra (Different Subcomponents)

  ➔ Background Reduction is essential to deduce m (or V) information

3-5. Kaon-Nucleus systems

- Kaonic Atoms



K meson (m_K〜 <u>500</u> MeV)

Binding energy

<u>order of 10keV〜MeV</u>

cf.) Normal atom electron (m_e〜0.5MeV)

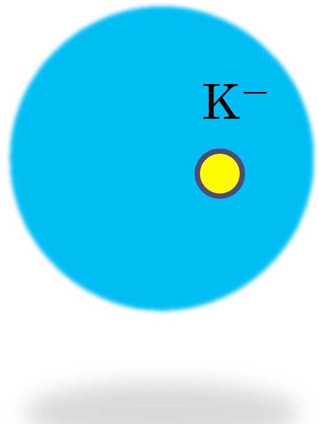
Binding Energy -- order of eV〜keV

- Kaonic Nuclei

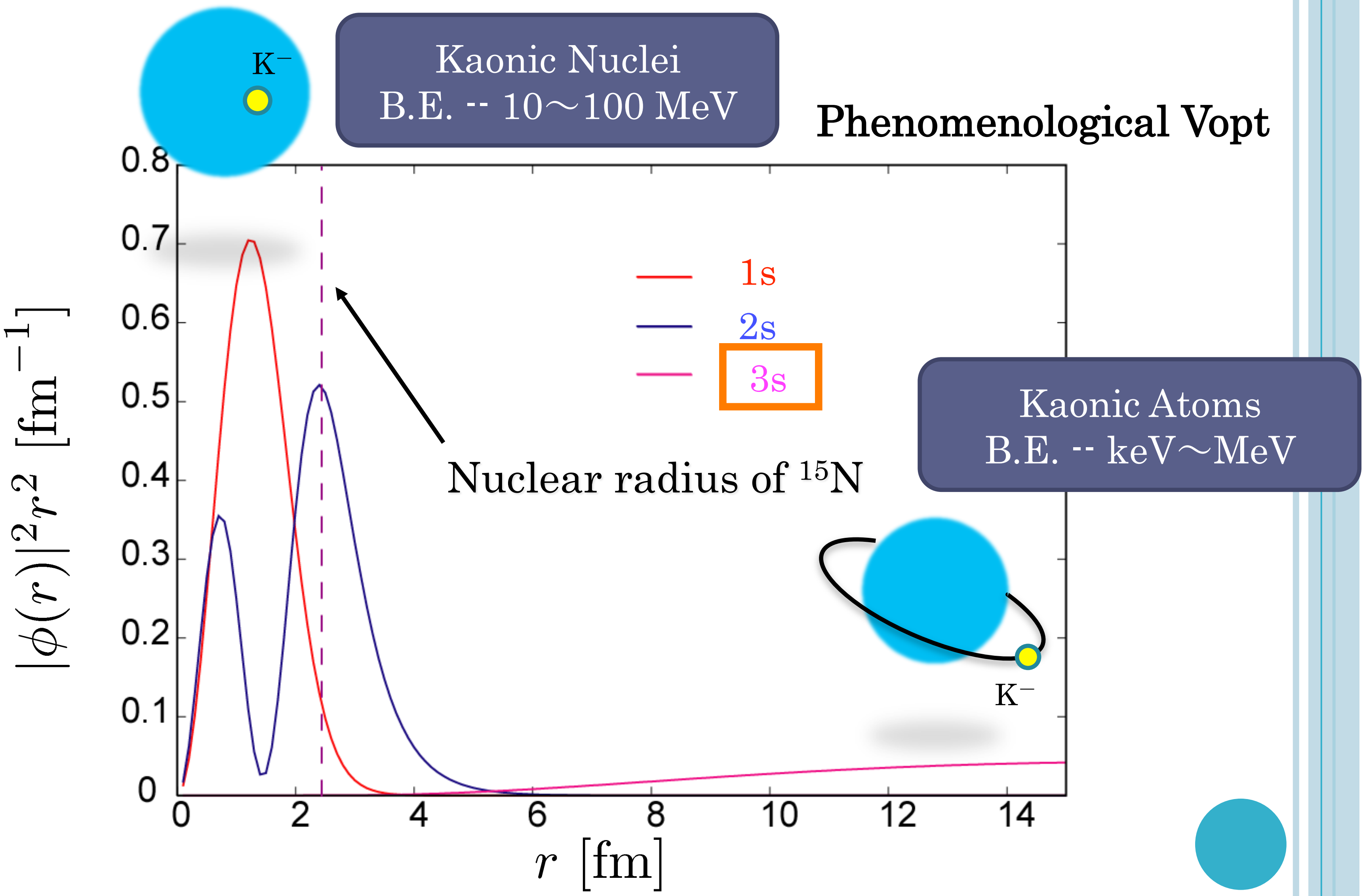
Very Deep !!

Binding Energy

<u>10 〜100 MeV</u>



Kaon density distributions



- Study of Kaonic Atoms --- for long time
  - To know the kaon properties at finite density
  - X-ray spectroscopy

    ➔ Deeply bound state were not observed

⇨ (K^-,p) reaction -- Formation spectra is very interesting!

Many Subcomponents
Width

- Study of Kaonic Nuclei
  - Narrow Width? ➔ It seems to have large decay width.
  - Observable? ➔ It seems difficult to observe clear peak.

^{12}C、^{16}O : Theor : Yamagata, Nagahiro, Hirenzaki(Structure, Reaction)
: Mares, Friedman, Gal (Structure)
Exp. : Kishimoto, Hayakawa (Osaka Group)

^{4}He : Exp. : Iwasaki, Suzuki (RIKEN Group)
Theor. : Akaishi, Yamazaki, Dote (Structure)

- Kpp system : 永江さん and 池田さん's talk

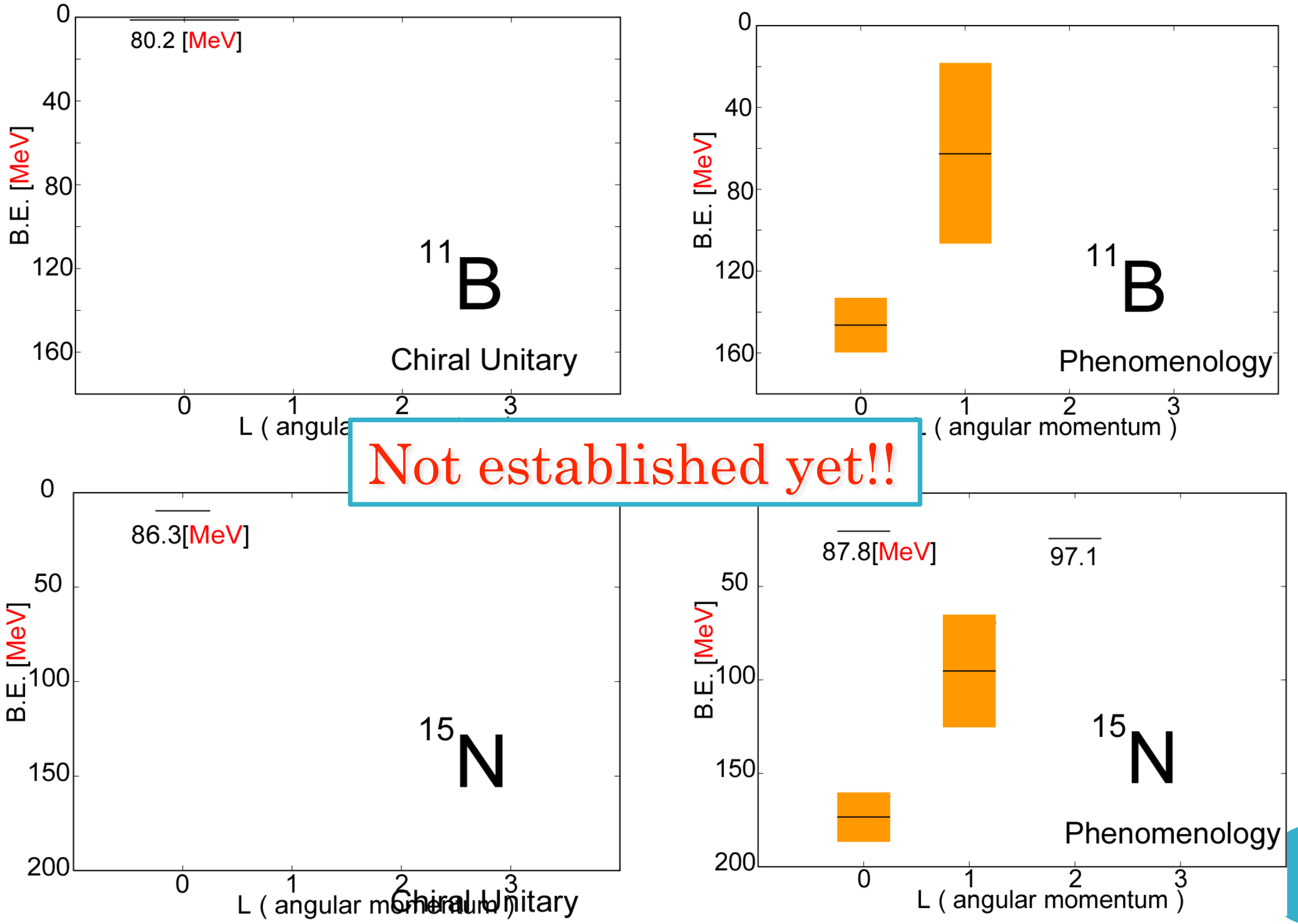
Our Study

Yamagata, Nagahiro, Okumura, Hirenzaki,
PTP114(05)301 ; Errata 114(05)905
Yamagata, Nagahiro, Hirenzaki,
PRC74(06)014604
Yamagata, Hirenzaki, EPJA31(07)255
Yamagata, Nagahiro, Kimura, Hirenzaki
PRC76(07)045204
Yamagata-Sekihara, Jido, Nagahiro, Hirenzaki
arXiv: 0812. 4359 [nucl-th]

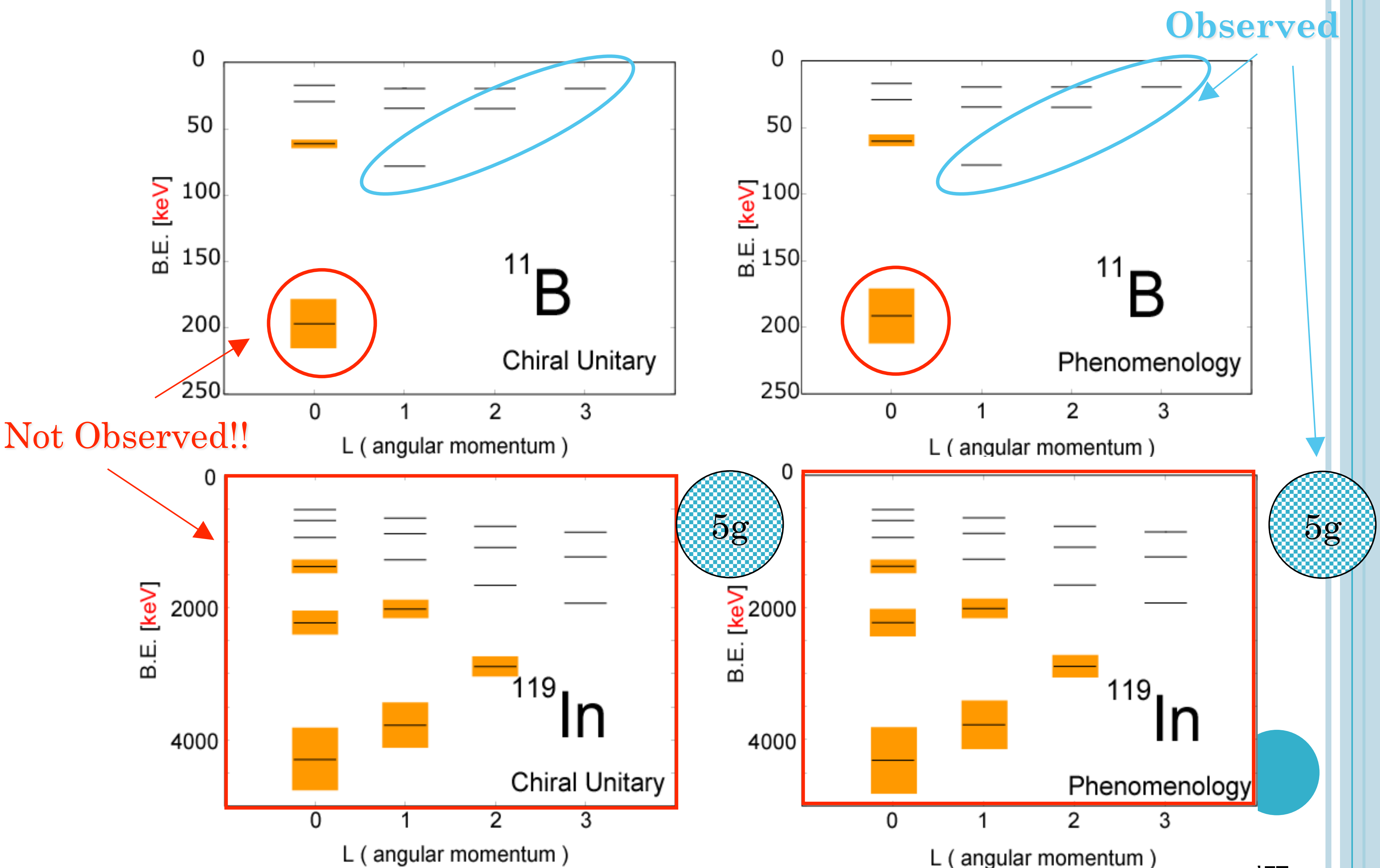
1. Kaonic Nucleus
   - Target : ^{12}C、^{16}O
   - In-flight(K-,p) reactions
   - Comparison with Exp. data
2. Kaonic Atom
   - Interesting structure in the formation spectra （dip、spike etc…）
3. Kaon Absorption Process
   - 1 body abs. : 2 body abs. = 80 : 20
   - E and ρ dependence of the imaginary optical potential
4. Exclusive spectra

   ^{3}He(K,N), ^{12}C(K,N)

Kaonic Nuclei (^{12}C,^{16}O target)

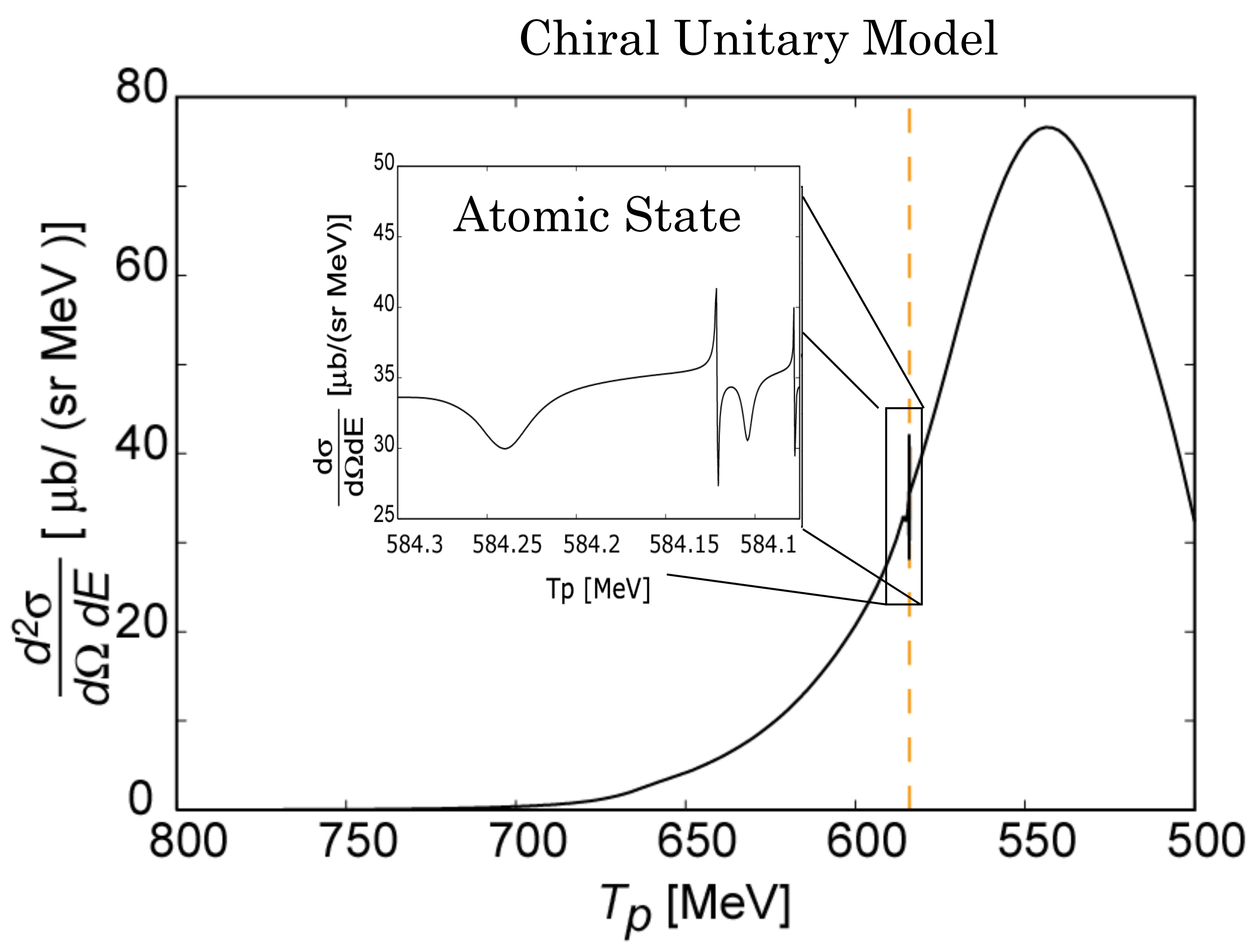


Kaonic Atoms (^{12}C, ^{120}Sn target)



Formation Spectra

- $^{12}\mathrm{C}(\text{In–flight } K^-, p)$ $P_{K^-} = 976$ MeV/c $(T_{K^-} = 600$ MeV)



Effective density

$$S(r) = \underbrace{\rho(r)}_{N}\underbrace{|R_{nl}(r)|^2}_{K} r^2$$ ：Overlapping density

p

T. Yamazaki, S. Hirenzaki PLB557 (03)20

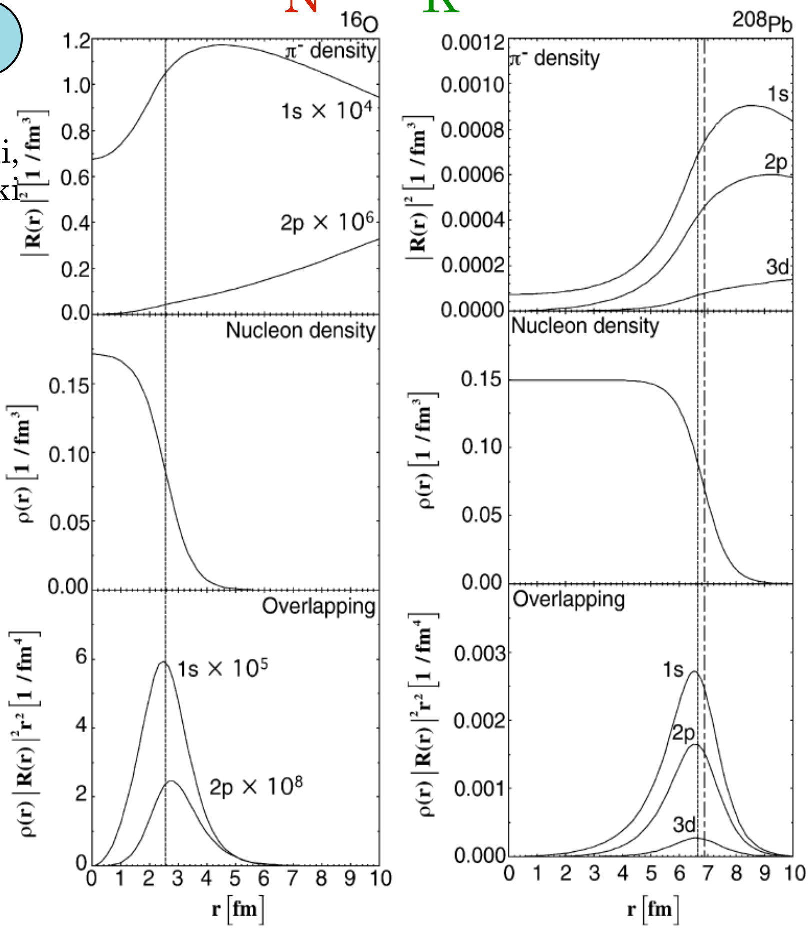
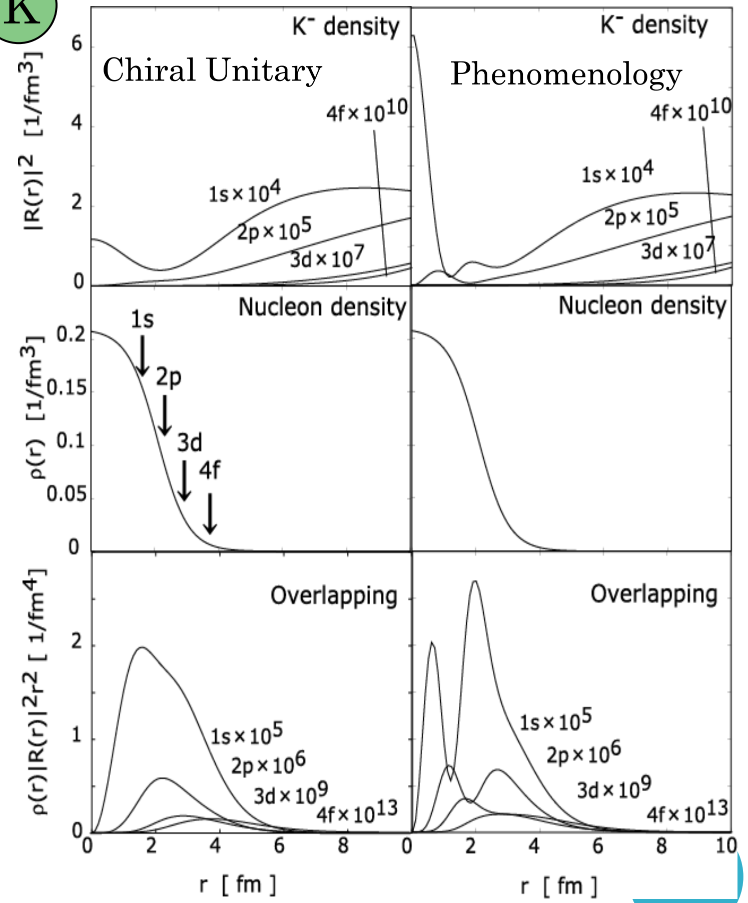


Fig. 1. Overlapping probabilities (lower frame) of the π^- densities (upper frame) with the nucleon densities (middle frame) in typical pionic bound states: (left) ^{16}O; (right) ^{208}Pb. The vertical broken lines show the half-density proton radii and the vertical dash-dotted line is for the half-density neutron radius in ^{208}Pb.

K

^{12}C



Kaon-Nucleus systems

1. Kaonic Nucleus
   - ^{12}C, ^{16}O targets
   - In-flight(K^-,p) reaction
   - Comparison with Exp. data

   ⇒ Kaonic Nuclei exist.
   But, because of the large decay width, it is very hard to observe these states.

2. Kaonic Atom
   - Interesting structure in the formation spectra
     （dip、spike etc…）

     ⇒ These states exist as quasi-stable states.
   - Probe various nuclear density　Robust structure

3. Exclusive Spectra
   Yamagata-Sekihara, Jido, Nagahiro

KNΛ(1405) coupling ⇒兵藤さん

- Quark ←→ Hadron ←→ Meson-Nuclear systems
  - Reliable effective theory is necessary.

    (chiral unitary, chiral doublet, NJL, …)

- Mesic Nulcear spectra ←→ Spectral function in Matter

  (Finite sys.) (Infinite sys.)
  - Many states vs. A pole

    → Experimental feasibility problem

- Meson Property vs Resonances

-Meson+Nucleus $\leftrightarrow$ B*+(Nucleon-hole)

-N*(1535) vs. ηN

-Λ(1405) vs. $\overline{K}$ N

-Level crossing

- Background subtraction

-For all broad states

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 senses.

Study of meson-nucleus bound states is interesting and important !!