Meson Properties at Finite Density from Mesic Atoms and Mesic Nuclei

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Nara Women's University,

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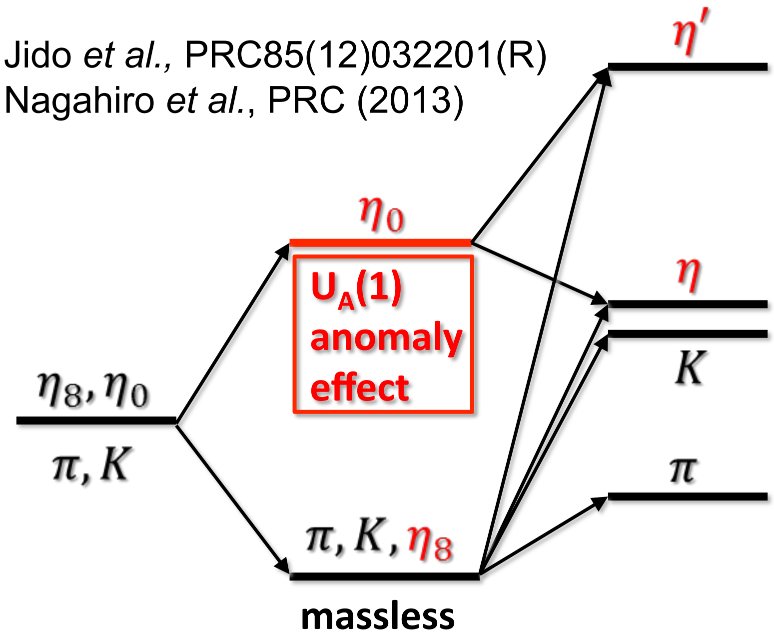
Meson mass spectrum and Symmetry Breaking Pattern (PS)

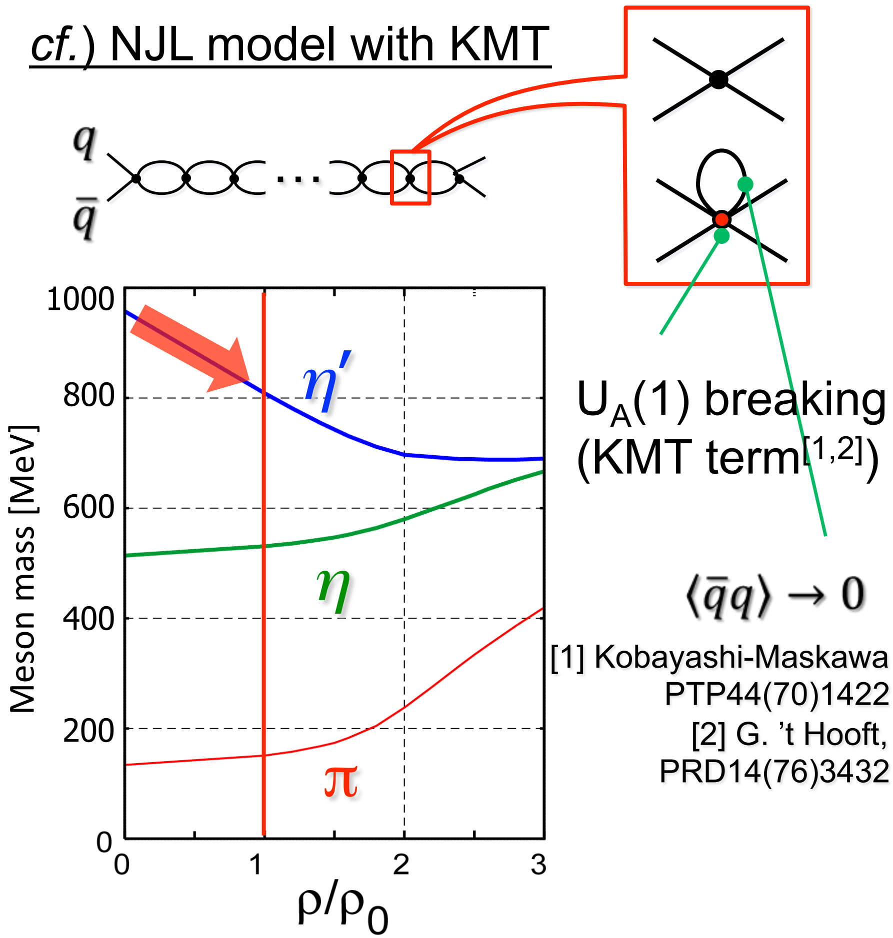
schematic view of the mass of π, K, η & η'

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



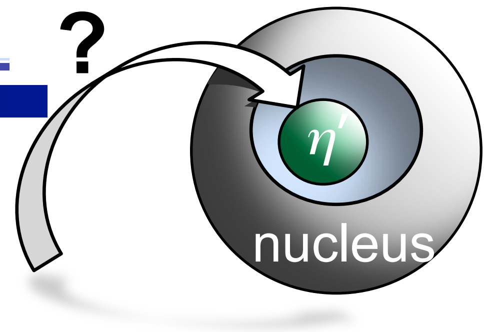
[1] Kobayashi-Maskawa PTP44(70)1422
[2] G. 't Hooft, PRD14(76)3432

$\Delta m \sim -150$ MeV @ ρ_0

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

η' property in medium

→ Phenomenologically poorly understood



✓ **small scattering length ?**

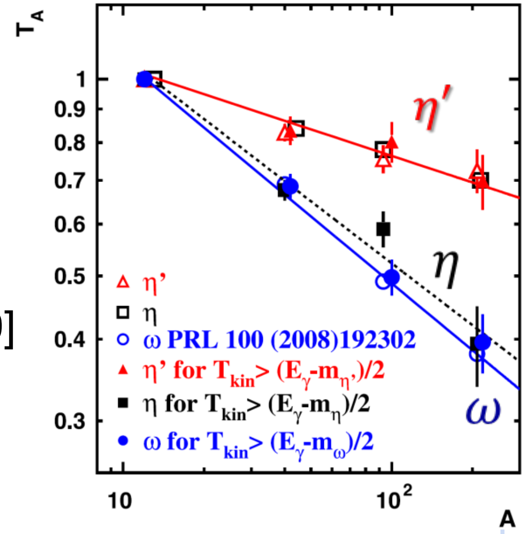
$|\mathrm{Re}\, a_{\eta' N}| < 0.8$ fm, [$pp \to pp\eta'$@ COSY, Moscal *et al.*, PLB474(00)416]

$|a_{\eta' N}| \sim 0.1$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]]

In-medium width of η'?

	mesic atom $(\pi$, K, ...)	mesic nuclei $(\omega, \eta, \ldots)$
attraction : Re(V)	coulomb	**strong int.**
absorption : Im(V)	strong int.	**strong int.**
	overlap → small sharp peak	overlap → large **broad peak or bump**

→ Γ large absorption width is a *fate* of mesic-nuclei ?

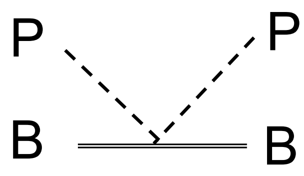
special property of η' ?

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

$$\Gamma_{\eta'}(\rho_0; \langle|\vec{p}_{\eta'}|\rangle \sim 1\text{GeV}/c) \sim 15-25\ \text{MeV}@\rho_0$$

Theoretical Model for eta(958)-N

Oset-Ramos, PLB704(11)334

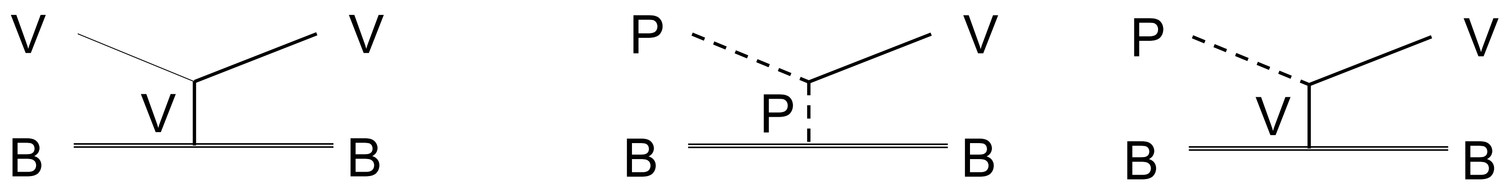


pseudoscalar-baryon (PB) : Weinberg-Tomozawa interaction

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

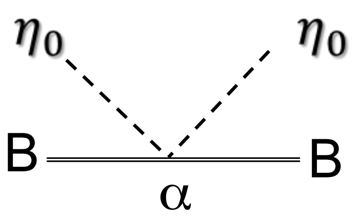
their result : $|a_{\eta' N}| = 0.01$ fm $\Leftrightarrow$ $|a_{\eta' N}| \sim 0.1 - 0.8$ fm [PLB'00]

vector-baryon channels : through PB-VB interaction



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

coupling of the singlet component of pseudoscalar to baryons



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

α … **free parameter**

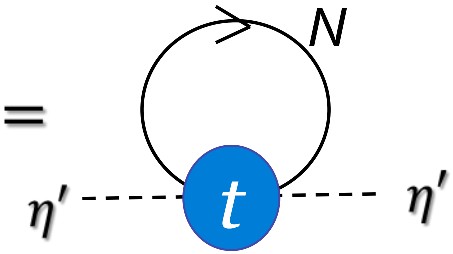
Borasoy , PRD61(00)014011
Kawarabayashi-Ohta, PTP66(81)1789

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

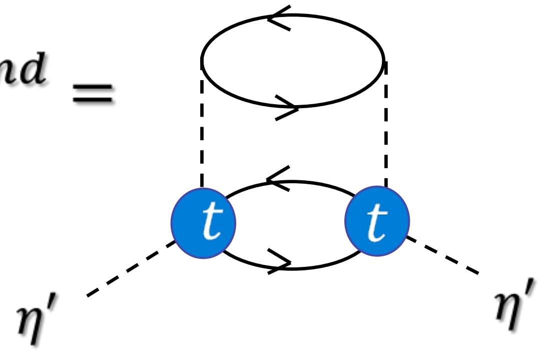
phenomenological estimation for $V_{\eta'}^{opt}$

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

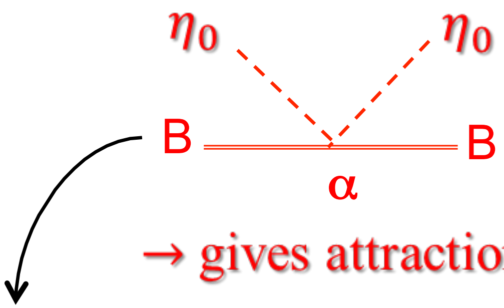
α	$\lvert a_{\eta' N} \rvert$ fm	$V_{\eta'}^{1st}(\rho_0)$	$V_{\eta'}^{2nd}(\rho_0)$	$V_{\eta'}^{total}(\rho_0)$
-0.193	0.1	$-8.6 - 1.7i$	$-0.1 - 0.1i$	$\mathbf{-8.7 - 1.8i}$
-0.834	0.3	$-26.3 - 2.1i$	$-0.6 - 0.9i$	$\mathbf{-26.8 - 3.0i}$
-1.79	0.5	$-43.8 - 3.0i$	$-1.3 - 2.5i$	$\mathbf{-44.1 - 5.5i}$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

Re V $\gg$ Im V

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

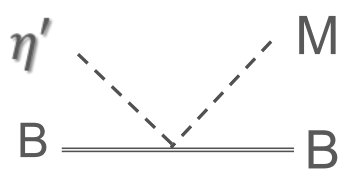
The reason why Re $V \gg$ Im V in the chiral unitary calculation

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**

ongoing work [A. Hinata, H. Nagahiro et al.]

- ✓ **energy-dependent** singlet-baryon interaction, which is important when we discuss over a wide energy range (deep bound state ↔ $a_{\eta' N}$ at threshold)
- ✓ possible α value evaluated from, ex.) $\pi N \to \eta' N$ cross section

Formation by (p,d) reaction

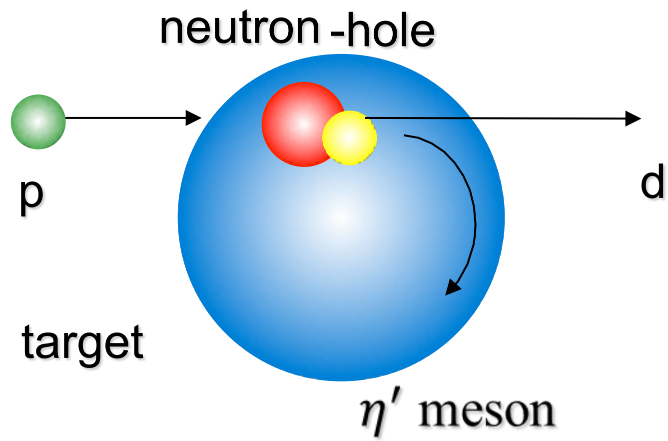
<u>missing mass spectroscopy</u>

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

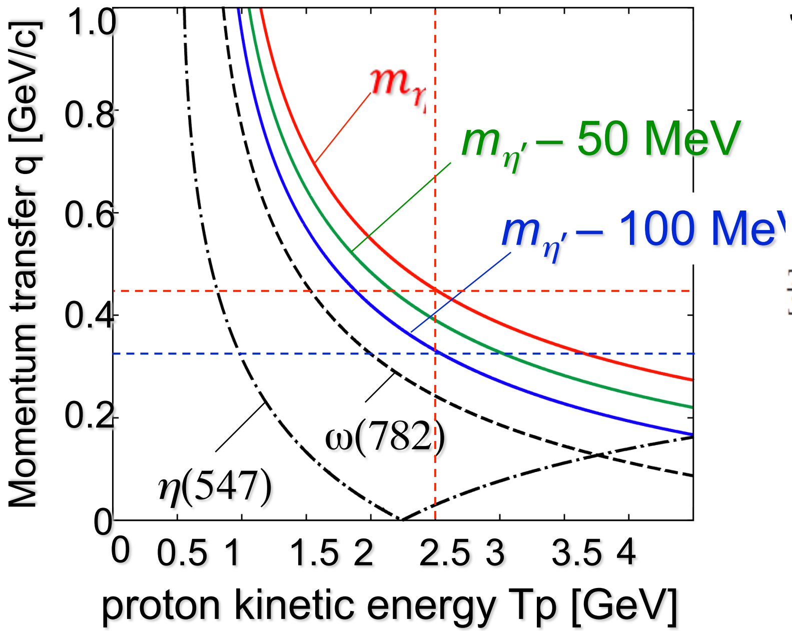
proton kinetic energy $T_p = 2.5$ GeV

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

forward reaction : θ_d = 0 deg.

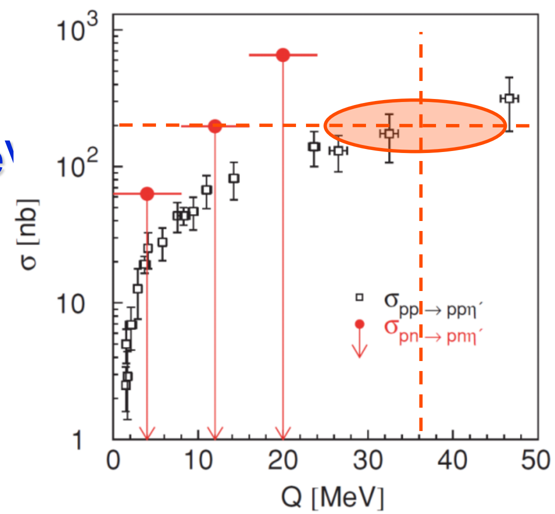


momentum transfer



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

target-nucleus dependence [merit / demerit] to see peaks

light nucleus ⟵⟶ **heavy nucleus**

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

observed spectrum = (η' bound states) ⊗ (one neutron-hole states)

η' bound states : $(V_0, W_0) = -(100, 10)$ MeV case

^{11}C	^{15}O	^{39}Ca
s, p	s, p, d	s, p, d, f, g

one neutron-hole state (excited states of daughter nucleus)

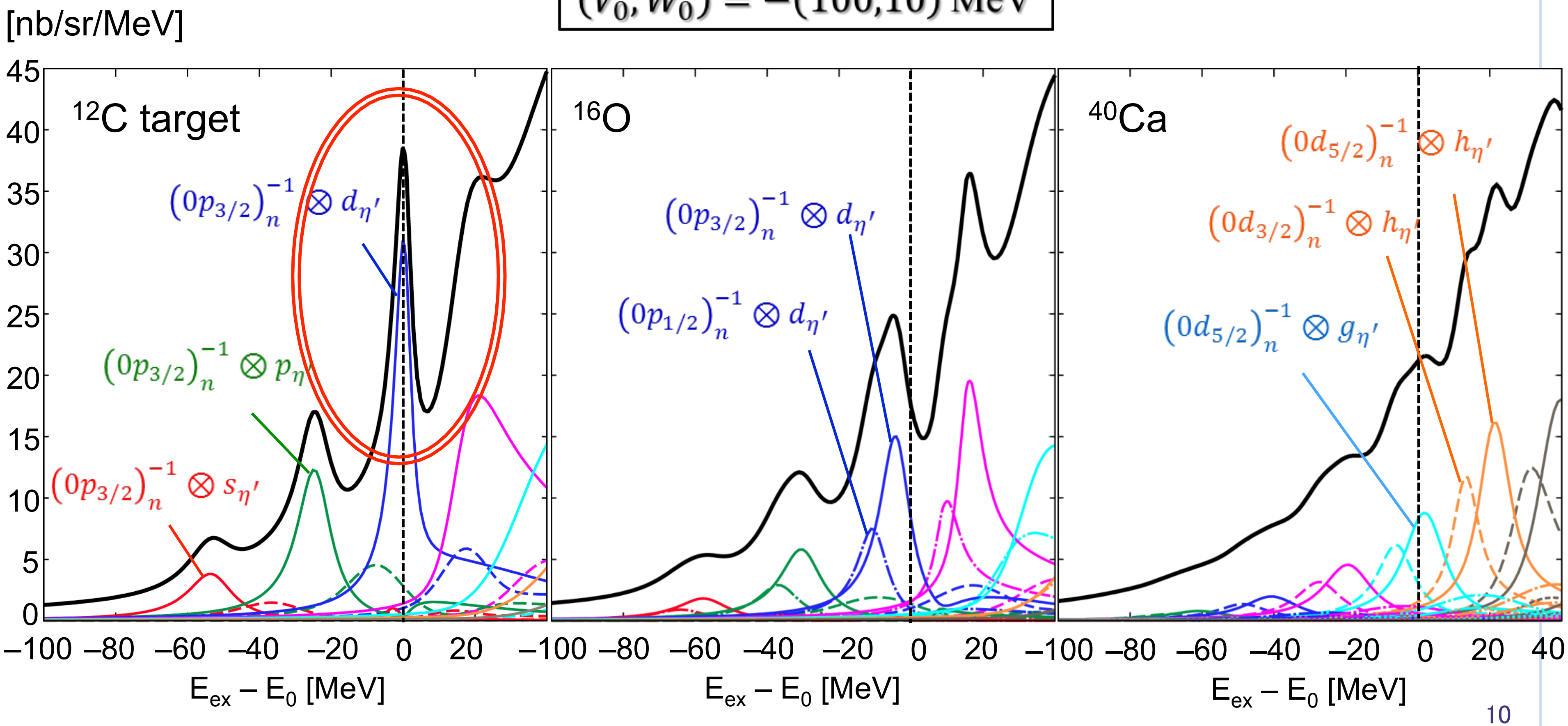
hole	ΔS_p	Γ	hole	ΔS_p	Γ	hole	ΔS_p	Γ
$0p_{3/2}$	–	–	$0p_{1/2}$	–	–	$0d_{3/2}$	–	–
$0s_{1/2}$	**18**	12	$0p_{3/2}$	**6.3**	**0**	$1s_{1/2}$	**3.2**	**7.7**
			$0s_{1/2}$	29	19	$0d_{5/2}$	**8**	**3.7**
						$0p_{1/2}$	25	21.6
						$0p_{3/2}$	25	21.6
						$0s_{1/2}$	48	30.5

$^{12}C(p,d)^{11}C\,\eta'$: 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

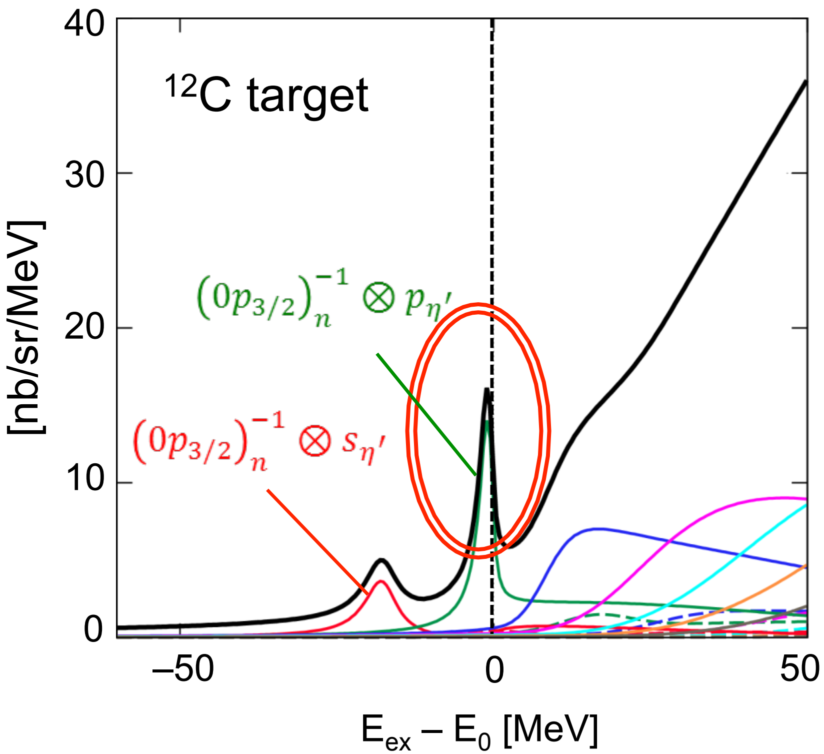


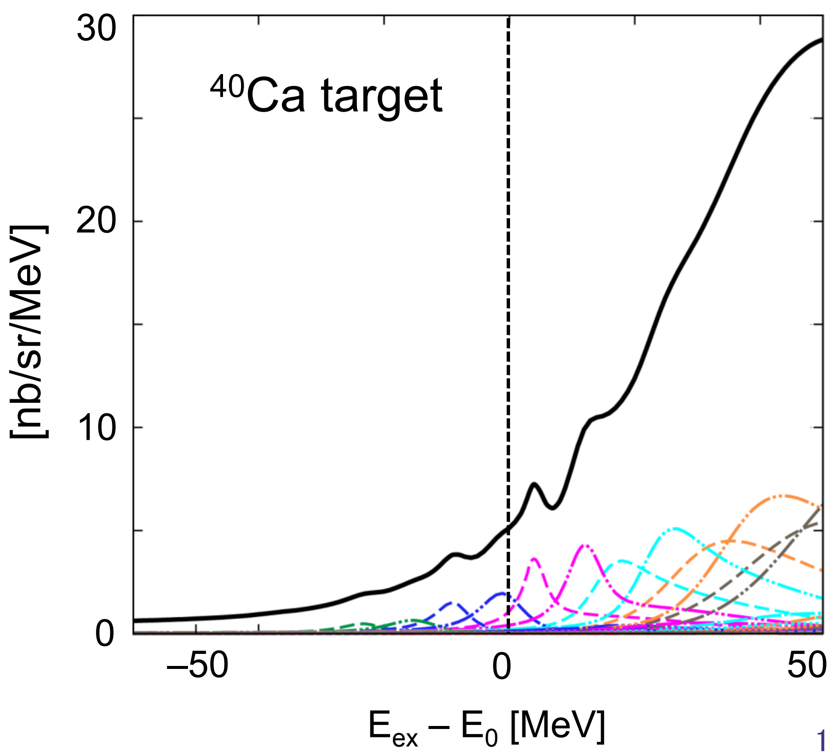
$^{12}C(p,d)^{11}C\,\eta'$: shallower case $(V_0, W_0) = -(50,5)$ MeV

light nucleus ⟷ **heavy nucleus**

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

Shallower case : $(V_0, W_0) = -(50,5)$ MeV

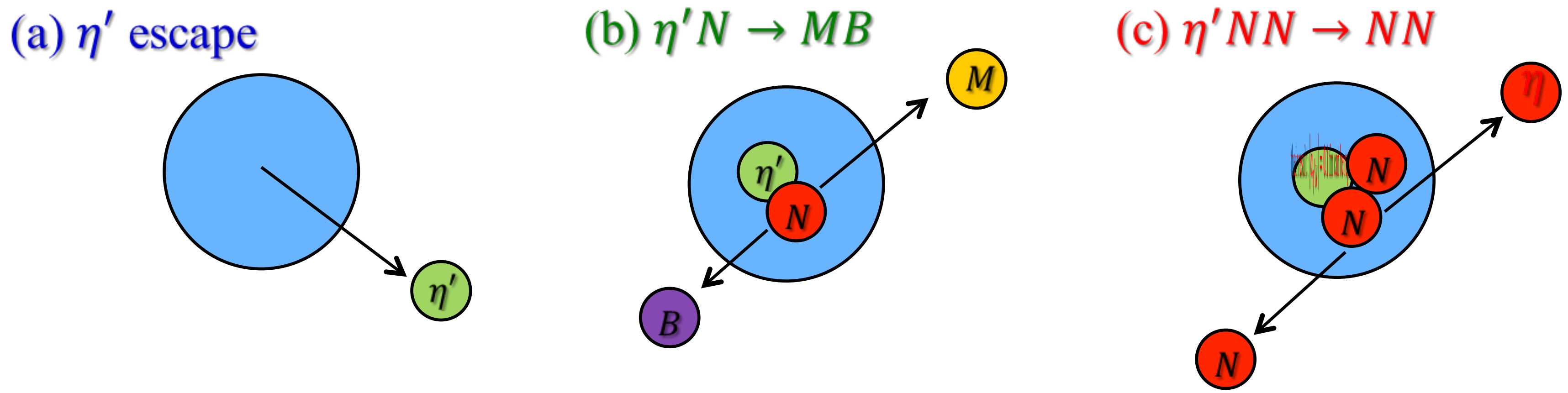


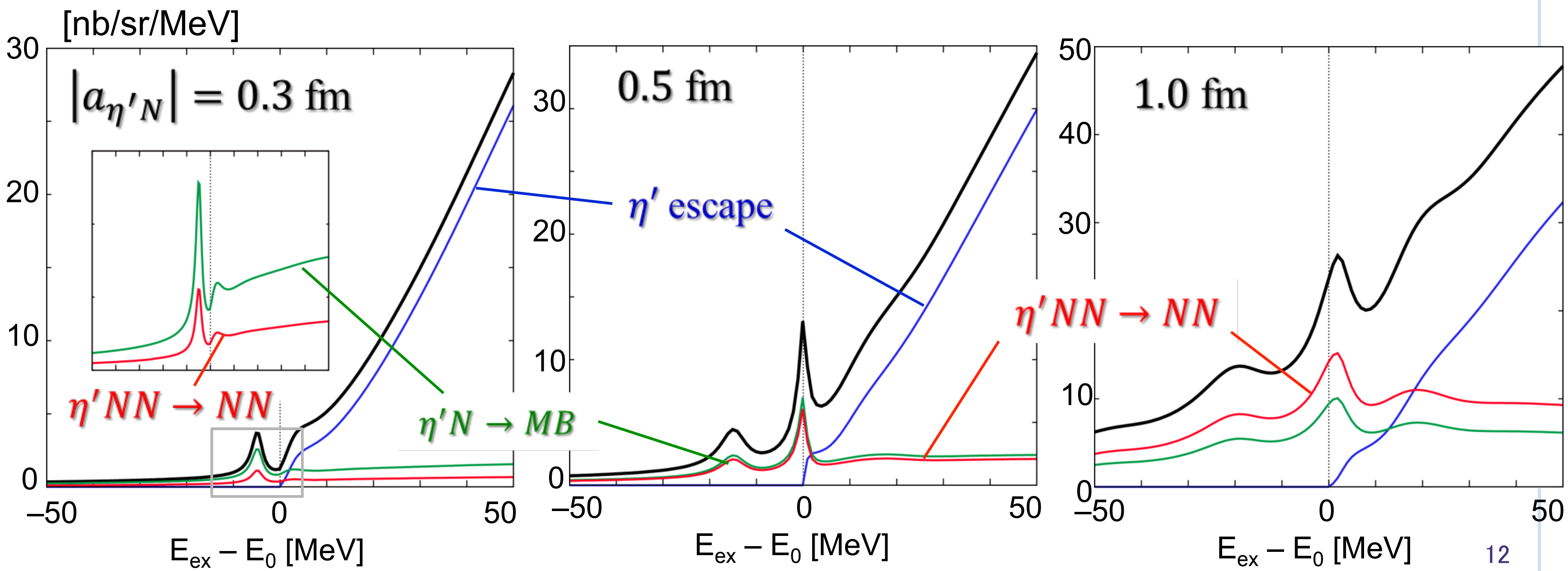


decomposition into different final states

based on the chiral unitary model

three final states





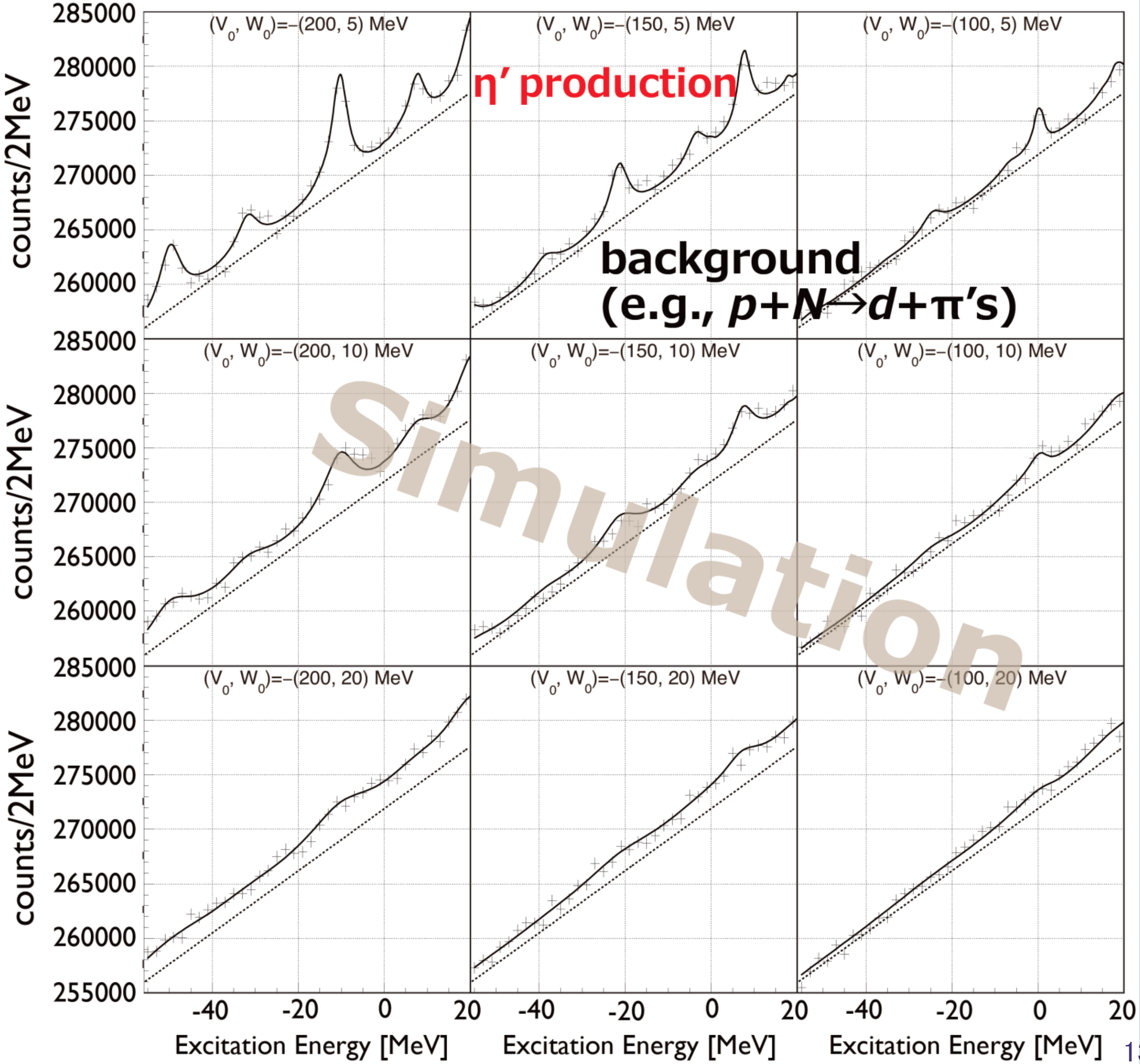
Experimental plan at GSI

- 1st Step : Inclusive measurement of (*p,d*) reaction with FRS at GSI

Simulation of spectra

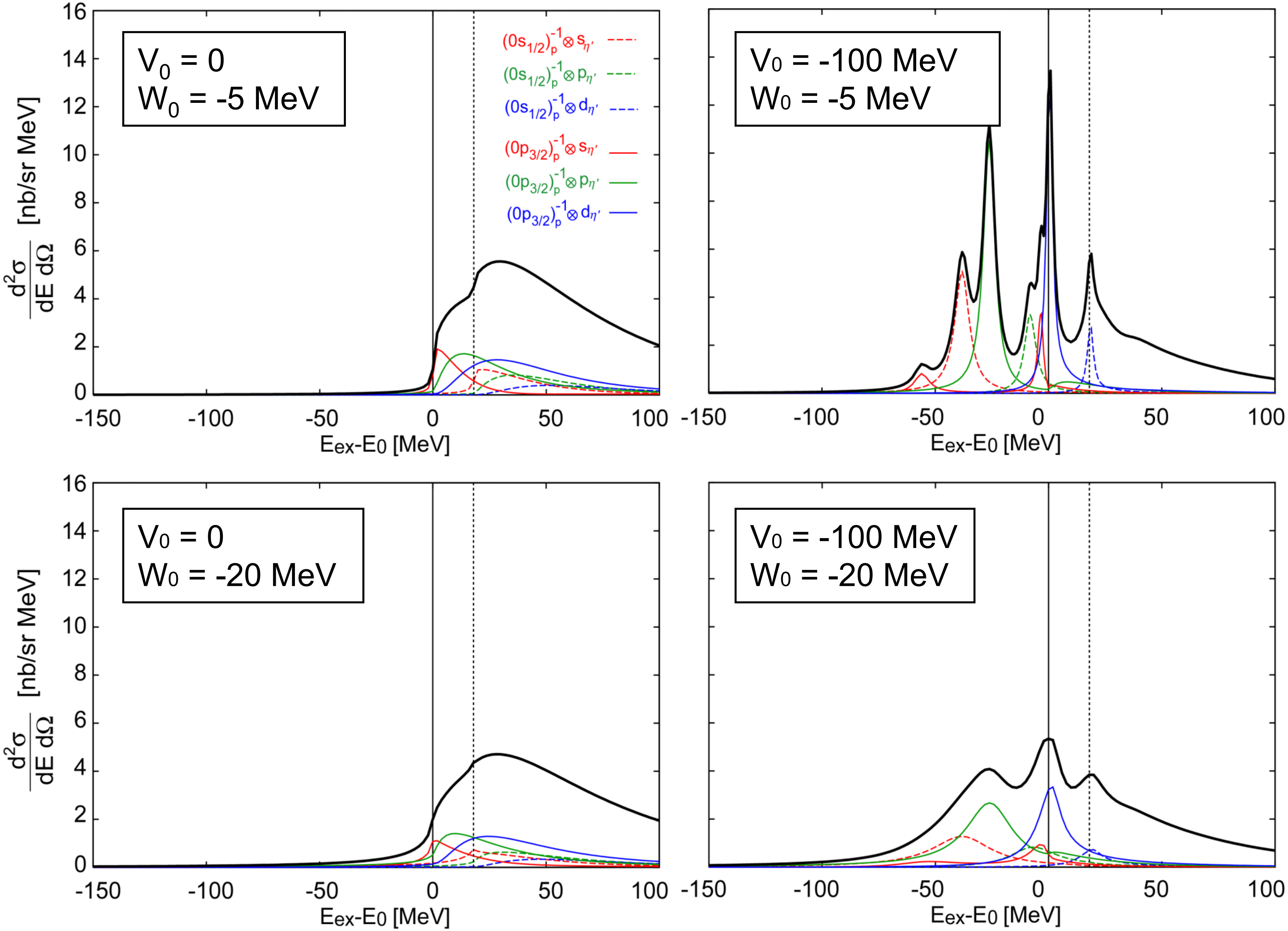
- $\eta' \times$ C formation and background processes

- 4.5 days DAQ assumed



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

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

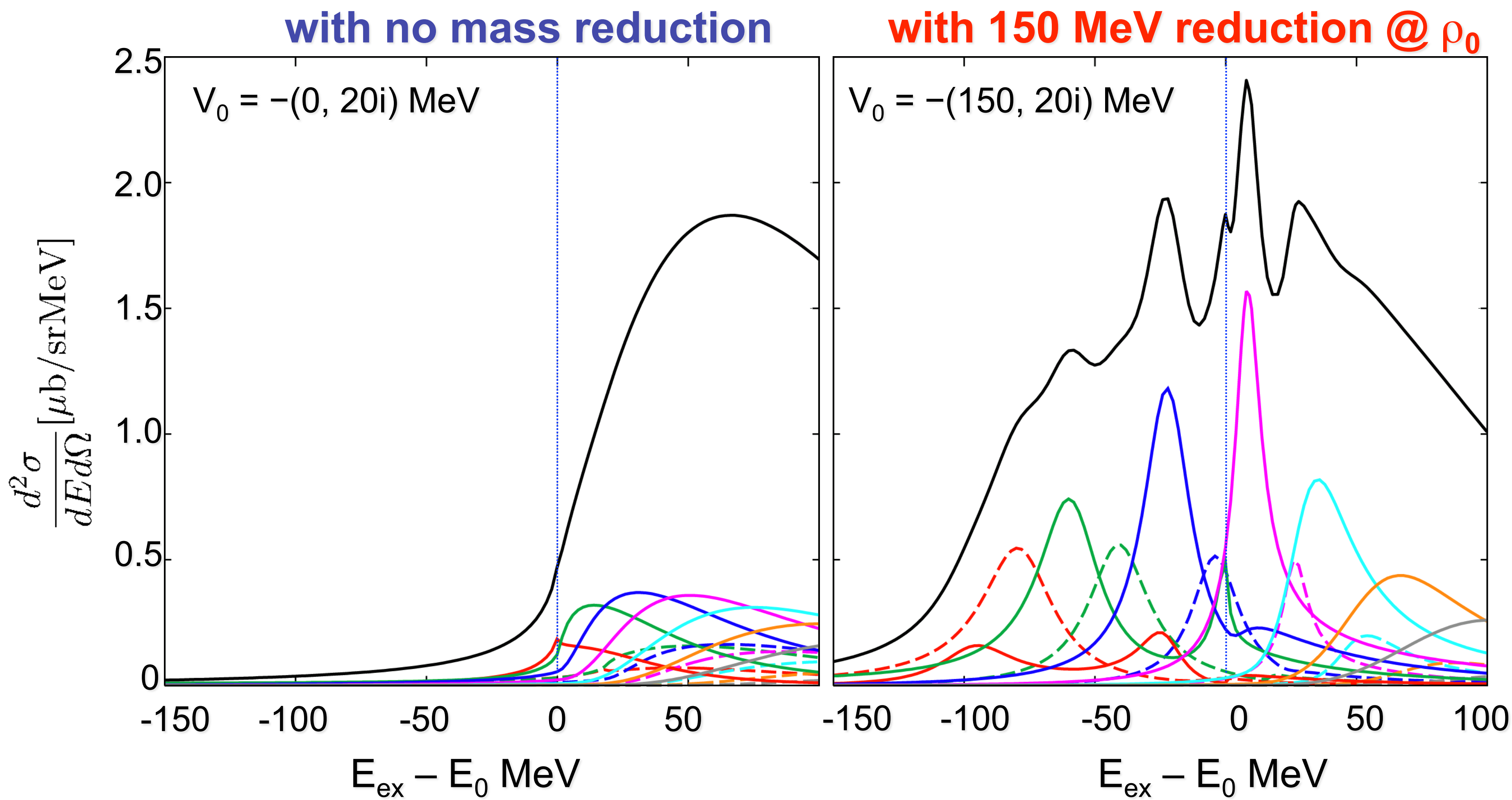


η'-mesic nuclei formation spectra : ^{12}C target : (π^+,p)reaction@JPARC

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

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

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



Summary for 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 contact interaction
- ✓ smaller inelastic channel

possibilities to observe bound state peaks

➔ Experiment

•Scattering length vs. attractive potential
➔ A. Hinata, H. Nagahiro

η-mesic nuclei : Introduction

works for η mesic nuclei & η-nucleus systems

- (π^+,p) * Liu, Haider, PRC34(1986)1845 **[theo]**
  * Chiang, Oset, and Liu, PRC44(1988)738 **[theo]**
  * Chrien *et al.*, PRL60(1988)2595 **[exp]** ←
  * Kohno, Tanabe, PLB231(1989)219; NPA519(1990)755 **[theo]**
  * Nagahiro, Jido, Hirenzaki, PRC80(2009)025205 **[theo]**
  * K.Itanashi, H.Fujioka, S.Hirenzaki, D.Jido, H.Nagahiro, **[LoI for J-PARC]**
- (d,^{3}He) * Hayano, Hirenzaki, Gilltzer, EPJ.A6(1999)99 **[theo]**
  * D. Jido, H.Nagahiro, S. Hirenzaki, PRC66(2002)045202 **[theo]**
  * Exp. at GSI (Yamazaki, Hayano group) 2005-**[exp]**
- . η-^{3}He system : PRL92(04)252001:TAPS@MAMI **[exp]**
  ←→ "Comment" by Hanhart, PRL94(05)049101.
- (γ,p) * H.Nagahiro, D.Jido, S.Hirenzaki, NPA761(2005)92 **[theo]**
- (γ,η) @ Tohoku, CBELSA/TAPS, etc.. : strong FSI, (no) N* width broadening, etc.. **[exp]**

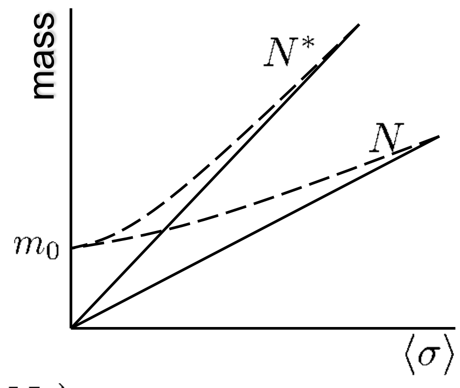
today's talk

- Formation of η-mesic nuclei by (π, N) reaction
  π and K beams are available **at J-PARC**
  with the chiral doublet model & chiral unitary model
- appropriate kinematics
- comparison with the (π^+,p) experiment at 1988

Chiral models for N*(1535) in medium

Chiral doublet model

DeTar, Kunihiro PRD39(89)2805
Jido, Nemoto, Oka, Hosaka NPA671(00)471
Jido, Oka, Hosaka PTP106(01)873
Kim, Jido, Oka NPA640(98)77



Extended SU(2) linear sigma model
for N and N*

Lagrangian

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

N* : chiral partner of N

N* ~ elementary particle

N & N* masses

$$m^*_{N,N^*} = \frac{1}{2}\left[\sqrt{(g_1+g_2)^2\langle\sigma\rangle^2 + 4m_0^2} \mp (g_2 - g_1)\langle\sigma\rangle\right]$$

mass difference of N* and nucleon

$$m^*_N(\rho) - m^*_{N^*}(\rho) = (1 - C\frac{\rho}{\rho_0})(m_N - m_{N^*})$$

Medium effect

$$\langle\sigma\rangle = \left(1 - C\frac{\rho}{\rho_0}\right)\langle\sigma\rangle_0$$

C ~ 0.2 : strength of chiral restoration at the saturation density ρ_0

mass gap reduction in the nuclear medium

Chiral models for N*(1535) in medium

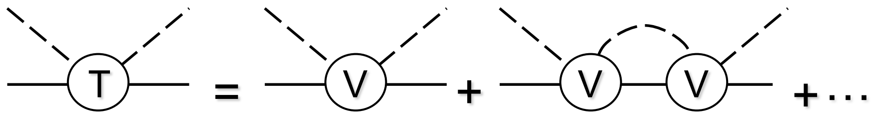
Chiral Unitary model

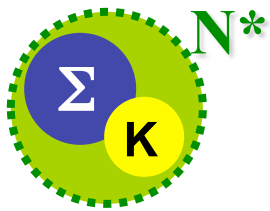
Kaiser, Siegel, Weise PLB362(95)23
Waas, Weise NPA625(97)287
Garcia-Recio, Nieves, Inoue, Oset PLB550(02)47

Inoue, Oset NPA710(02)354

coupled channel Bethe-Salpater eq. in-medium

$\{\pi N, \eta N, KY, \pi\pi N\}$

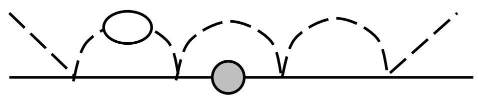




N*(1535) … dynamically generated in the meson-baryon scattering → **quasi-bound state of KΣ**

medium effect

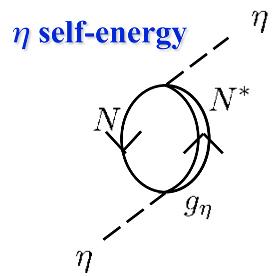
In-medium correction (hadron dressing, Pauli blocking) for intermediate hadron

N* ~ 

no Pauli blocking for Σ in nuclear medium

no mass shift is expected in the nuclear medium

η-nucleus interaction : potential descriptions



optical potential

$$V_{\rm opt} \equiv \frac{\Pi_\eta}{2\mu} = \frac{g_\eta^2}{2\mu}\frac{\rho(r)}{\omega - (m_{N^*}(\rho) - m_N(\rho)) + i\Gamma_{N^*}(s;\rho)/2} + \text{(crossed term)}$$

potential nature at η threshold

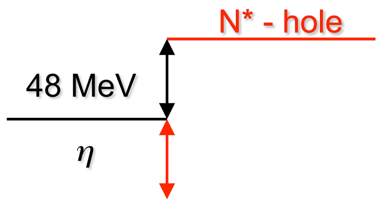
$$m_\eta - (m_{N^*} - m_N) < 0$$

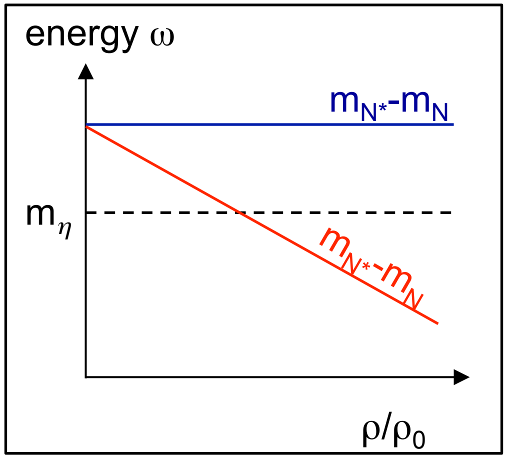
attractive

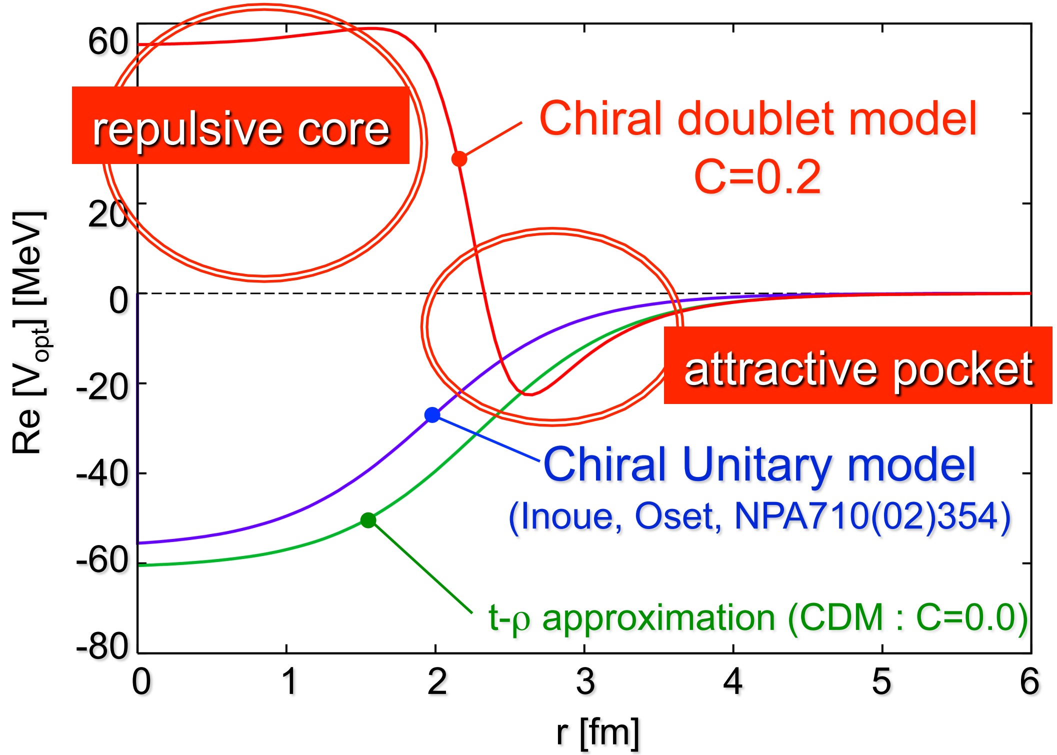
medium effect

$$m_\eta - (m_{N^*}(\rho) - m_N(\rho)) > 0$$

repulsive







Bound states

Klein-Gordon equation

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

bound states

Chiral doublet model (C=0.2)

	(B.E., Γ) [MeV]			
A=11	1s	(91.3, 26.3)	1p	(79.3, 31.1)
	2s	(75.1, 33.0)		

deep bound state

Chiral unitary model

	(B.E., Γ) [MeV]			
A=12	1s	(9.71, 35.0)	1p	–
A=40	1s	(17.88, 34.38)	1p	(7.04, 38.6)

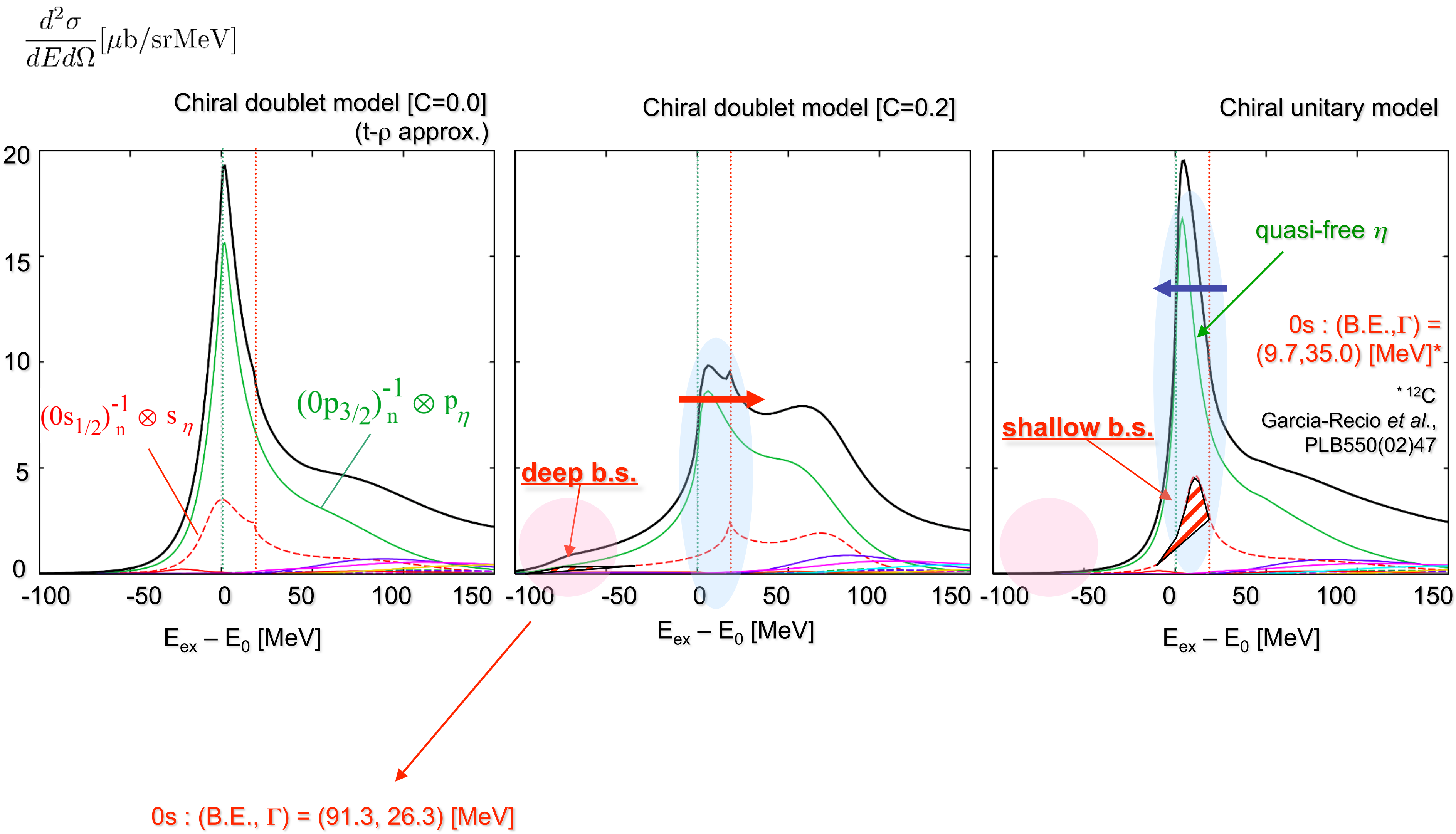
shallow bound state

C.Garcia-Recio, T. Inoue, J. Nieves, E. Oset, PLB550(02)47, Table 1

(π^+,p) spectra : ^{12}C target : Green function method

T_π = 820 MeV (p_π = 950 MeV/c) : θ = 0 deg. (Lab)

recoilless at η threshold

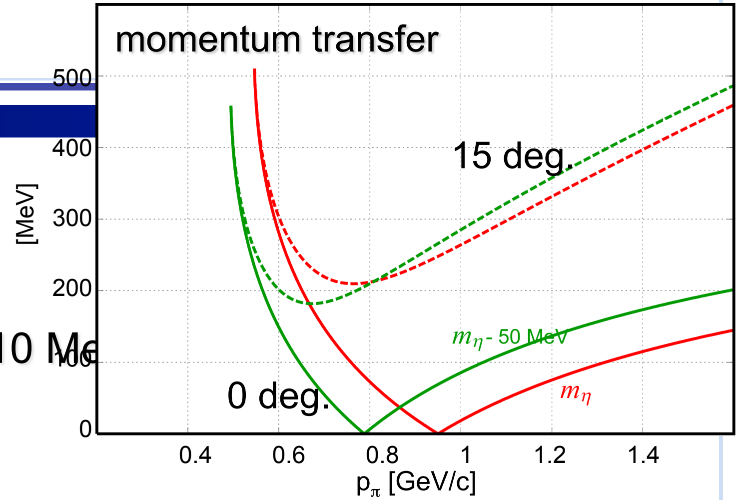


- the past experiment of (π^+,p) [1988, Chrien et al.]
  - the meaning of "negative result"
  - comparison of our results with the experimental data
  - appropriate experimental condition

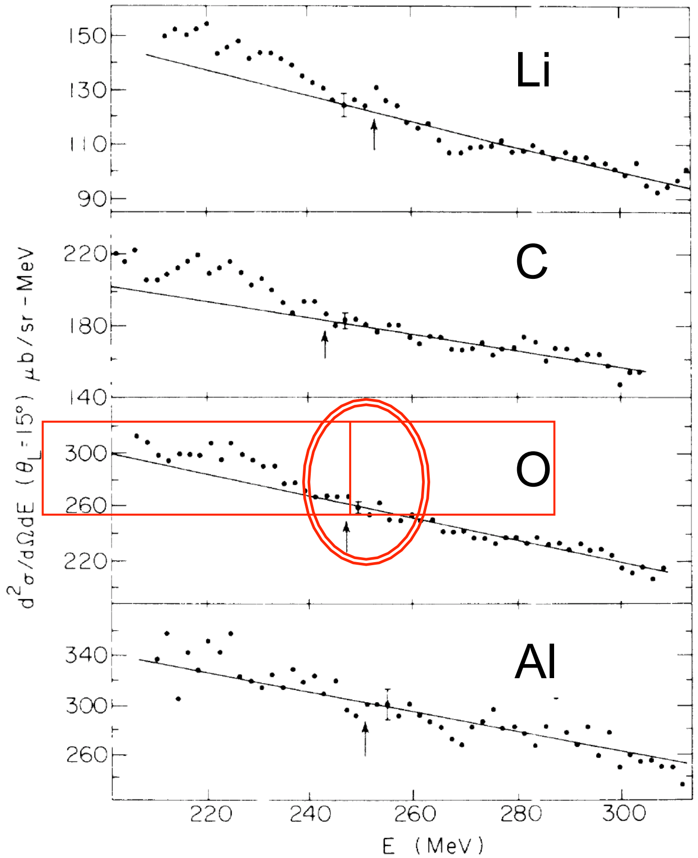
(π^+,p) spectra : Brookhaven in 1988

- Chrien et al., PRL60(1988)2595
  - » p_π = 800 MeV/c
  - » proton angle : 15 deg. (Lab.)
  - » search for predicted narrow bound state (ex. $\Gamma \sim$ 10 MeV)

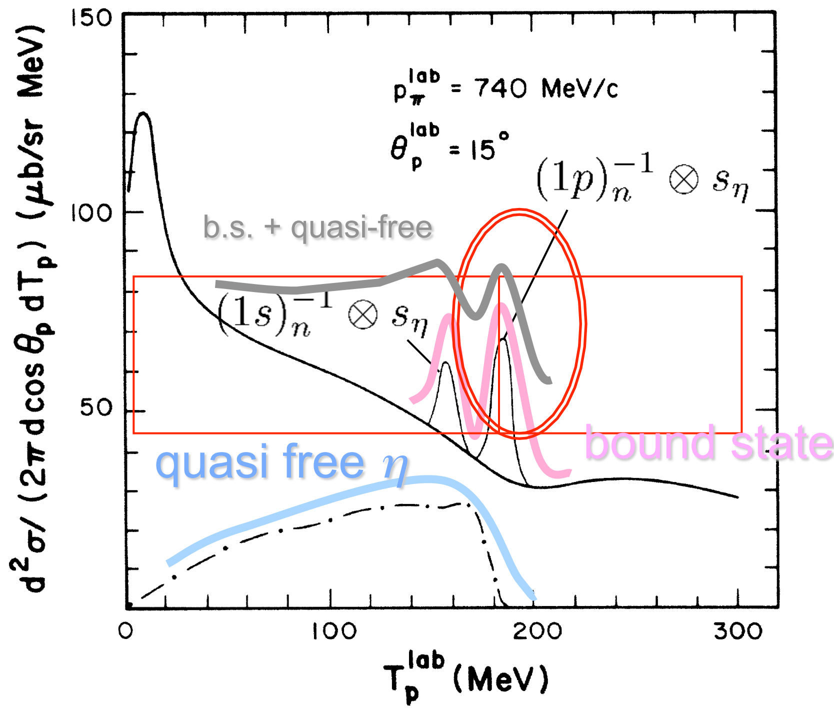
→ negative results (bound state was not observed)



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

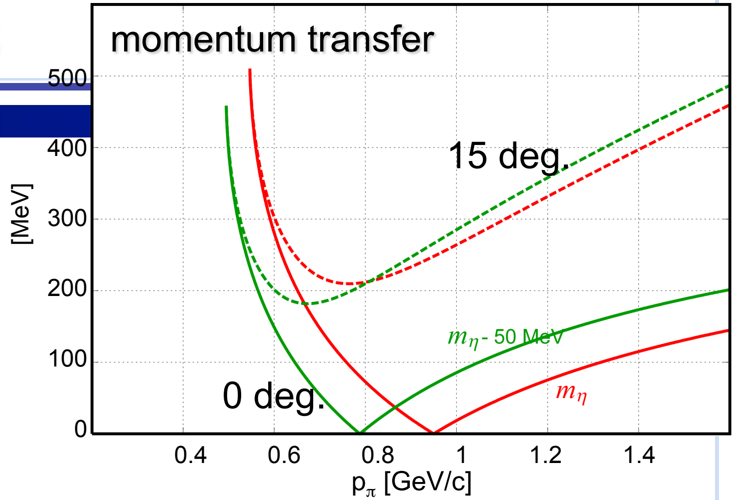


Liu, Haider, PRC34(86)1845, Fig.7



(B.E, Γ/2) = (2.65, 4.77) [MeV]

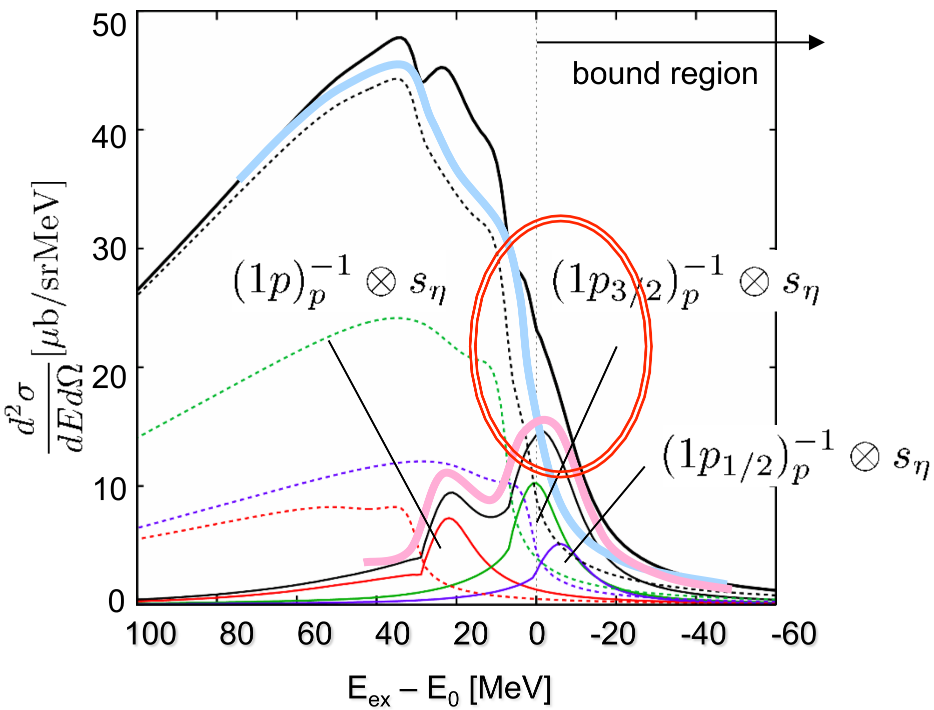
(π^+,p) spectra : past experiment in 1988



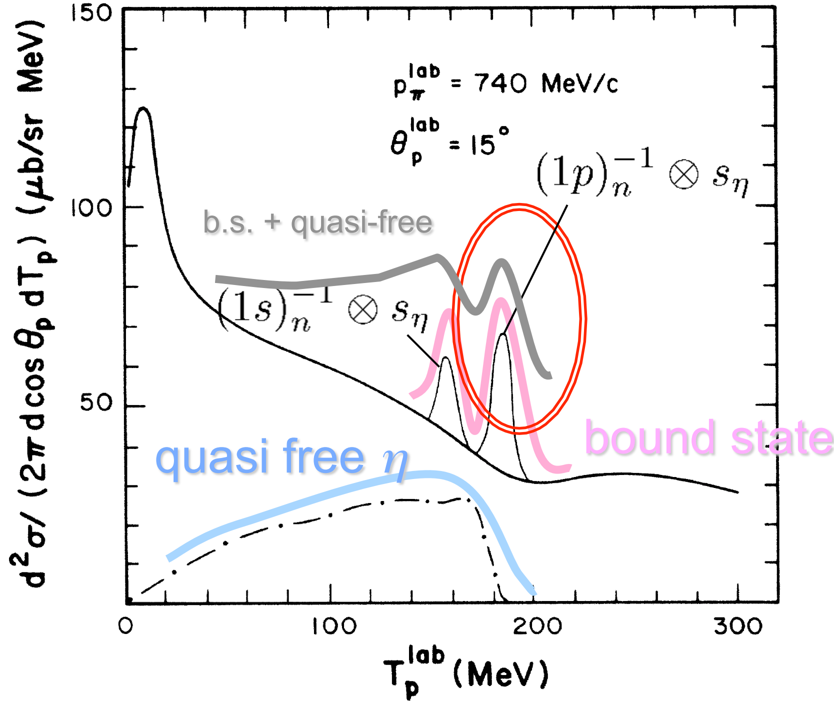
Problems are :

- quasi-free contribution [Also commented in Kohno et al, NPA519(90)755]
  - » virtual η absorption (due to Imaginary potential)
  - → The peak structure is hidden in quasi-free contribution
- Difference of nucleon separation energy in ^{16}O
  - » 1p1/2 ←→ 1p3/2 ←→ 1s1/2
    ~ 6 MeV ~ 23 MeV

Green's function method (V_0,W_0) = -(34,15) [MeV]

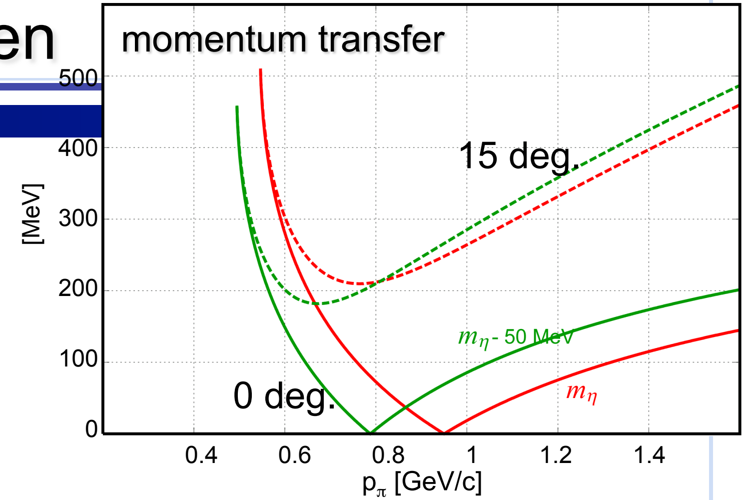


Liu, Haider, PRC34(86)1845, Fig.7



(B.E, $\Gamma/2$) = (2.65, 4.77) [MeV]

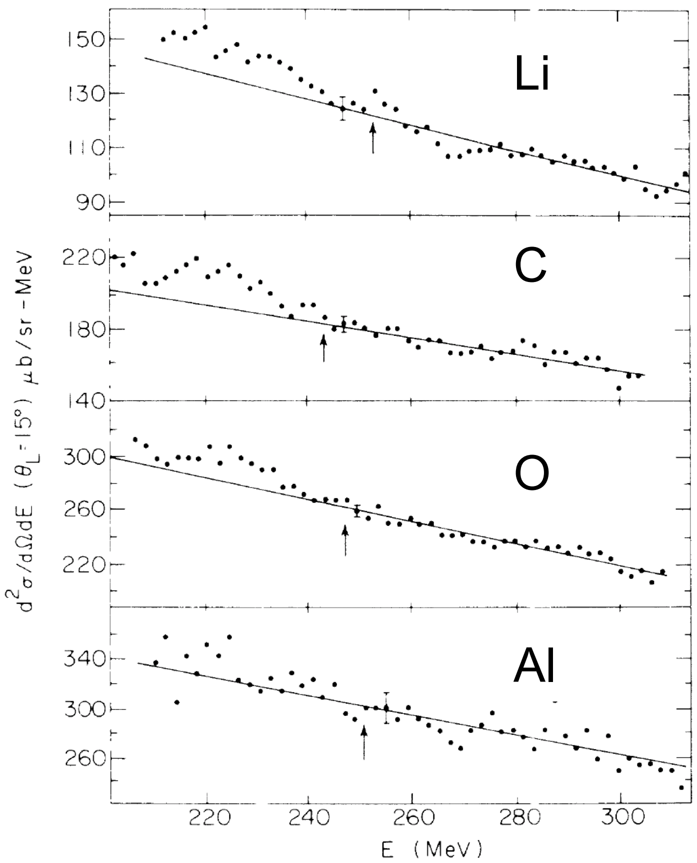
(π^+,p) spectra : experiment at Brookhaven

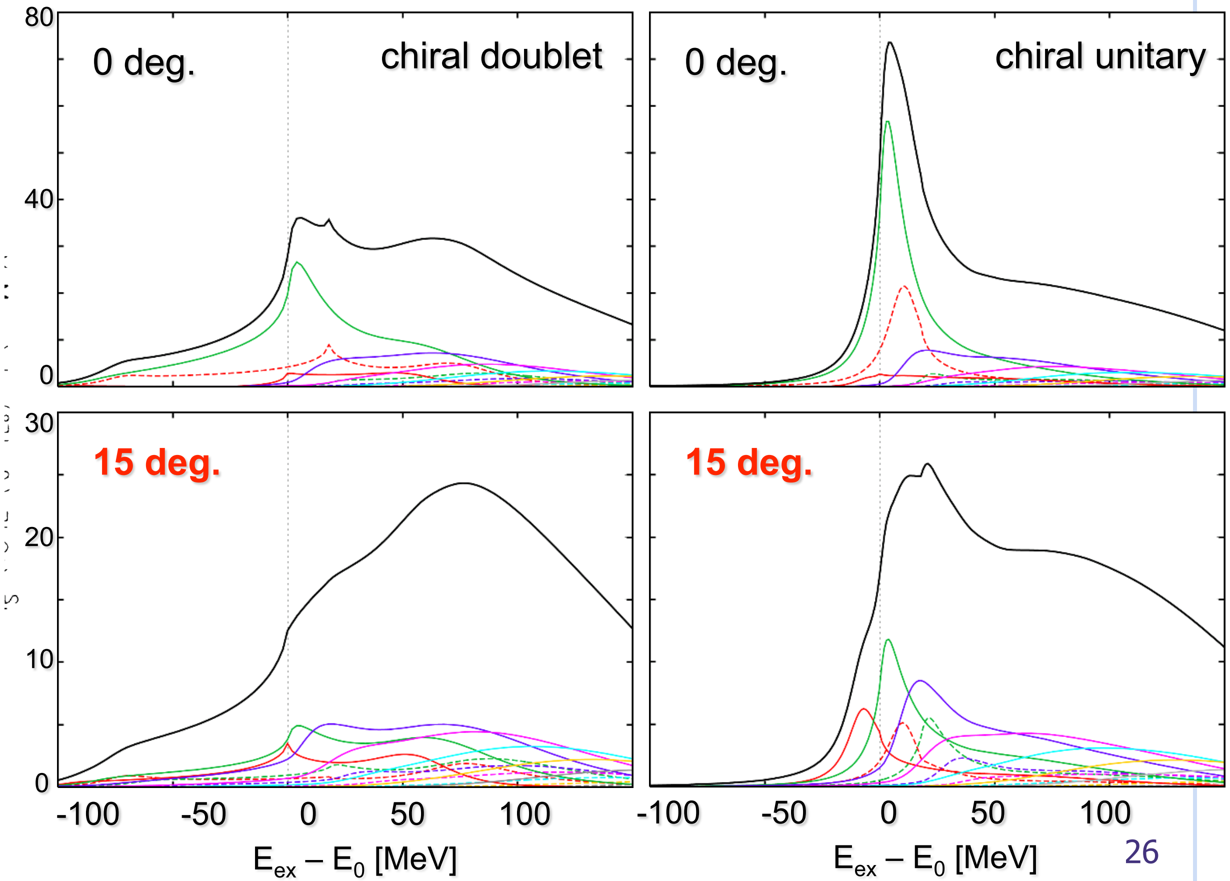


- Chrien et al., PRL60(1988)2595
  - » p_π = 800 MeV/c : proton angle : **15 deg. (Lab.)**
  - » search for predicted narrow bound state by Liu, Haider, PRC34(86)1845

→ negative results (bound state peak was not observed)

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





(π^+,p) spectra : experiment at Brookhaven

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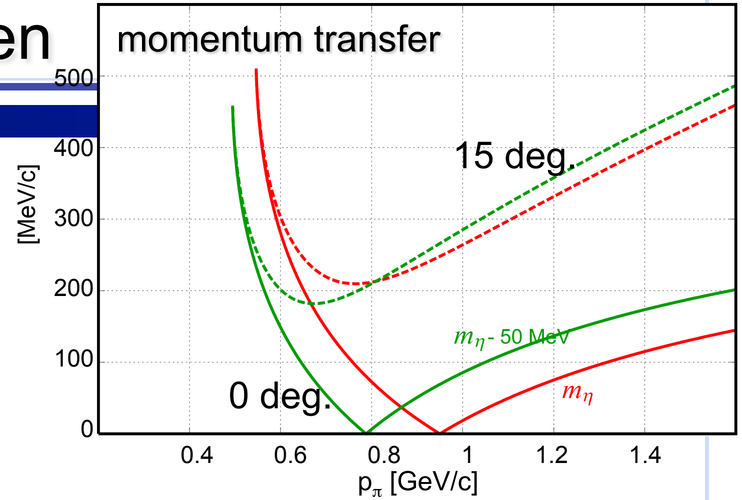
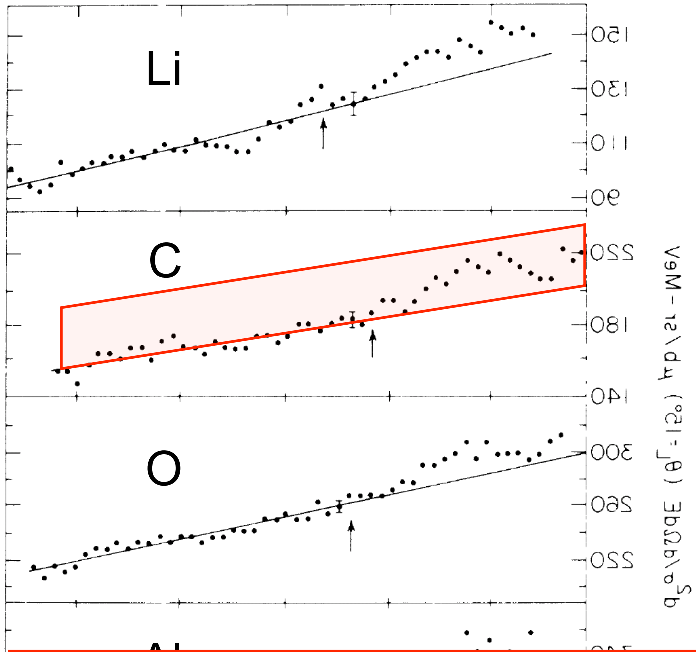
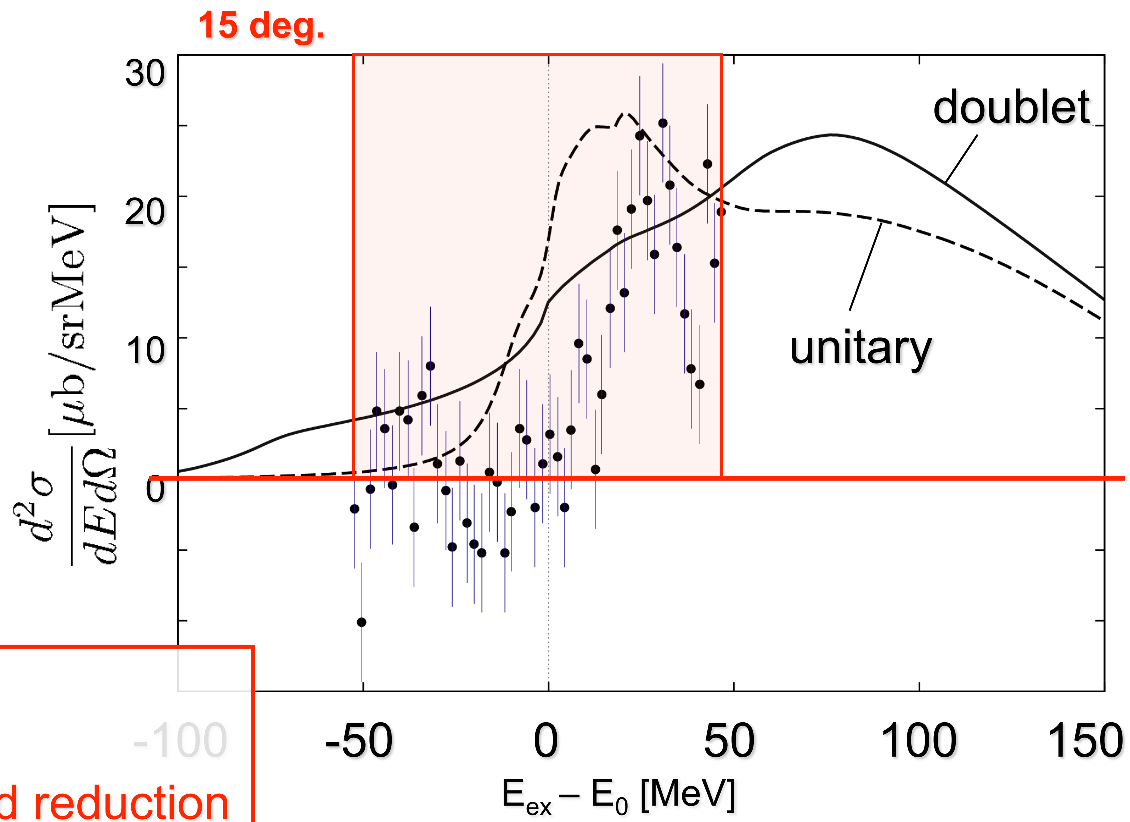


Chrien at al., PRL60(88)2595, Fig.1





- wider energy range
- proton angle = 0 degree
- S/N ~ 1/10 → need background reduction

Summary for eta-mesic nuclei

- Formation of η-mesic nuclei
  - **In-medium properties of N*(1535) resonance**
    - Chiral doublet model : deep bound state(s)
      - pocket-like potential, level crossing of η and N*-hole modes
    - Chiral unitary model : shallow bound state(s)
- (π^+,p) reaction
  - incident pion kinetic energy
    - T_π = 820 MeV (p_π ~ 950 MeV/c) : recoilless at η threshold
- Reconsideration of the experimental data at 1988 by Chrien *at al.*
  - Is the 15°proton angle appropriate?
    - Not sensitive to the N* properties in-medium
  - We should discuss the whole shape itself in the case that the imaginary part might be large
  - the proton angle ~ 0 deg.
- **possible at J-PARC ?**