Meson Properties at Finite Density from Meson-Nucleus systems

Satoru Hirenzaki

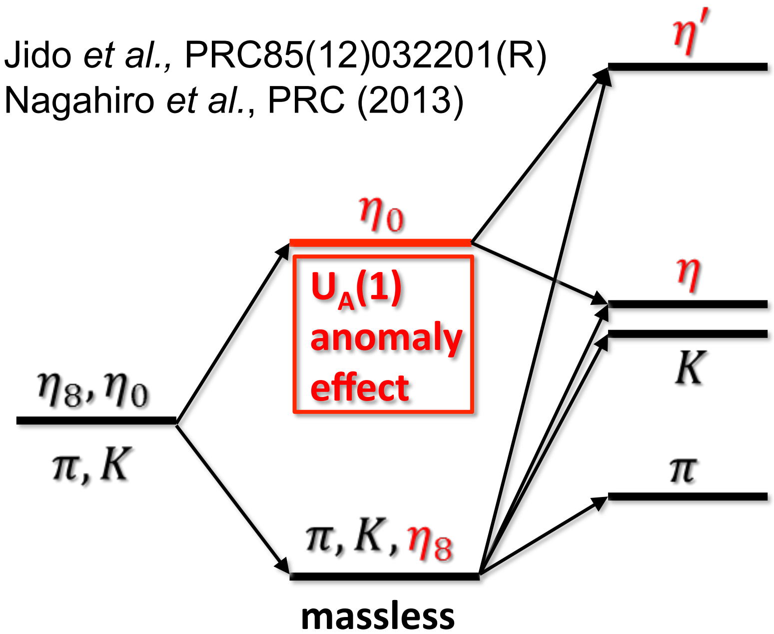
Nara Women's University / KEK

Workshop on J-PARC Hadron Physics in 2014,
Tokai, Ibaraki, Japan, Feb. 10 - 12, 2014

Meson mass spectrum and Symmetry Breaking Pattern (PS)

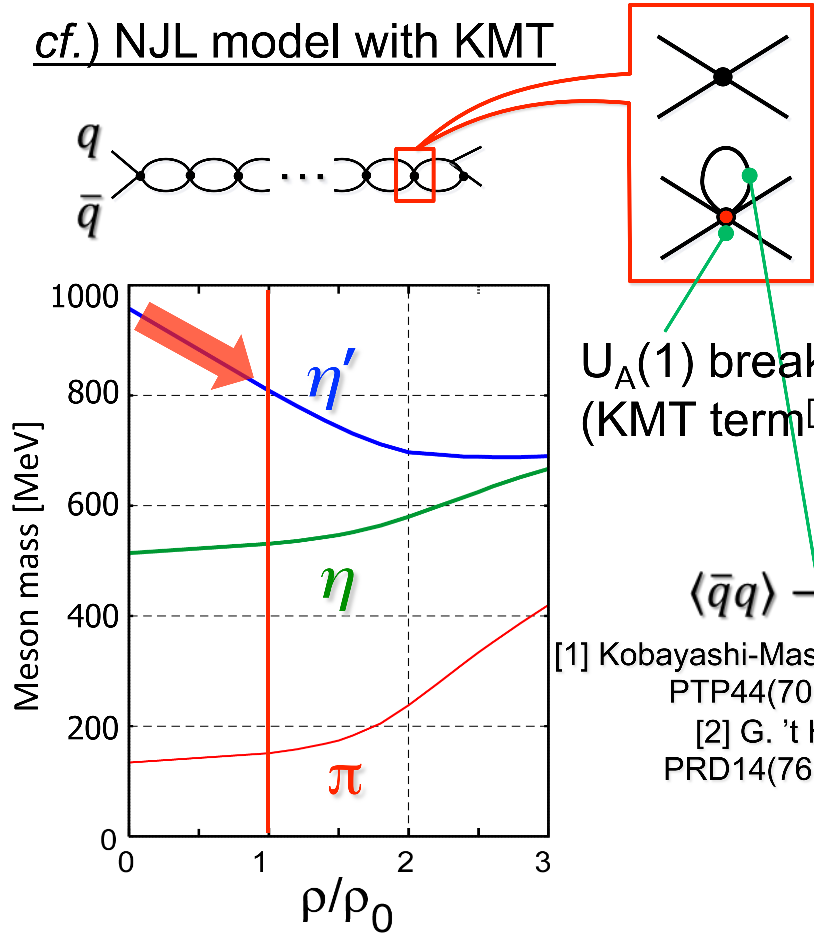
schematic view of the mass of π, K, η & η'

Jido *et al.*, PRC85(12)032201(R)
Nagahiro *et al.*, PRC (2013)



$m_q, m_s = 0$	$m_q, m_s = 0$	$m_q, m_s \neq 0$
$\langle \bar{q}q \rangle = 0$	$\langle \bar{q}q \rangle \neq 0$	$\langle \bar{q}q \rangle \neq 0$
ChS manifest	**dynamically broken**	**dyn. & explicitly broken**

cf.) NJL model with KMT



$\mathrm{U_A(1)}$ breaking (KMT term[1,2])

$\langle \bar{q}q \rangle \to 0$

[1] Kobayashi-Maskawa PTP44(70)1422
[2] G. 't Hooft, PRD14(76)3432

$\Delta m \sim -150$ **MeV @** ρ_0

Costa *et al.*,PLB560(03)171,
Nagahiro-Takizawa-Hirenzaki, PRC74(06)045203

■ *Recent Activities on Pionic Atoms*

= N. Ikeno, H. Nagahiro . . .

= K. Itahashi, T. Nishi, Y. Watanabe . . .

= GSI $\longrightarrow$ RIBF/RIKEN

N. Ikeno , J. Yamagata-Sekihara, H. Nagahiro and S. Hirenzaki, PTEP(2013) 063D01
N. Ikeno, H. Nagahiro and S. Hirenzaki, EPJA47 (2011) 161
N. Ikeno, R. Kimura, J. Yamagata-Sekihara, H. Nagahiro, D. Jido, K. Itahashi, L. S. Geng and S. Hirenzaki, PTP126 (2011) 483

Introduction

Deeply bound pionic atom

… Useful system to study pion properties at finite density and partial restoration of chiral symmetry

Current status

- $(d,{}^3He)$ reaction in $^{116, 120, 124}Sn$:
  Observation of pionic 1s states
- Pion-Nucleus optical potential

$$2\mu V^s_{\mathrm{opt}} = -4\pi[\varepsilon_1\{b_0\rho(r) + b_1\delta\rho(r)\} + \varepsilon_2 B_0\rho^2(r)]$$

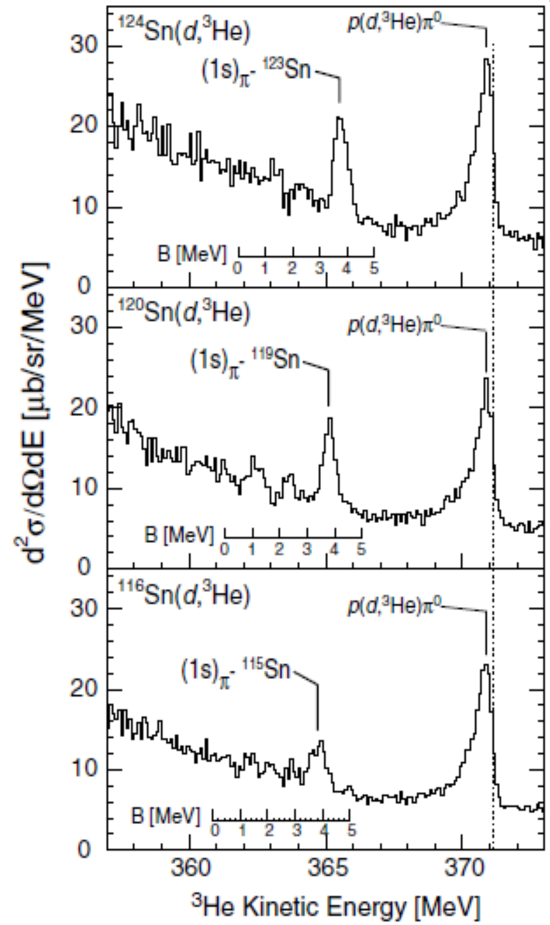
- GOR relation + Tomozawa-Weinberg

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

$$\sim 0.67 \ @\ \rho = \rho_0$$

Theoretical basis
Kolomeitsev, Kaiser, Weise, PRL90(2003)092501
Jido, Hatsuda, Kunihiro, PLB 670(08)109

K. Suzuki *et al.*, PRL92(2004)072302



What's next ?

Interests

$\bar{q}q$ condensate: beyond the linear density approx. (Goda, Jido)

: in asymmetric (n or p rich) Nuclear Matter

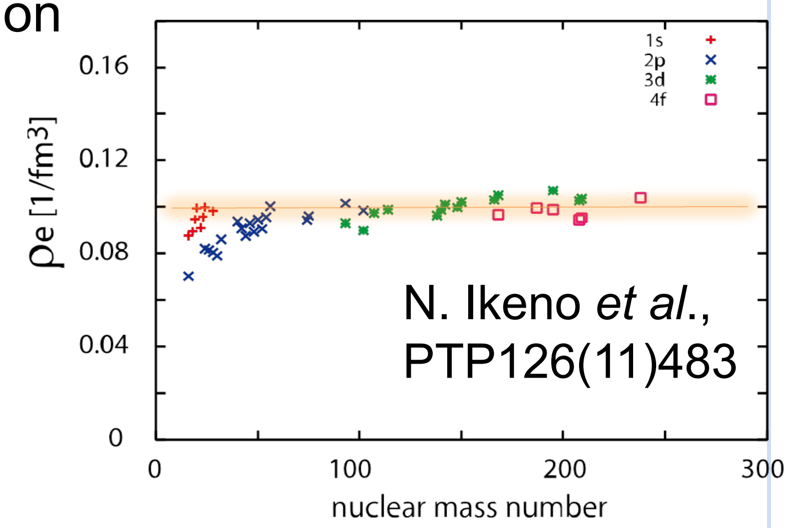
➔ Aspects of symmetry in "various extreme conditions"

Difficulties for precise studies

= Limited sensitivity of known atomic pion to $\rho \simeq 0.6\rho_0$ (Seki-Masutani)

= Uncertainties of Neutron density distribution

= Residual Interaction effects



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Difficulties for precise studies

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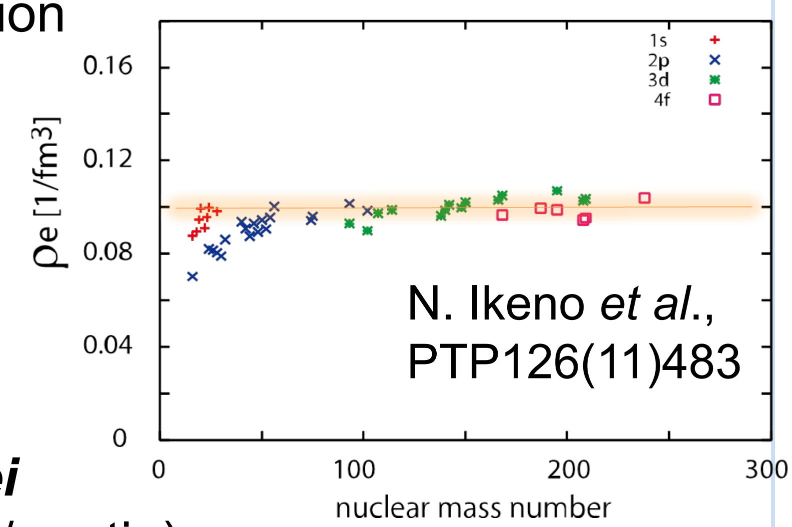
How we can..

= Several atomic states data (ex. 1s, 2s, 2p) in each nucleus
(=> reduction of ρ_n ambiguities)
= Systematic 'precise' observation for various nucleus ***including unstable nuclei***
(=> observation of various effective ρ and p/n ratio)

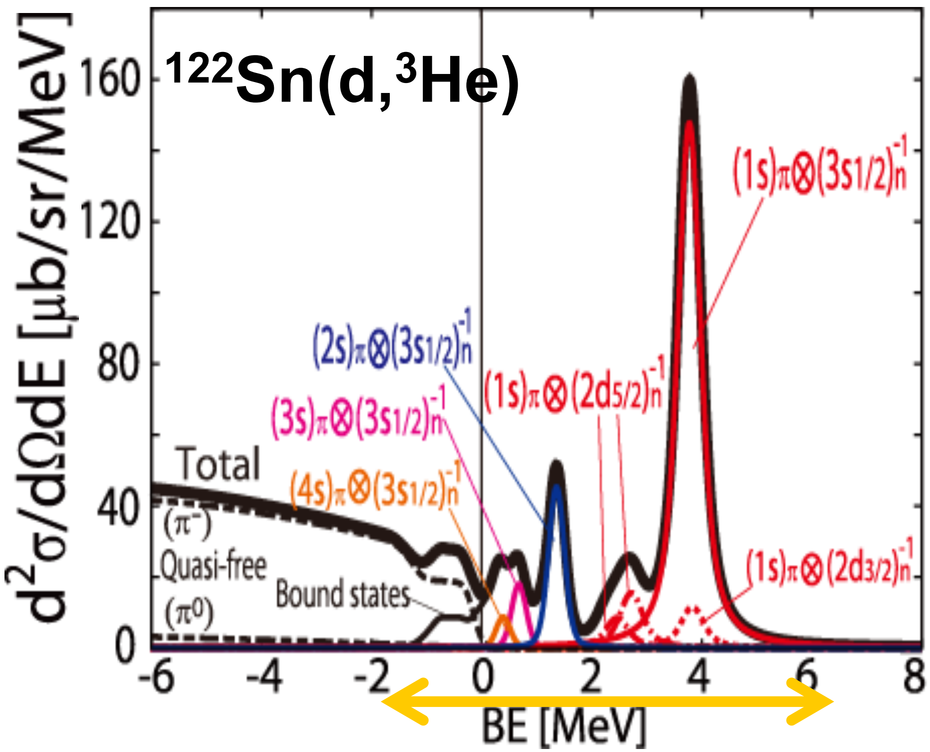


It will be
Study of Quark condensate by Hadronic atoms in Nuclear chart

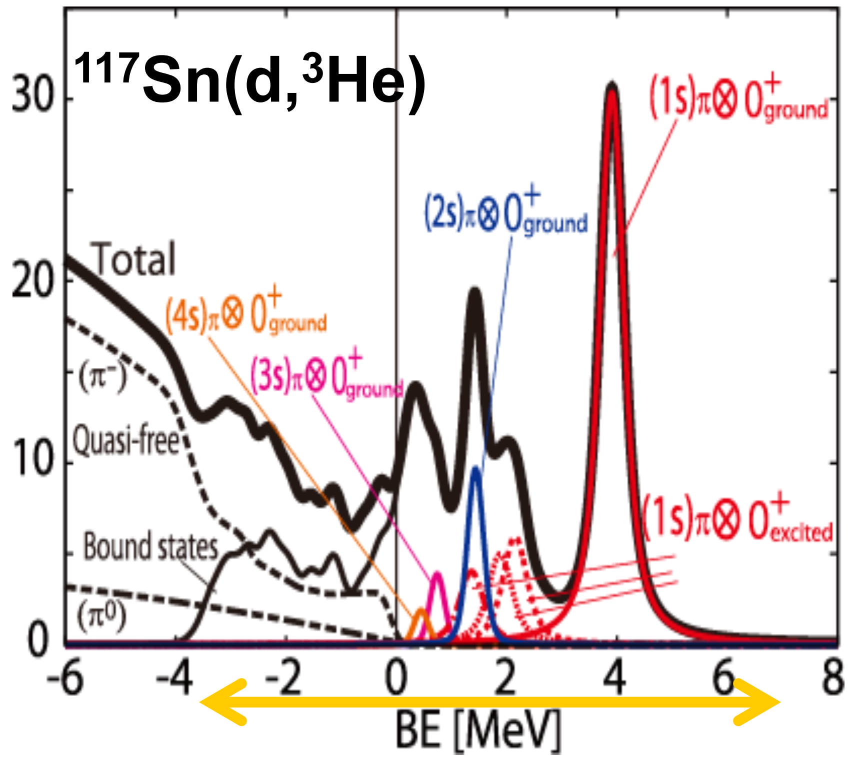
Some Numerical Results (by N. Ikeno)

0 degree

Even target: ^{122}Sn (0^+)



Odd target: ^{117}Sn ($1/2^+$)

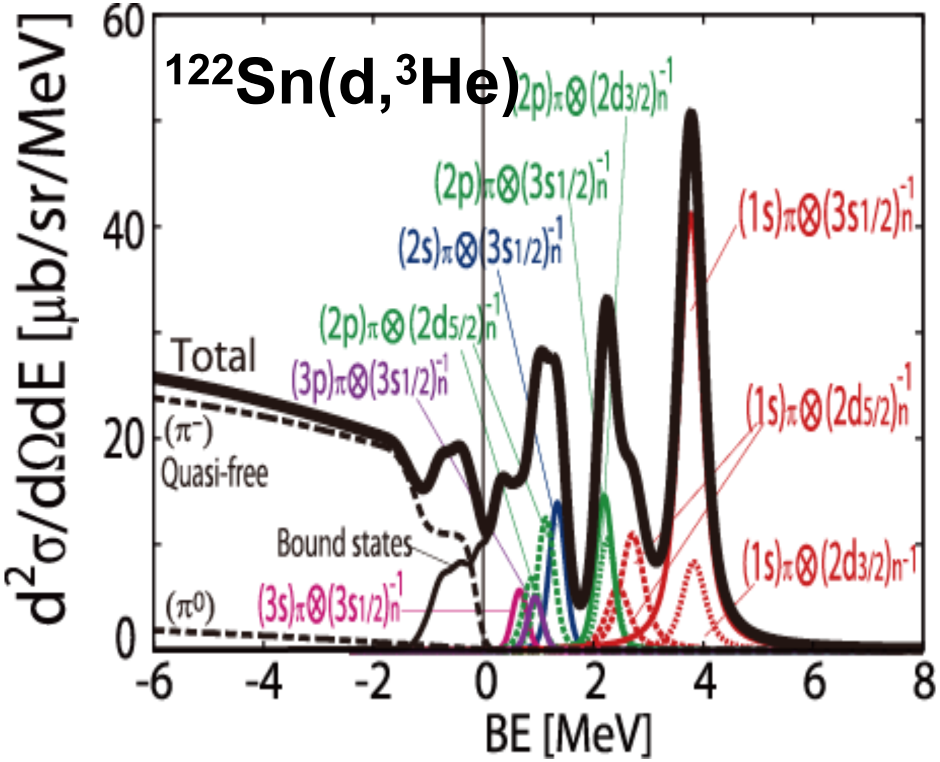


- Pionic 1s state formation with neutron s-hole state
- Spectrum of ^{117}Sn(d,^{3}He) is spread over wider energy range.
- Cross section of ^{117}Sn(d,^{3}He) is smaller.
- Pionic 1s and 2s states can be observed

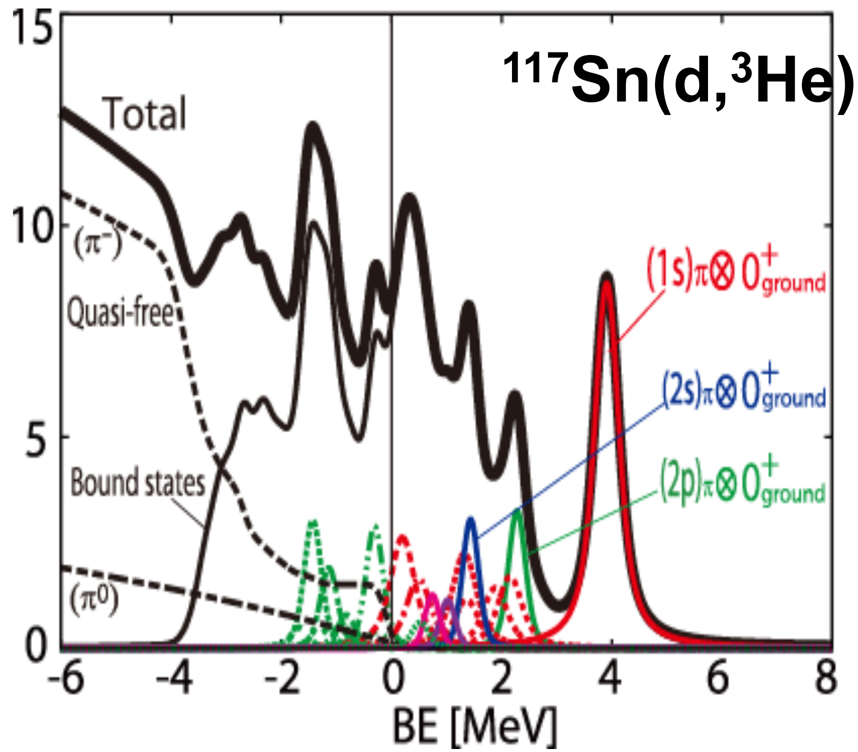
Some Numerical Results (by N. Ikeno)

2 degree

Even target: ^{122}Sn (0^+)



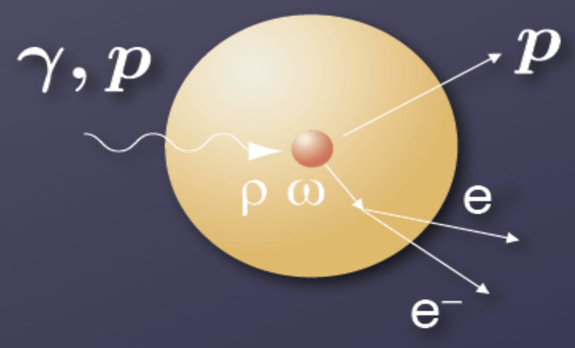
Odd target: ^{117}Sn ($1/2^+$)



- Pionic *2p* state contributions become relatively larger.

Vector Meson Mass Shift by Invariant mass

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

TABLE I. Properties of vector mesons (Amsler *et al.*, 2008).

	Mass (MeV/c^2)	Γ (MeV/c^2)	$c\tau$ (fm)	Main decay	$\frac{\Gamma e^+e^-}{\Gamma_{tot}}$ [a] ($\times 10^{-5}$)
ρ^0	775.49±0.34	149.4±1.0	1.3	$\pi^+\pi^-$ (~100%)	4.7
ω	782.65±0.12	8.49±0.08	23.2	$\pi^+\pi^-\pi^0$ (89%)	7.2
ϕ	1019.455±0.020	4.26±0.04	46.2	K^+K^- (49%)	29.7

[a]These branching ratios are at the pole mass.

Observation of 『mass shift』

1, Mass reduction will be equivalent to attractive V in Eq. of Motion..

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

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

2, But " Attractive ➔ Mass reduction " is wrong. Ex.) Coulomb case.
Origin of the attraction is important.

$$p^2 + (m - \Delta m)^2 = (E + V)^2$$

➔ $$M_{\mathrm{inv}}^2 = E^2 - p^2 \sim m^2 \left(1 - \frac{2}{m}(\Delta m + V)\right)$$

Invariant mass data ONLY at small kinetic energy

3, Thus, "exclusive" and/or "systematic" are important !

==> ∗ Bound state spectroscopy
(Quantum number selection rules, No vacuum background)

∗ Systematic info. on invariant mass
(Not simply 'mass', 'width')

Vector Meson Mass Shift by Invariant mass

TABLE IV. Compilation of experimental results on the in-medium mass and width of the ρ, ω, and ϕ mesons produced with elementary reactions, measured in different experiments. This is based on updating the table prepared by Metag (2008a).

	Invariant mass			Attenuation	
	E325 @ KEK	CLAS-g7 @ JLab	CBELSA/TAPS		LEPS @ SPring-8
Reaction	pA 12 GeV	γA 0.6–3.8 GeV	γA 0.7–2.5 GeV		γA 1.5–2.5 GeV
Momentum	$p>0.5$ GeV/c	$p>0.8$ GeVc	$p<0.5$ GeV/c	$0.4<p<1.7$ GeV/c	$1.1<p<2.2$ GeV/c
ρ	↑ $\Delta m(\rho_0)/m=-9\%$	$\Delta m\approx 0$ Some broadening			
ω	↓ No broadening		$\Delta m(\rho_0)/m=-14\%$[a]	$\Gamma_\omega(\rho_0)=130$–$150$ MeV/c^2 $\to\sigma_{\omega N}\approx 70$ mb	
ϕ	$\Delta m(\rho_0)/m=-3.4\%$ $\Gamma_\phi(\rho_0)\approx 15$ MeV/c^2				$\sigma_{\phi N}=35$ mb $\to\Gamma_\phi(\rho_0)\approx 80$ MeV/c^2

[a]This may change as a result of the ongoing reanalysis (Metag, 2008b).

…….Various data. Not consistent.

- Precise/High statistics data at JPARC … Necessary !!
- Momentum dependence of Φ data (as expected in E16) is important as Systematic info.
- On the other hand, Φ mass shift could be small.

(Philipp Gubler, Poster yesterday.)

===>

- Experimental determination of <N|sbar s|N> by in-medium Φ . Imporatnt quantity !

$\eta'(958)$ mesic nucleus

H.Nagahiro, S.Hirenzaki, Phys.Rev.Lett.94 (2005)232503
H.Nagahiro, M.Takizawa, S.Hirenzaki, Phys.Rev.C74 (2006)045203
D. Jido, H. Nagahiro, S. Hirenzaki, Phys.Rev.C 85, 032201 (R) (2012)
H. Nagahiro, S. Hirenzaki, E. Oset, A. Ramos, Phys. Lett. B 709 (2012) 87-92

K. Itahashi, H. Fujioka, H. Geissel, R. S. Hayano, S Hirenzaki, S. Itoh, D. Jido, V. Metag, H. Nagahiro, M. Nanova, T. Nishi, K. Okochi, H. Outa, K. Suzuki, Y. K. Tanaka, H. Weick, Prog. Theor. Phys. 128 (2012) 601-613.

H. Nagahiro, D. Jido, H. Fujioka, K. Itahashi, S. Hirenzaki, Phys. Rev. C 87, 045201 (2013).

Introduction

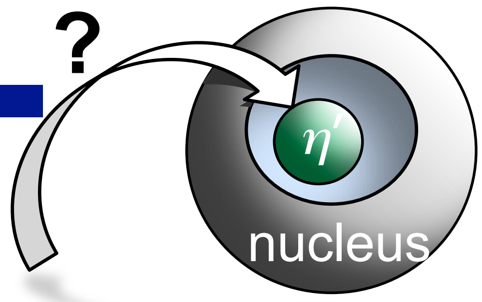
- η'(958) meson …close connections with U$_A$(1) anomaly
  - Theoretical works
    - the effects of the U$_A$(1) anomaly on η' properties
    - at finite temperature/density
      - T. Kunihiro, PLB219(89)363
      - R.D.Pisarski, R.Wilczek, PRD29(84)338
      - Y. Kohyama, K.Kubodera and M.Takizawa, 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 $\rho \neq 0$**
  - Poor experimental information

    on the U$_A$(1) anomaly at finite density

- Proposal for the study of the η'-mesic nuclei
  - U$_A$(1) anomaly effect in medium from the "mesic nuclei"
  - the η' properties at finite density

η' property in medium



- ✓ **small scattering length ?**

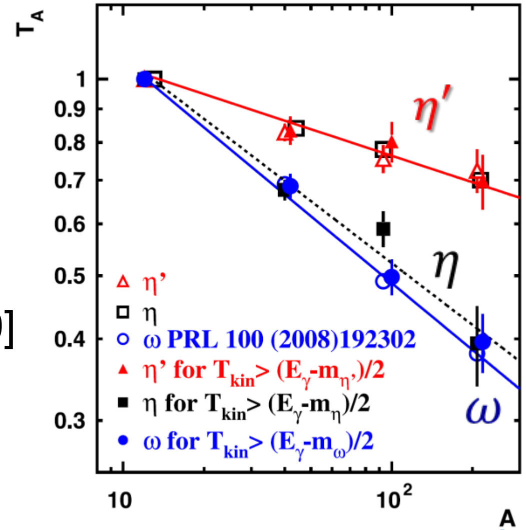
  $|\mathrm{Re}\, a_{\eta' N}| < 0.8$ fm, [$pp \to pp\eta'$@ COSY, Moscal *et al.*, PLB474(00)416]

  $|a_{\eta' N}| \sim 0.1$fm, [… , Moscal *et al.*, PLB482(00)356]

- ✓ **smaller absorption width in medium ?**

  CBELSA/TAPS [M.Nanova *et al.*, PLB710(12)600]

  [estimated transparency ratio $\gamma A \to \eta' X$]



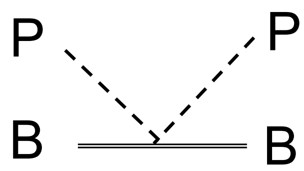
- ✓ **mass reduction in finite T/ρ?**

  $\langle \bar{q} q \rangle \longrightarrow 0$ [NJL model w/ KMT interaction]

  [experimentally observed enhanced production of soft pions
  Interpreted as mass reduction of η' in the hot medium [Csorgo et al., PRL105(10)182301]]

Theoretical Model for eta(958)-N

Oset-Ramos, PLB704(11)334

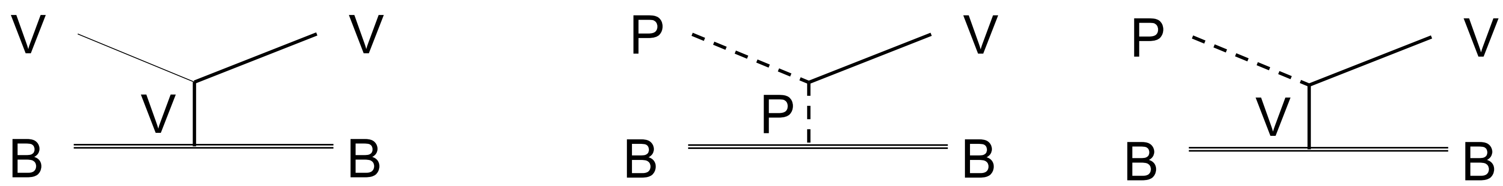


pseudoscalar-baryon (PB) : Weinberg-Tomozawa interaction

$\pi N, \eta N, K\Lambda, K\Sigma$ $+ \boldsymbol{\eta' N}$ by the η -η' mixing

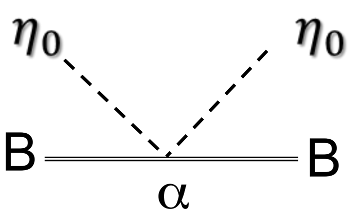
their result : $|a_{\eta' N}| = 0.01$ fm $\Leftrightarrow$ $|a_{\eta' N}| \sim 0.1 - 0.8$ fm [PLB'00]

vector-baryon channels : through PB-VB interaction



their result : $|a_{\eta' N}| = 0.03$ fm

coupling of the singlet component of pseudoscalar to baryons



$$\mathcal{L}_{\eta_0 B} \propto \eta_0^2 \langle \partial_\mu \bar{B} \gamma^\mu B - \bar{B} \gamma^\mu \partial_\mu B \rangle$$

Borasoy , PRD61(00)014011
S. Bass, Phys.Lett. B463 (1999) 286
Kawarabayashi-Ohta, PTP66(81)1789

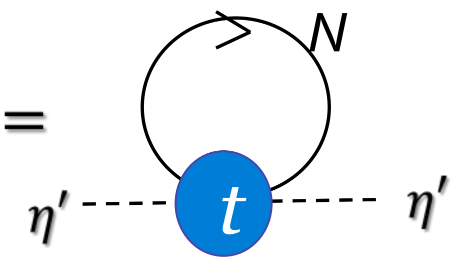
α … free parameter

their result : $|a_{\eta' N}| = 0.1$ fm can be reproduced

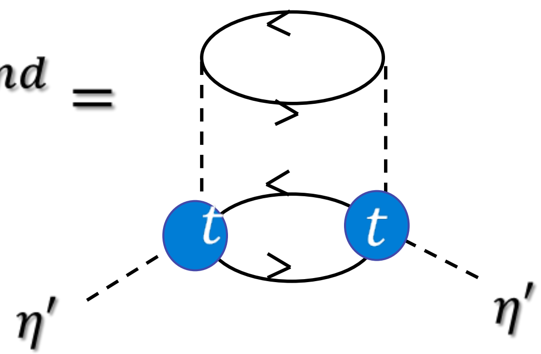
phenomenological estimation for $V_{\eta'}^{opt}$

Optical potential $V_{\eta'}$ [H.Nagahiro, S. Hirenzaki, E. Oset, A. Ramos, PLB709(12)87]

$V_{\eta'}^{1st} =$



$V_{\eta'}^{2nd} =$



We consider only the **attractive** case & **energy-independent** potential.

Re $V_{\eta'}$ and Im $V_{\eta'}$ with various α values

in unit of MeV

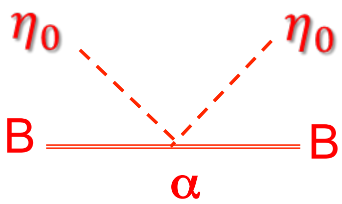
α	$\|a_{\eta' N}\|$ fm	$V_{\eta'}^{1st}(\rho_0)$	$V_{\eta'}^{2nd}(\rho_0)$	$V_{\eta'}^{total}(\rho_0)$
−0.193	0.1	$-8.6 - 1.7i$	$-0.1 - 0.1i$	$\mathbf{-8.7 - 1.8i}$
−0.834	0.3	$-26.3 - 2.1i$	$-0.6 - 0.9i$	$\mathbf{-26.8 - 3.0i}$
−1.79	0.5	$-43.8 - 3.0i$	$-1.3 - 2.5i$	$\mathbf{-44.1 - 5.5i}$
−9.67	1.0	$-87.7 - 6.9i$	$-4.1 - 10.4i$	$\mathbf{-91.8 - 17.2i}$

Re V ≫ Im V

phenomenological estimation for $V_{\eta'}^{opt}$

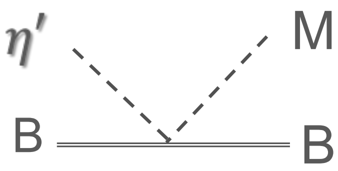
The reason why Re V $\gg$ Im V in the chiral unitary calculation

Kawarabayashi-Ohta, PTP66(81)1789
Borasoy , PRD61(00)014011



→ gives attraction

WT interaction for η'

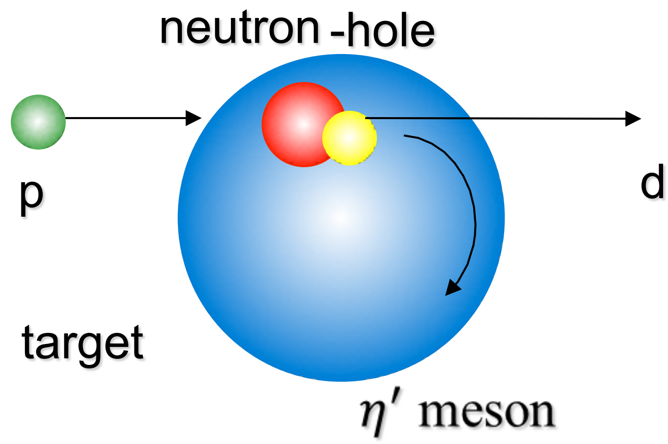


→ **width [small]**

This interaction …

- ✓ *resembles* that of the anomaly effect discussed by D. Jido PRC85(12)
- ✓ seems to **dominate** the $\eta' N$ interaction
- ✓ contributes mostly to the η' **elastic channel** & barely to the **inelastic channel**

Formation by (p,d) reaction



missing mass spectroscopy

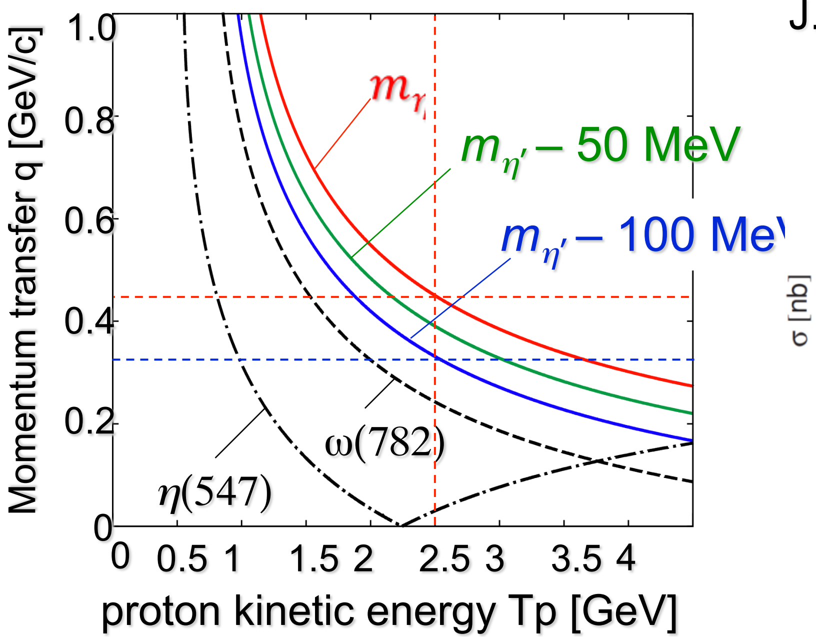
K. Itahashi, H. Fujioka *et al.*, PTP128(12)601

proton kinetic energy $T_p = 2.5$ GeV

target : ^{12}C, (^{16}O, ^{40}Ca)

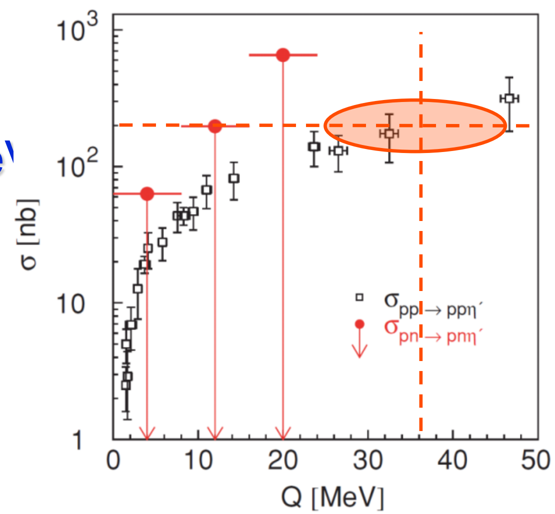
forward reaction : $\theta_d = 0$ deg.

momentum transfer



elementary cross section $pn \to \eta' d$ ***No information***

J.Klaja et al., PRC81(10)035209 (COSY)



$$\sigma_{pp \to pp\eta'}$$

↓

assumptions

↓

$$\left(\frac{d\sigma}{d\Omega}\right)^{lab}_{pn \to \eta' d} = 30\ \mu b/sr$$

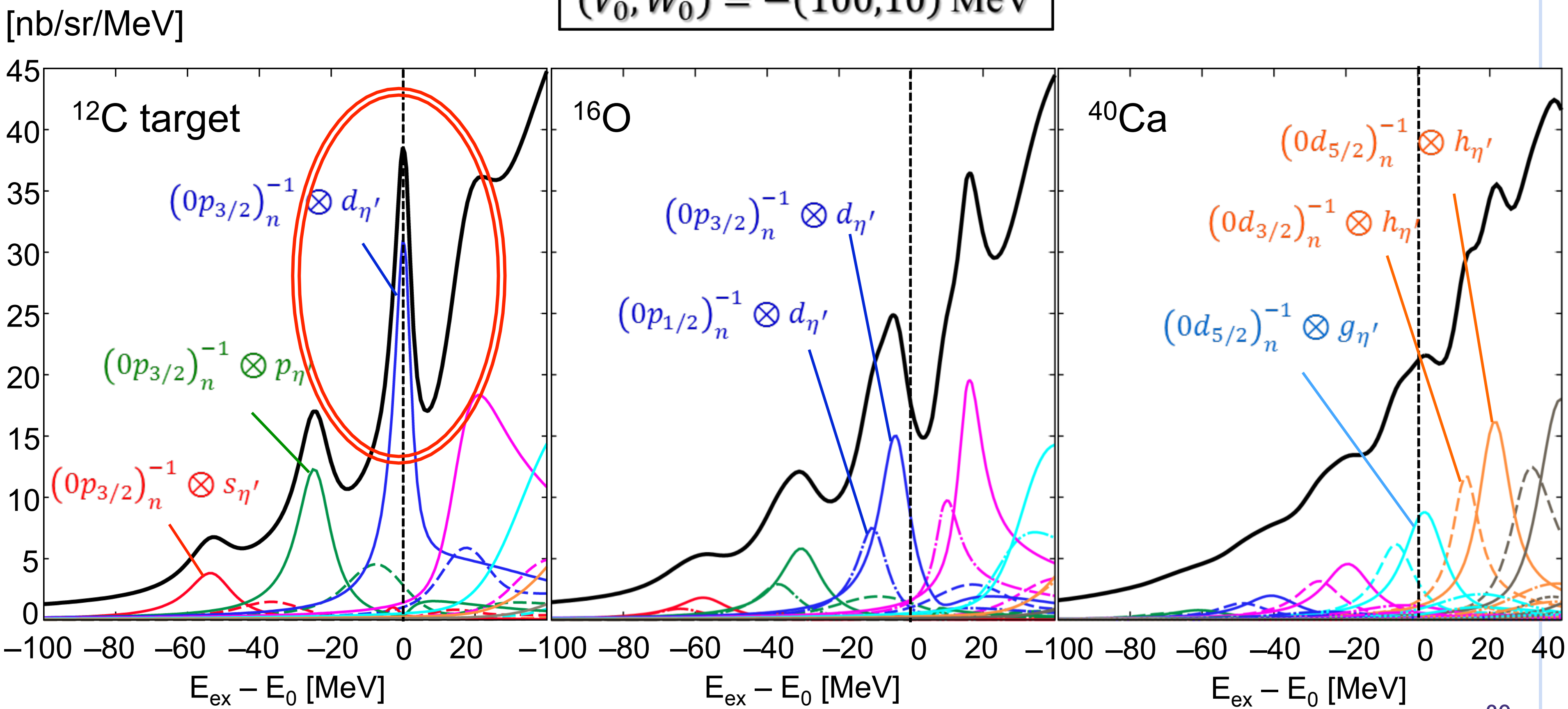
K.Nakayama in private comm
Itahashi *et al.*, PTP128(12)601

$^{12}C(p,d)^{11}C\ \eta'$: strong attraction $(V_0, W_0) = -(100,10)$ MeV

light nucleus ⟷ **heavy nucleus**

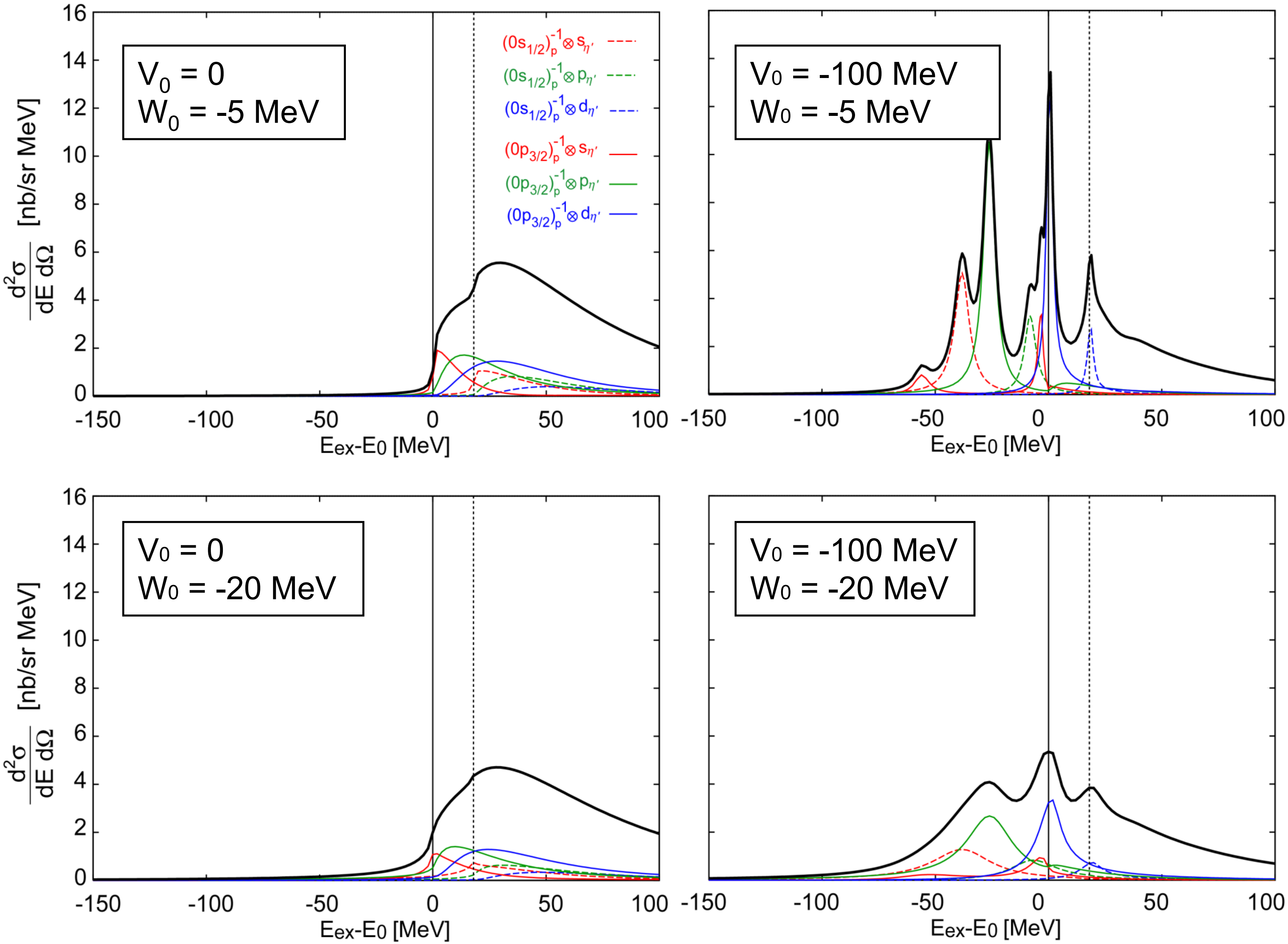
less (shallow) η' bound states | many (deeper) η' bound states
less hole-states | many hole-states
✓ simpler structure | ✓ complex structure

$(V_0, W_0) = -(100,10)$ MeV



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

H.Nagahiro, S.Hirenzaki, Phys.Rev.Lett.94 (2005)232503

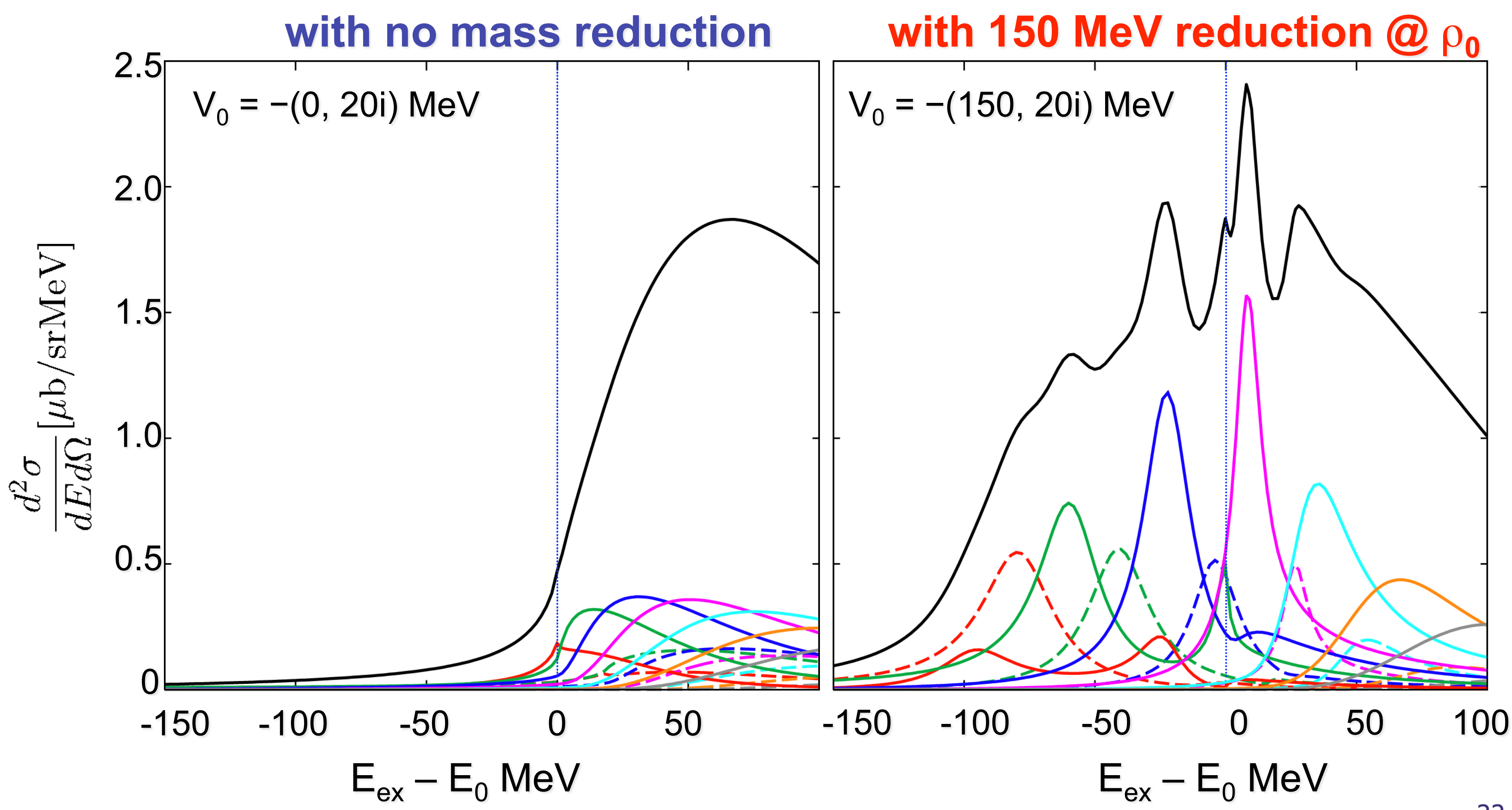


η'-mesic nuclei formation spectra : ^{12}C target : (π^+,p)reaction@JPARC

- p_π = 1.8 GeV/c
- proton angle = 0 deg.

$$\left(\frac{d\sigma}{d\Omega}\right)^{Lab.} = 100\mu b/sr$$ case

By H. Nagahiro
PTP Suppl. 186(2010)316.



η'(958)-meson-nucleus bound system

Partial restoration of Chiral sym and $U_A(1)$ anomaly effect in the viewpoint of mesic-nuclei

(possible) large mass reduction **without** large absorption

$$\mathrm{Re}V \gg \mathrm{Im}V$$

special feature of η'

- ✓ attraction from 'elastic' interaction
- ✓ smaller inelastic channel

possibilities to observe bound state peaks

➔ Experiment

Summary

- Meson property at finite density,
  Meson-Nucleus systems

- Pionic atom: for getting deeper insights
  = information at various ρ and ρ_p / ρ_n ratio
  = Pionic atom in various nucleus including unstable nuclei

- $\eta'(958)$: Anomaly effect at finite density
  (S. Sakai, Poster yesterday)

- Experimental determination of <N|sbar s|N>
  by in-medium Φ .