Exotic Atoms and Exotic Nuclei

= New kind of Sub-atomic Matter =

Satoru Hirenzaki

Nara Women's University,

II SYMPOSIUM ON APPLIED NUCLEAR PHYSICS AND INNOVATIVE TECHNOLOGIES

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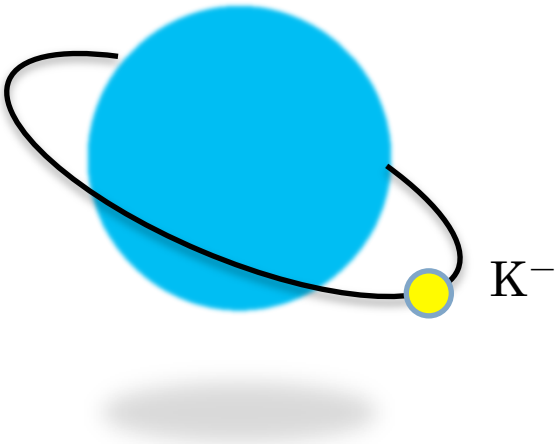
JAGIELLONIAN UNIVERSITY IN KRAKOW

FNP Foundation for Polish Science

KNOW

Objects -- Exotic Atoms and Exotic Nuclei --

- Exotic Atoms (ex. Kaon)



K meson (m_K～ **500** MeV)

Binding energy

order of 10keV～MeV

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

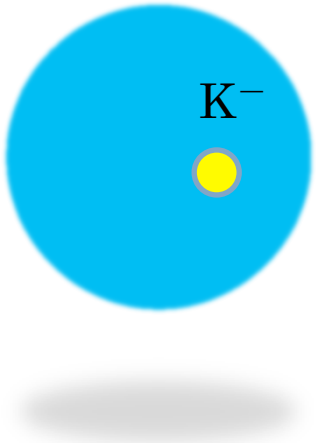
Binding Energy -- order of eV～keV

- Exotic Nuclei (ex. Kaon)

Very Deep !!

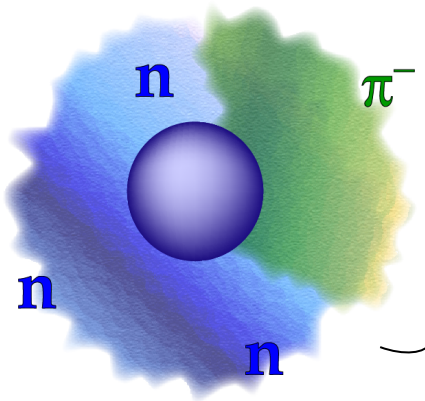
Binding Energy

10 ～100 MeV

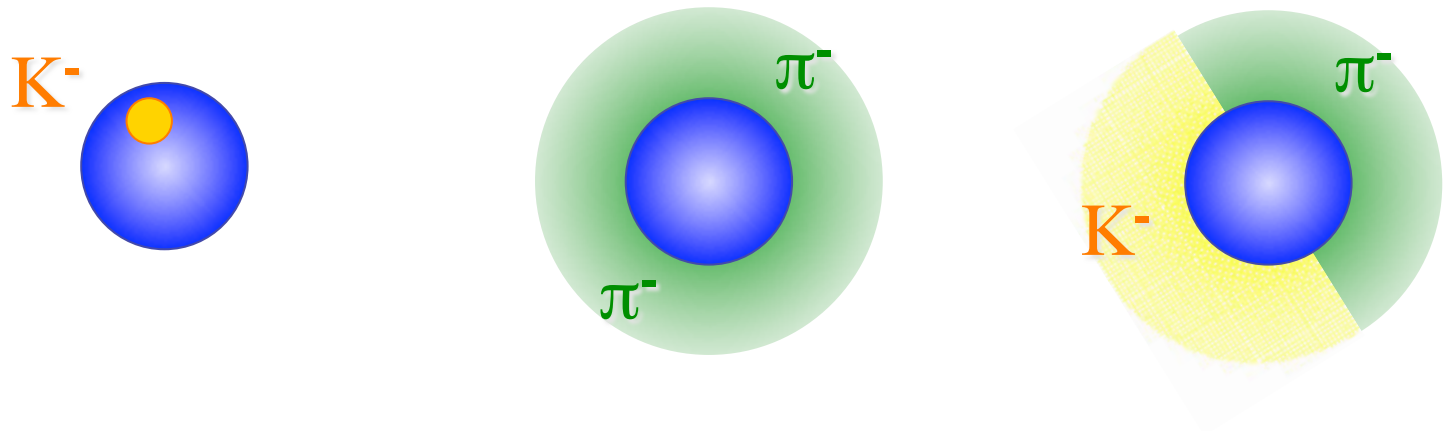


Interests ---- 2 way ! ----

[1]. Exotic Many Body Physics (Finite, Isolated)



Exotic few body systems.
(core, fermion, boson)

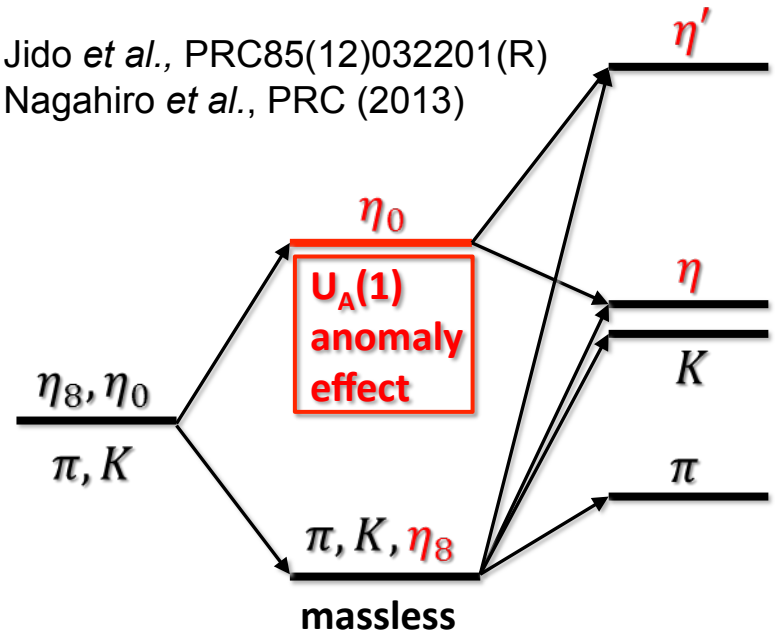


cf. Neutron/Proton rich nuclei, Hyper nuclei

[2]. Symmetry Breaking Pattern and Meson mass spectrum (PS)

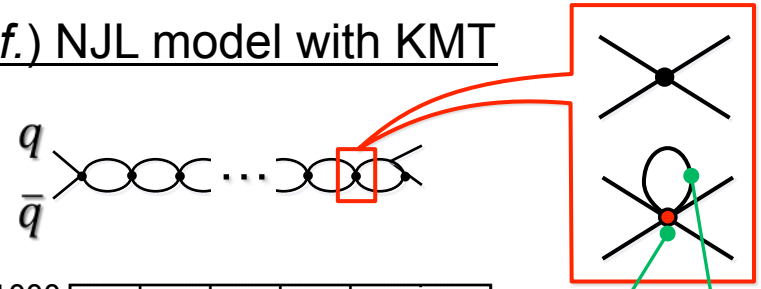
schematic view of the mass of π, K, η & η'

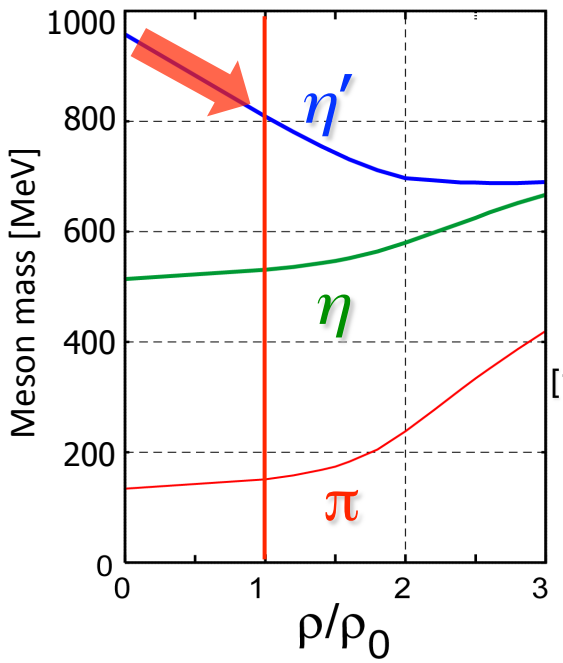
Jido *et al.*, PRC85(12)032201(R)
Nagahiro *et al.*, PRC (2013)



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

cf.) NJL model with KMT





$U_A(1)$ breaking (KMT term[1,2])

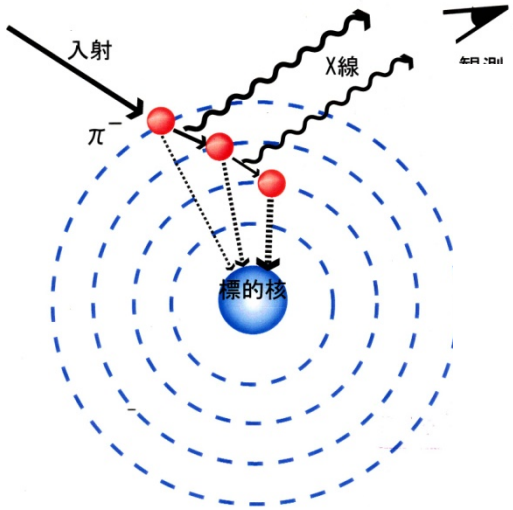
$\langle \bar{q}q \rangle \to 0$

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

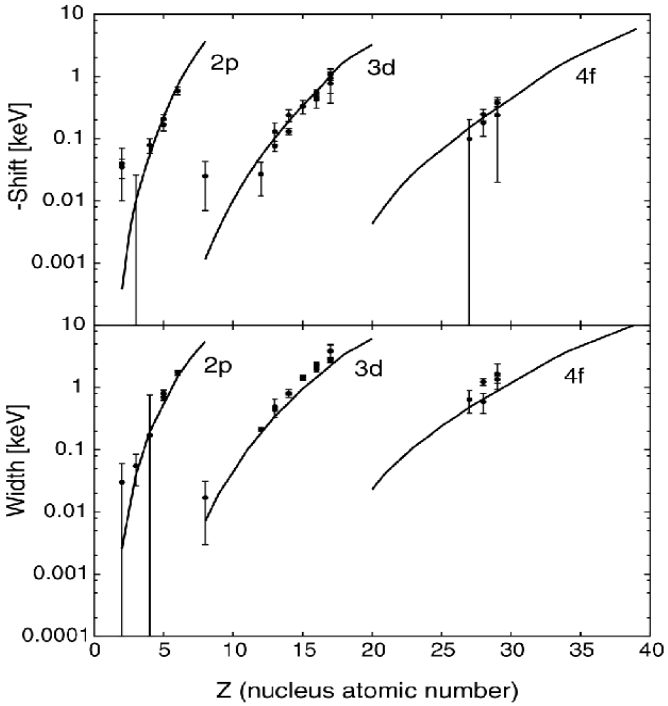
$\Delta m \sim -150$ MeV @ ρ_0

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

Observation of Mesonic Atoms by x-ray



Kaonic Atom data



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

Pionic X-ray data

(^{209}Bi)

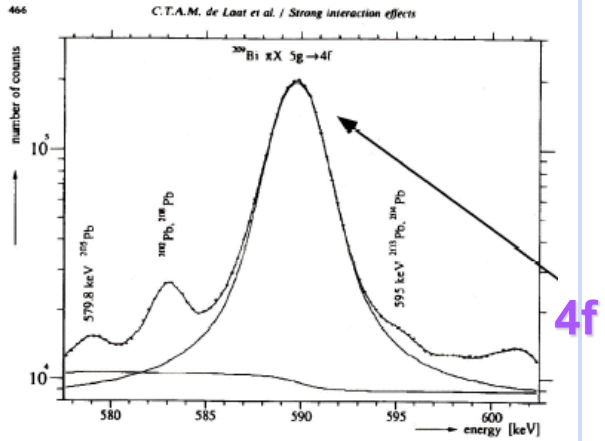


Fig. 5. Part of the pionic X-ray spectrum shown in fig. 4, showing the energy region of the pionic 5g→4f hyperfine complex from pions stopped in a ^{209}Bi target. The fit to the experimental data points is represented by the solid line. The background including the step function is also displayed by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

(^{209}Bi)

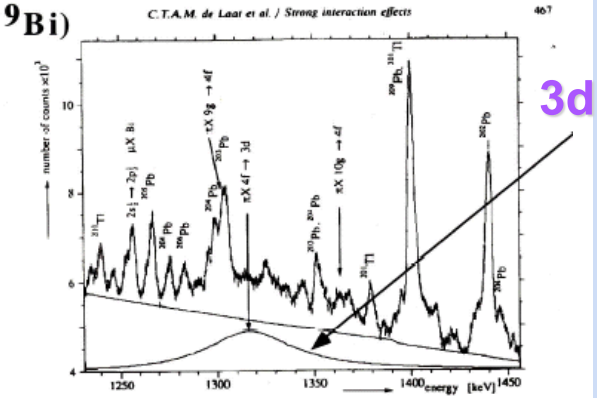
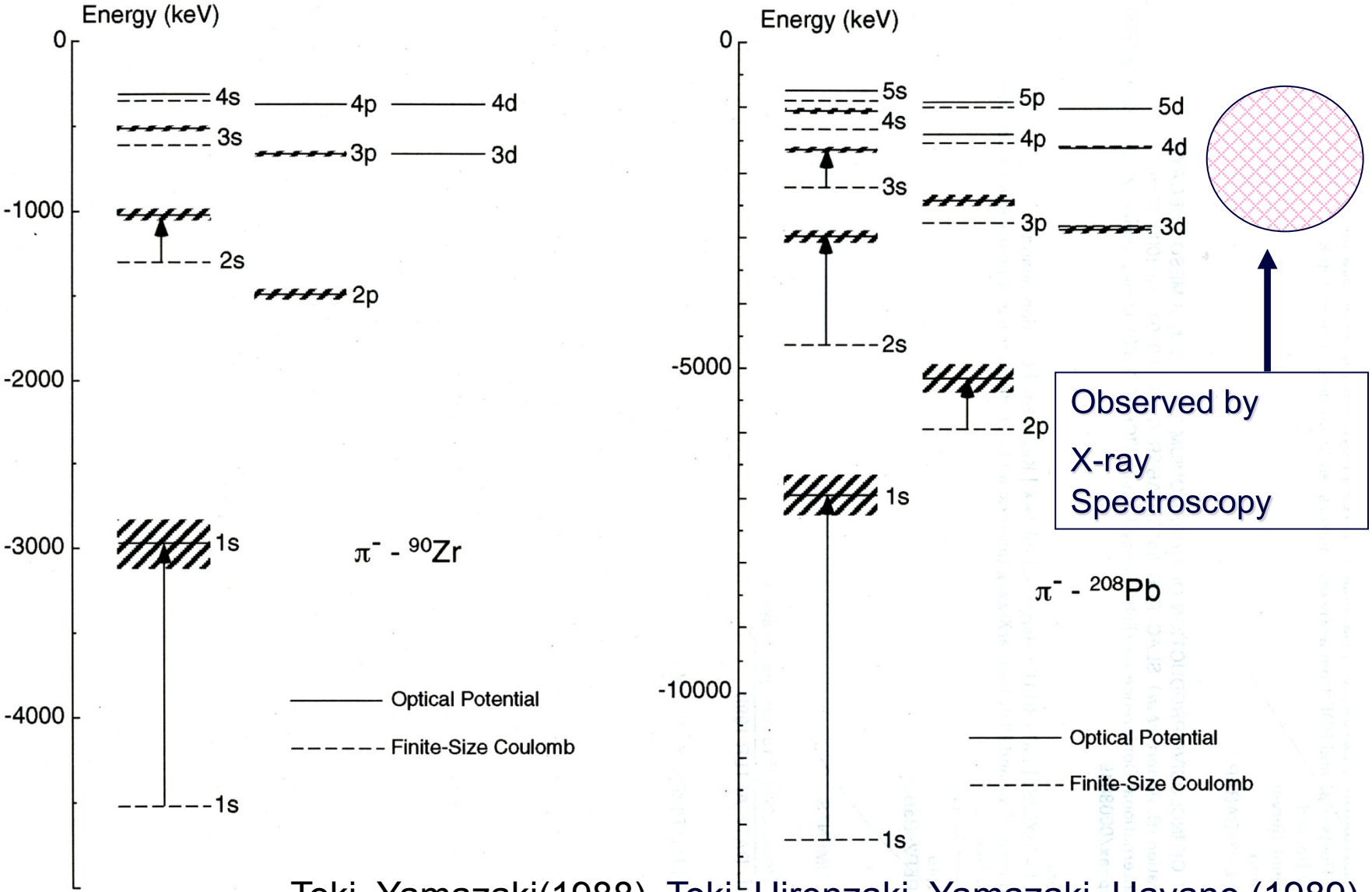


Fig. 6. This figure displays the 4f→3d hyperfine complex of the prompt pionic ^{209}Bi X-ray spectrum. The solid line represents the fit to the experimental data points. Also shown are the background (see text) and the resulting 4f→3d line. The various γ-rays also included in the fitting procedure have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

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

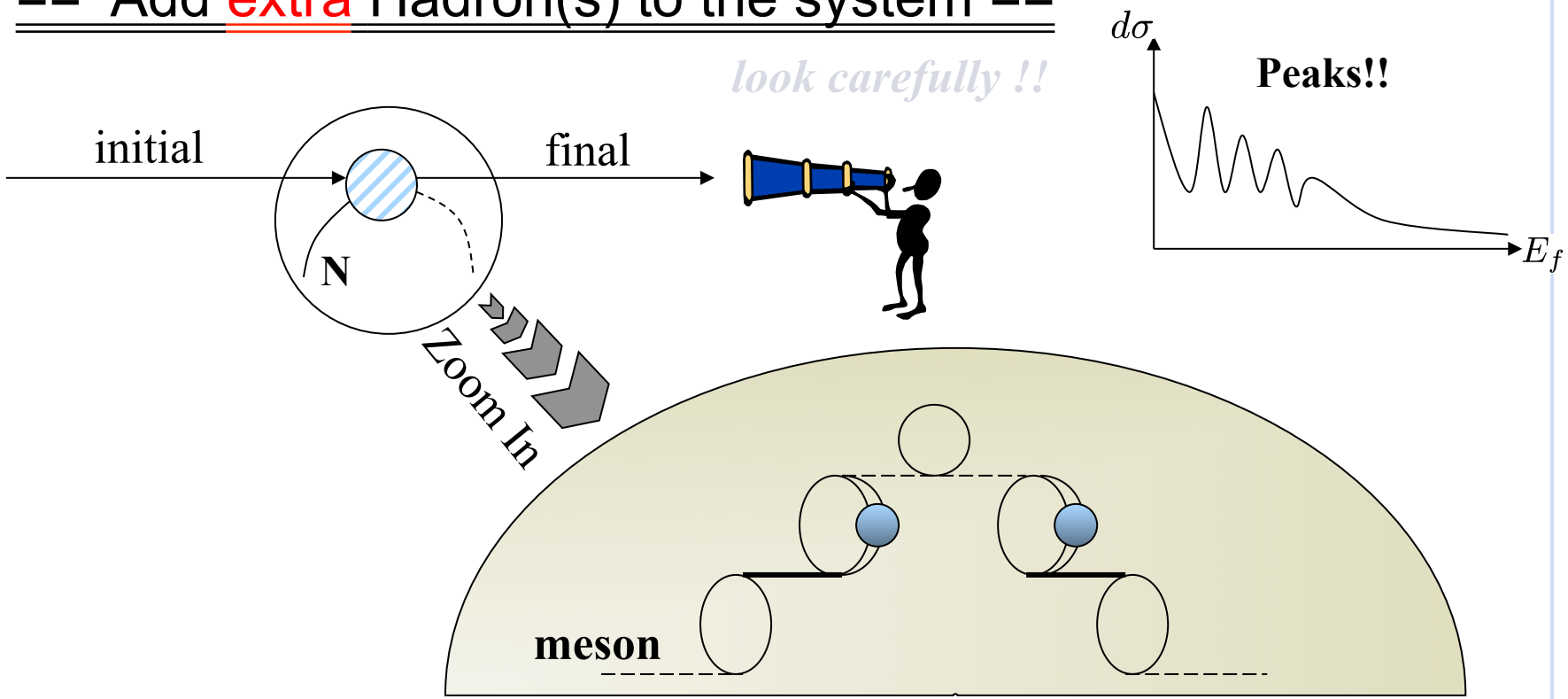
Theoretical Level Structure – Sates exist beyond the 'X-ray'



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

Missing Mass Spectroscopy

== Add extra Hadron(s) to the system ==



In-Medium Dispersion Relation

Medium Effects

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

First Observation

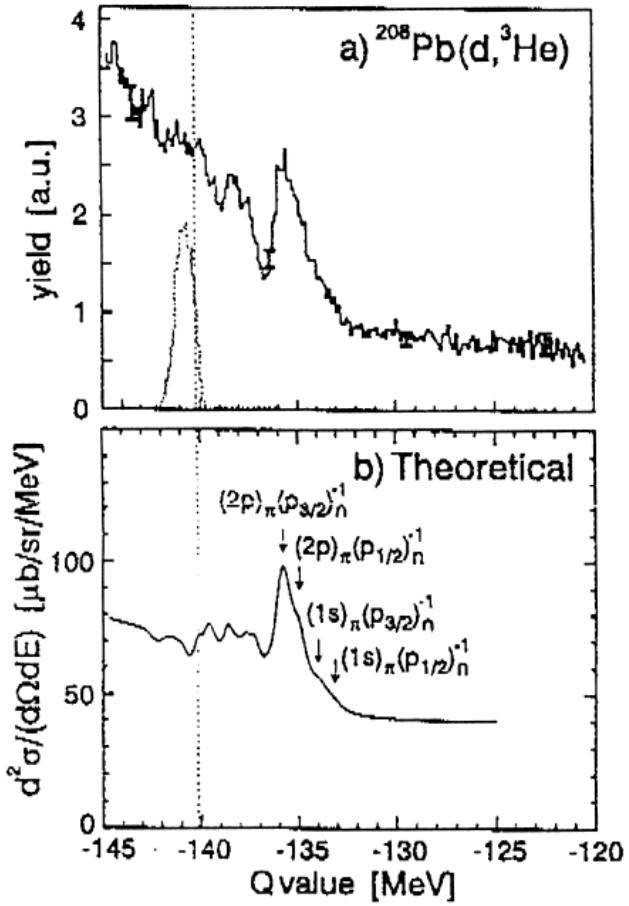
Cover of INS (inner-) News Letter, 1 Aug 1996 (Institute for Nuclear Study, University of Tokyo, Japan)

核研所内報

No. 295

1996. 8. 1

東京大学原子核研究所



深部束縛パイ中間子原子の発見

（上）：測定された $(d, {}^3\mathrm{He})$ 反応の励起スペクトル。縦の点線は負パイ中間子の発生しきい線。左下方にある点線ピークは $(CH_2)_n$ 標的の場合に現れる中性中間子発生に伴うもので，いかにバックグラウンドがないか，また分解能が良いかを示している。

（下）：比連崎らによる理論スペクトル。

First Observation

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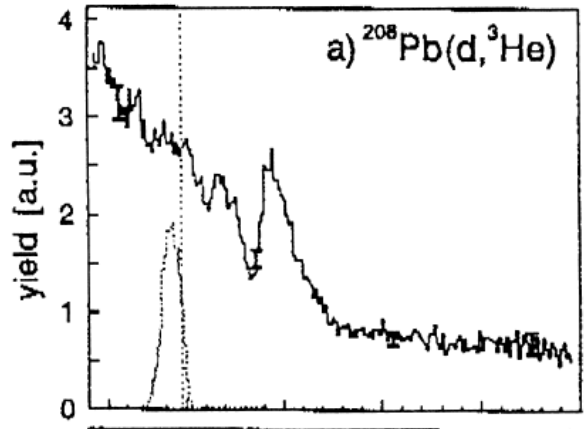

Physics Reports 514 (2012) 1–87

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journal homepage: www.elsevier.com/locate/physrep

Deeply bound pionic states in heavy nuclei

Toshimitsu Yamazaki [a,b], Satoru Hirenzaki [c,*], Ryugo S. Hayano [b], Hiroshi Toki [d]

[a] Nishina Center, RIKEN, Hirosawa 2-1, Wako-shi, Saitama-ken, 351-0198, Japan

[b] Department of Physics, School of Science, University of Tokyo, 7-3-1 Hongo, Bunkyo-ku, Tokyo, 113-0033, Japan

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

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

の発生しき
に伴うもの

Meson in Nucleus (recent topics)

- Deeply Bound Pionic Atoms

  precise $\bar{q}q$ condensate, beyond linear density, in asymmetric matter, exp.@RIBF/RIKEN (=> Ikeno's talk)
- Kaonic Atoms, Kaonic Nuclei

  $\Lambda(1405), K^{-}pp$, high-precision exp. plan (atom)

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  ϕ, ω mass shift, width and up dated QCD sum rule

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  ϕ, ω mass shift, width and up dated QCD sum rule
- η mesic nucleus

  couple to $N^{*}(1535)$, mix with η'
- $\eta'(958)$ mesic nucleus

  $U_A(1)$ anomaly effect @ finite density, Exp. GSI/FAIR
- Heavy Q mesons in Nucleus
- .....

$\eta'(958)$ mesic nucleus (theory side)

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.

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Latest experimental activitie ➔ Fujioka's Talk

Introduction

- $\eta'(958)$ meson …close connections with $U_A(1)$ anomaly

  - Theoretical works
    - the effects of the $U_A(1)$ anomaly on η' properties in VACUUM
    - At finite temperature/density
      - R.D.Pisarski, R.Wilczek, PRD29(84)338 (Linear Sigma Model)
      - T. Kunihiro, PLB219(89)363 (NJL model)

      etc…
    - the possible **character changes of η' at $\rho \neq 0$**

[2]. Symmetry Breaking Pattern and Meson mass spectrum (PS)

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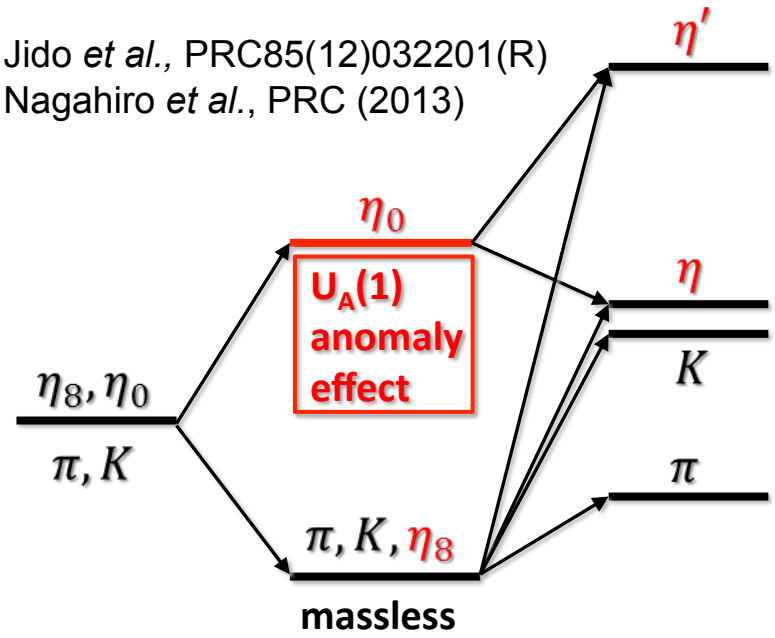

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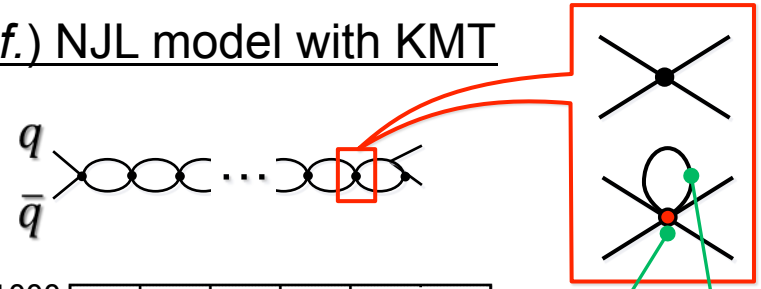

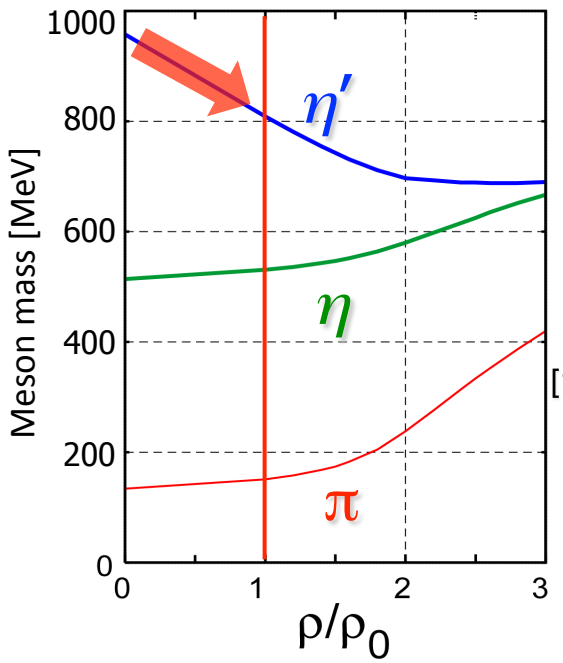

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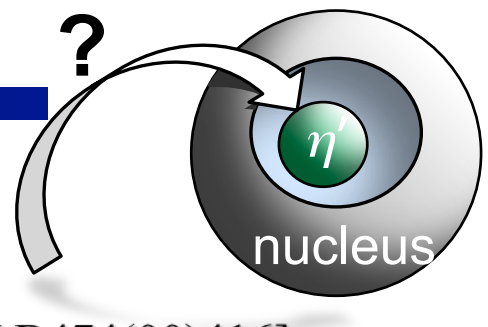
      etc…
    - › the possible **character changes of η' at $\rho \neq 0$**
  - » Poor experimental information on the $U_A(1)$ anomaly at finite density
- Proposal for the study of the η'-mesic nuclei
  - » $U_A(1)$ anomaly effect in medium from the "mesic nuclei"
  - » the η' properties at finite density

Experimental situation --- η' property in medium



(Please see Fujioka's GOOD compilation.)

- ✓ **Small scattering length ?**

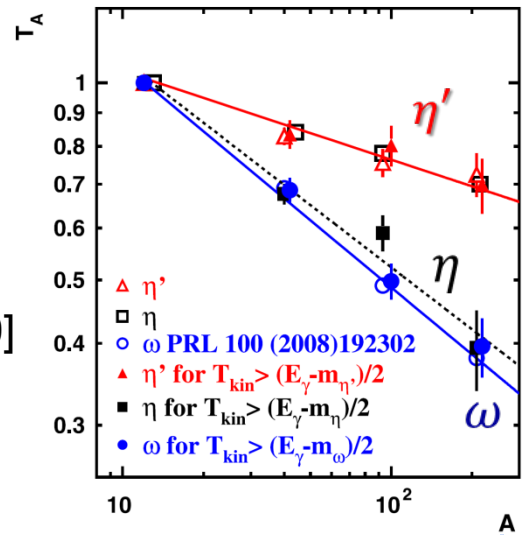
$|\mathrm{Re}\, a_{\eta' N}| < 0.8$ fm, [$pp \to pp\eta'$@ COSY, Moscal *et al.*, PLB474(00)416]

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

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

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

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



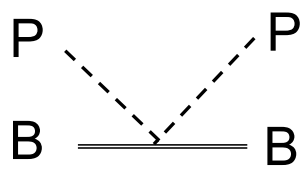
- ✓ **Mass reduction in finite T/ρ?**

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

E. Oset, A. Ramos; PLB704 (11) 334

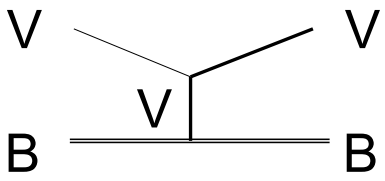


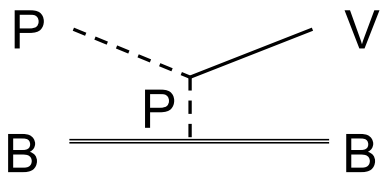
Pseudoscalar-baryon (PB) : Weinberg-Tomozawa interaction

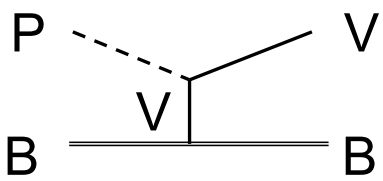
$\pi N, \eta N, K\Lambda, K\Sigma \; + \boldsymbol{\eta' N}$ by the η -η' mixing

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

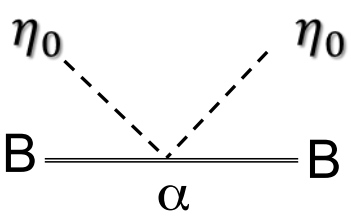






their result : $|a_{\eta' N}| = 0.03$ fm

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

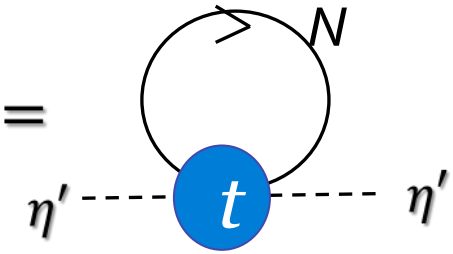
α … free parameter

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

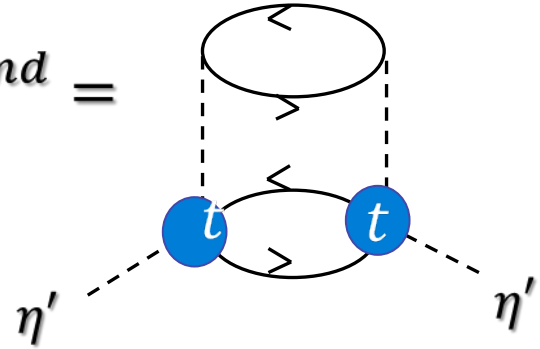
phenomenological estimation for $V_{\eta'}^{opt}$

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

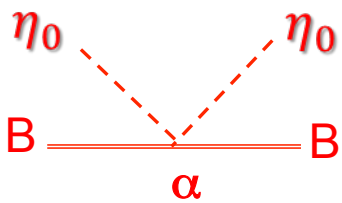
α	$\lvert a_{\eta' N}\rvert$ fm	$V_{\eta'}^{1st}(\rho_0)$	$V_{\eta'}^{2nd}(\rho_0)$	$V_{\eta'}^{total}(\rho_0)$
-0.193	0.1	$-8.6-1.7i$	$-0.1-0.1i$	$\mathbf{-8.7-1.8i}$
-0.834	0.3	$-26.3-2.1i$	$-0.6-0.9i$	$\mathbf{-26.8-3.0i}$
-1.79	0.5	$-43.8-3.0i$	$-1.3-2.5i$	$\mathbf{-44.1-5.5i}$
-9.67	1.0	$-87.7-6.9i$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

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

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

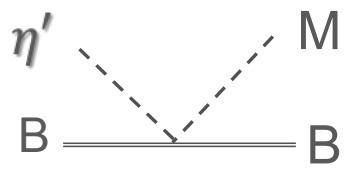
The reason why Re V $\gg$ Im V in the chiral unitary calculation

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

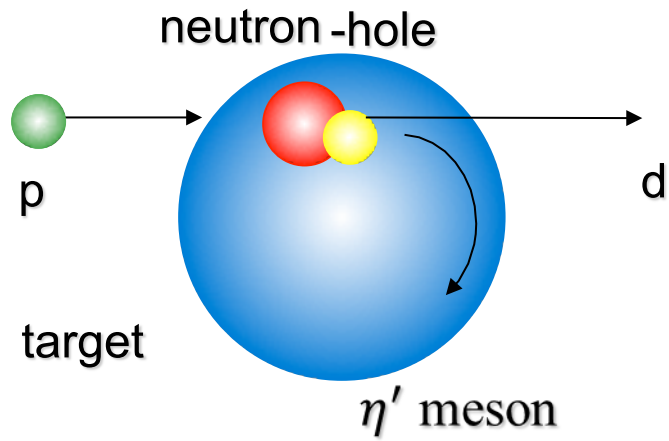
missing mass spectroscopy

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

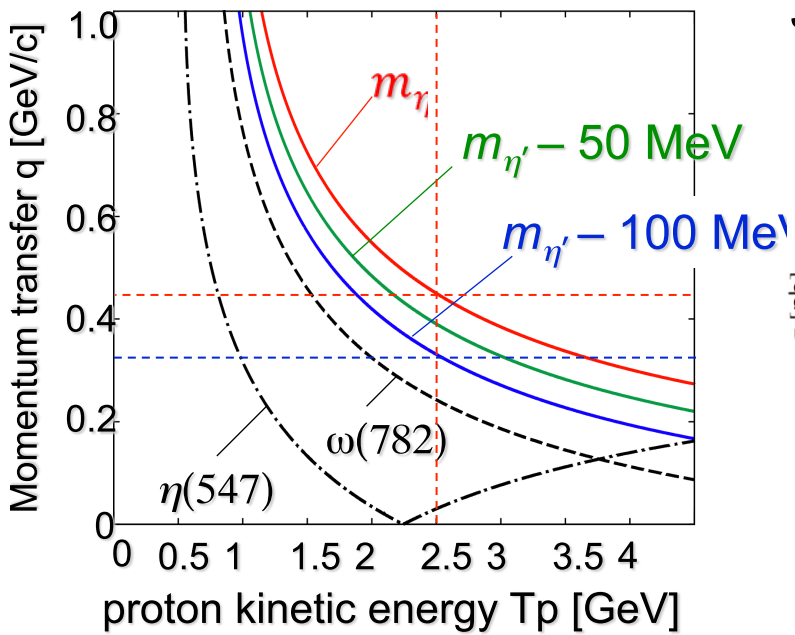
proton kinetic energy $T_p = 2.5$ GeV

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

forward reaction : $\theta_d = 0$ deg.

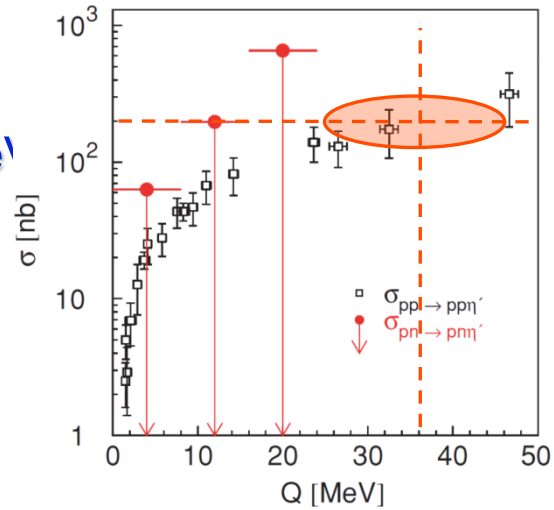


momentum transfer



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

Target-nucleus dependence { merit / demerit } to see peaks

Light nucleus ⟷ **Heavy nucleus**

less (shallow) η' bound states
less hole-states
✓ simpler structure

many (deeper) η' bound states
many hole-states
✓ complex structure

observed spectrum ⊗

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

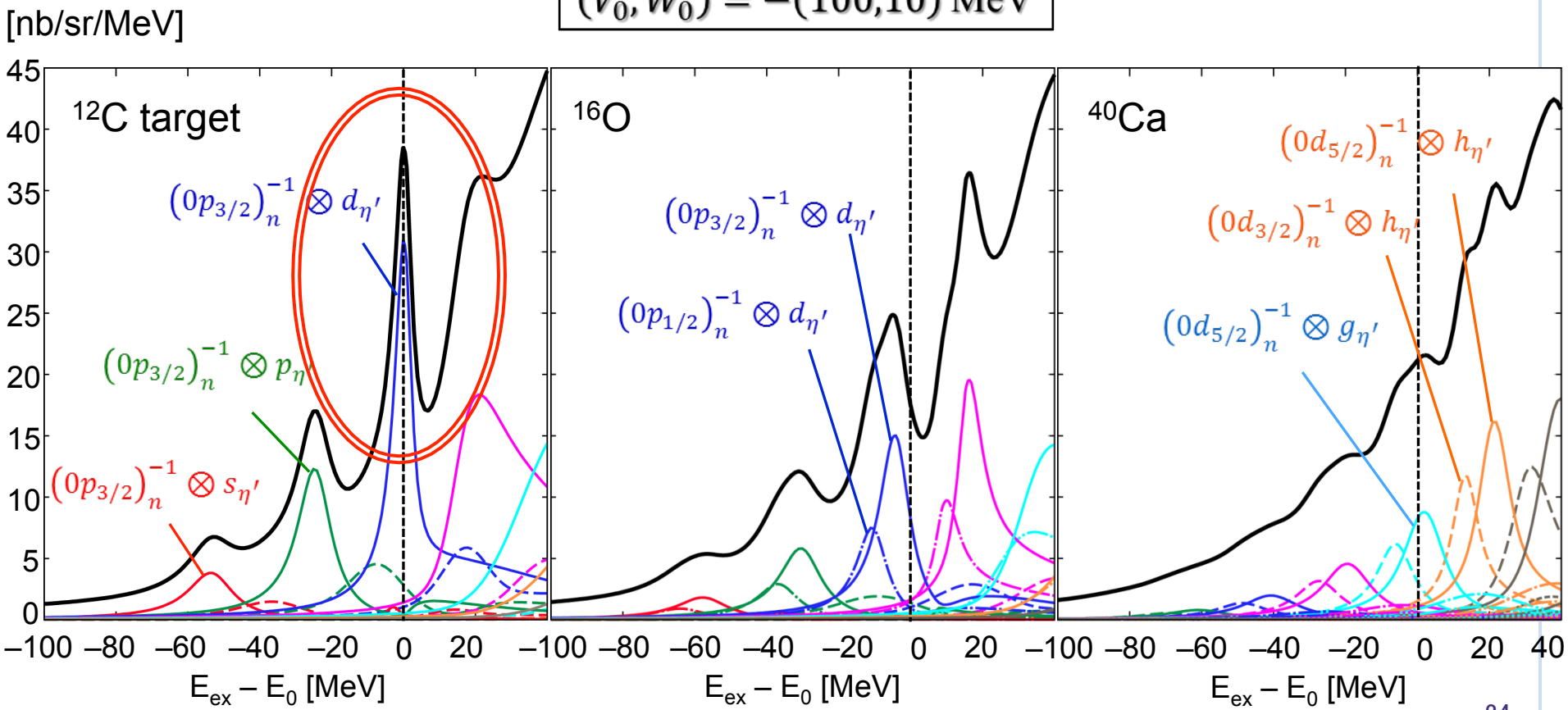
$^{12}C(p,d)^{11}C$ η': strong attraction $(V_0, W_0) = -(100,10)$ MeV

Light nucleus ⟷ **Heavy nucleus**

less (shallow) η' bound states
less hole-states
✓ simpler structure

many (deeper) η' bound states
many hole-states
✓ complex structure

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



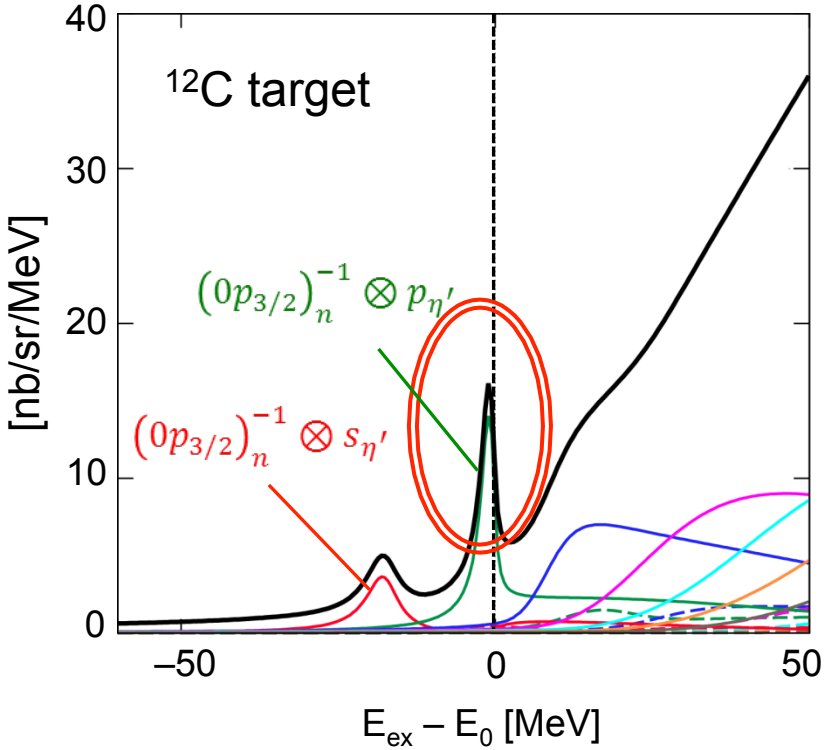
$^{12}C(p,d)^{11}C\ \eta'$: shallower case $(V_0, W_0) = -(50,5)$ MeV

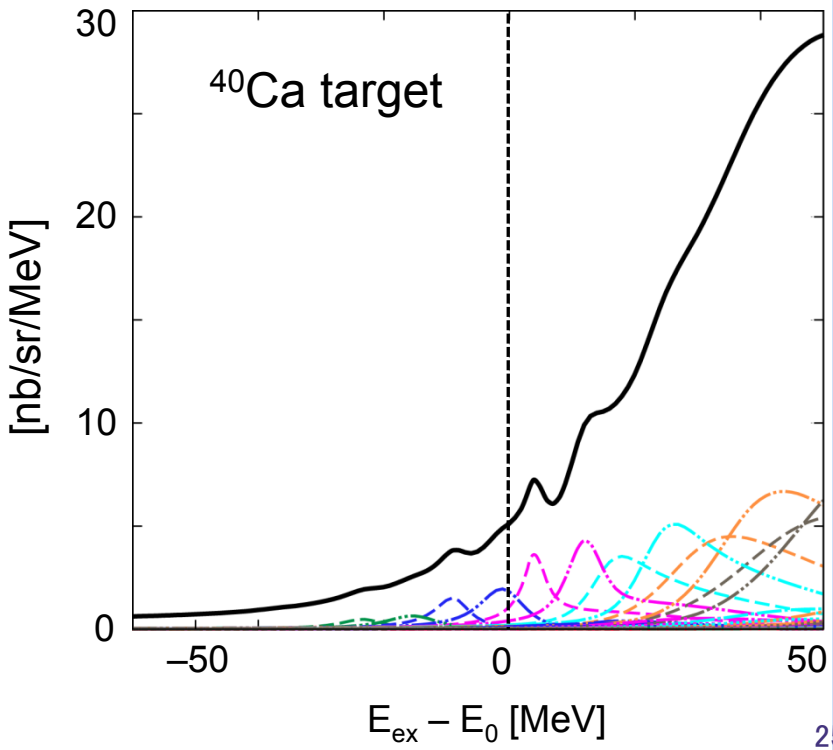
Light nucleus ⟷ **Heavy nucleus**

less (shallow) η' bound states
less hole-states
✓ simpler structure

many (deeper) η' bound states
many hole-states
✓ complex structure

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





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

η mesic nucleus

=Long History

=No Coulomb int., genuine ‘Mesic Nucleus’

=Couple to $N^*(1535)$, Mix with $\eta'(958)$

=Our theoretical approach to OLD data

η-mesic nuclei : Introduction

Some (old) works for η mesic nuclei & η-nucleus systems

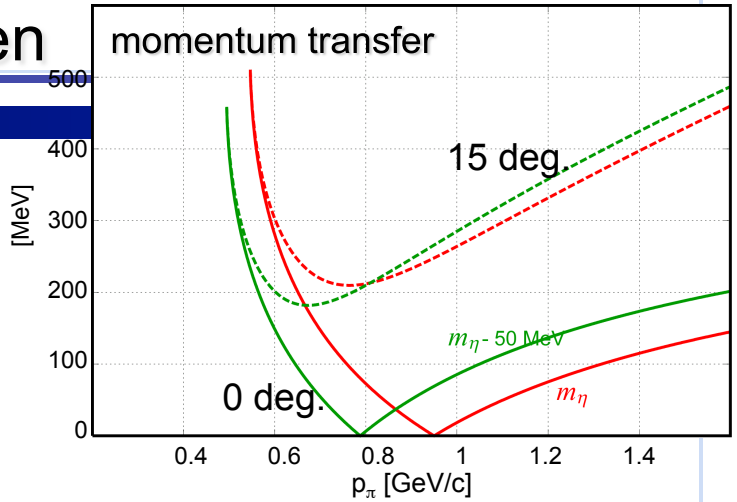
» (π^+,p) * Liu, Haider, PRC34(1986)1845 **[theo]**
* Chiang, Oset, and Liu, PRC44(1988)738 **[theo]**
* Chrien *et al.*, PRL60(1988)2595 **[exp]** ←

* Nagahiro, Jido, Hirenzaki, PRC80(2009)025205 **[theo]**
* K.Itanashi, H.Fujioka, S.Hirenzaki, D.Jido, H.Nagahiro, **[LoI for J-PARC]**

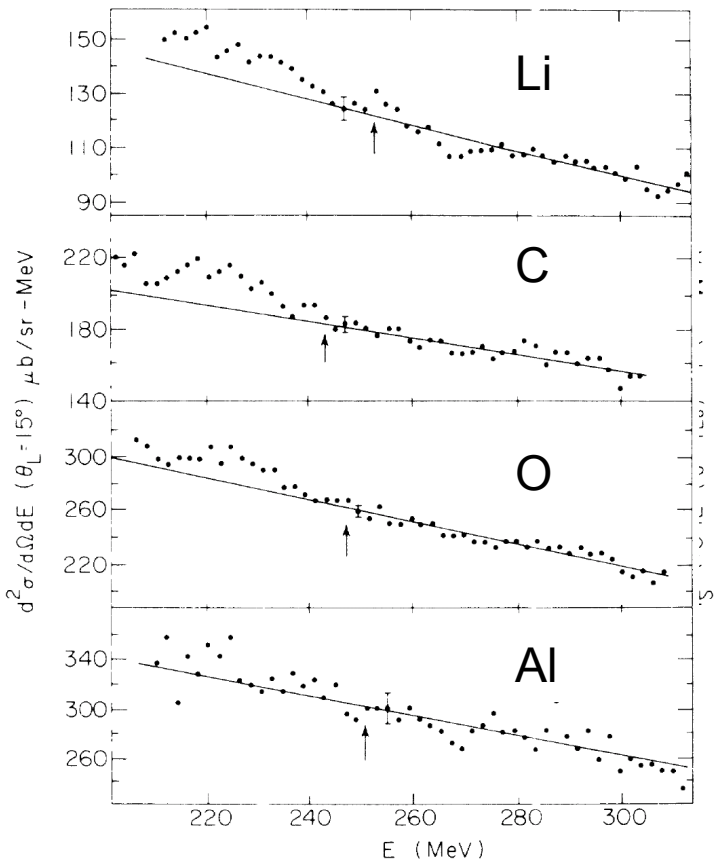
Remarks on the past experiment of (π^+,p) [1988, Chrien et al.]
based on H. Nagahiro, D.Jido, S.H., PRC80(2009)025205

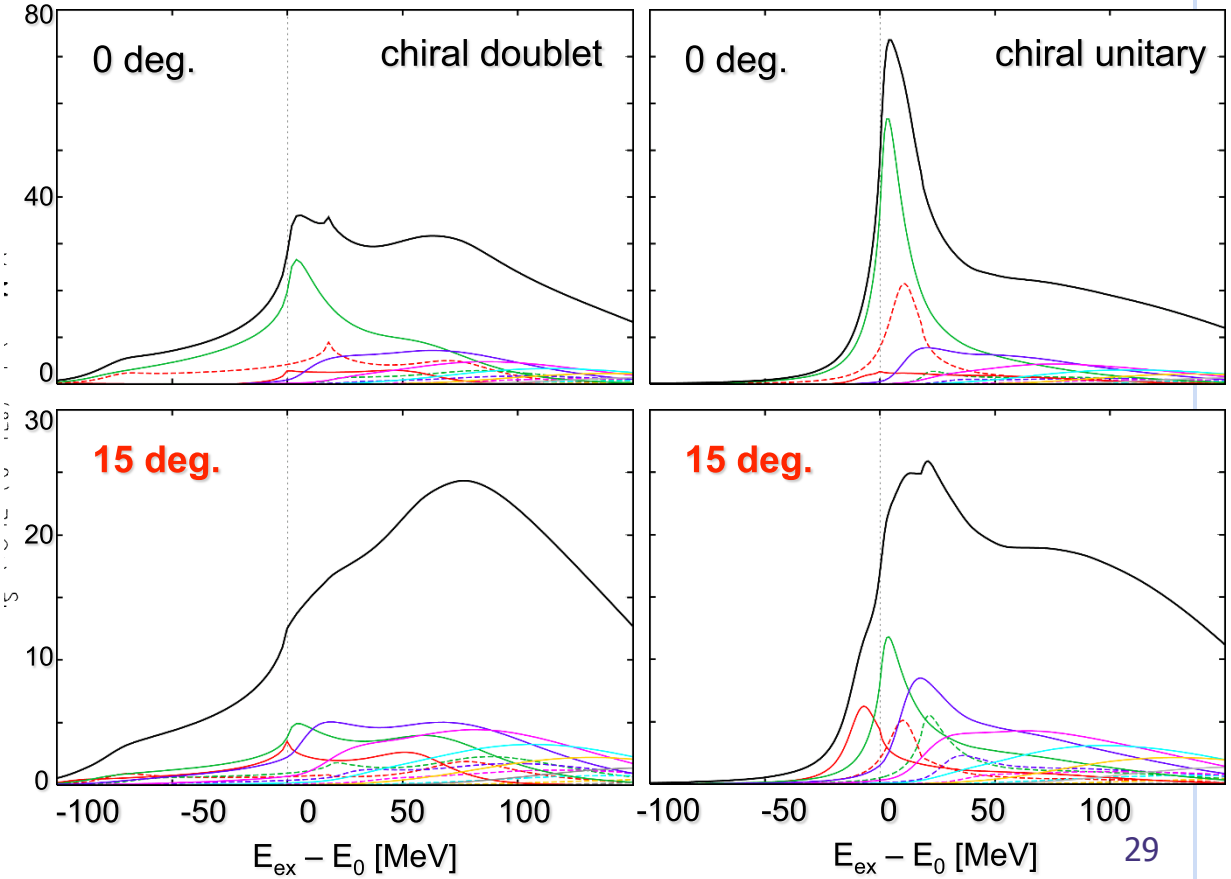
(π^+,p) spectra : experiment at Brookhaven

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





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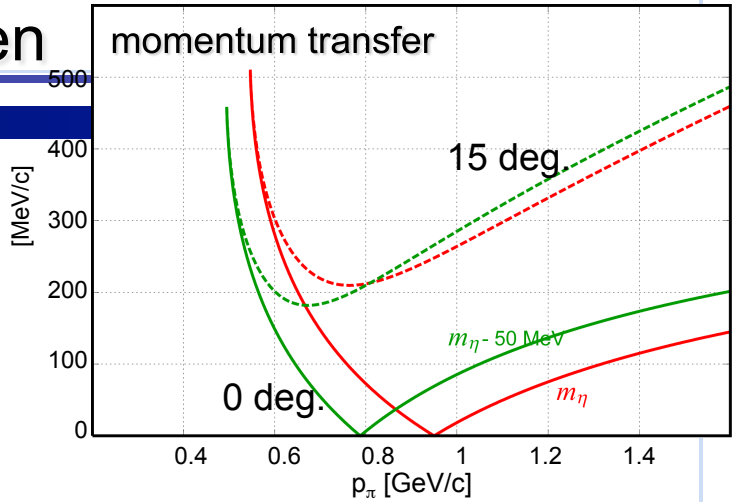
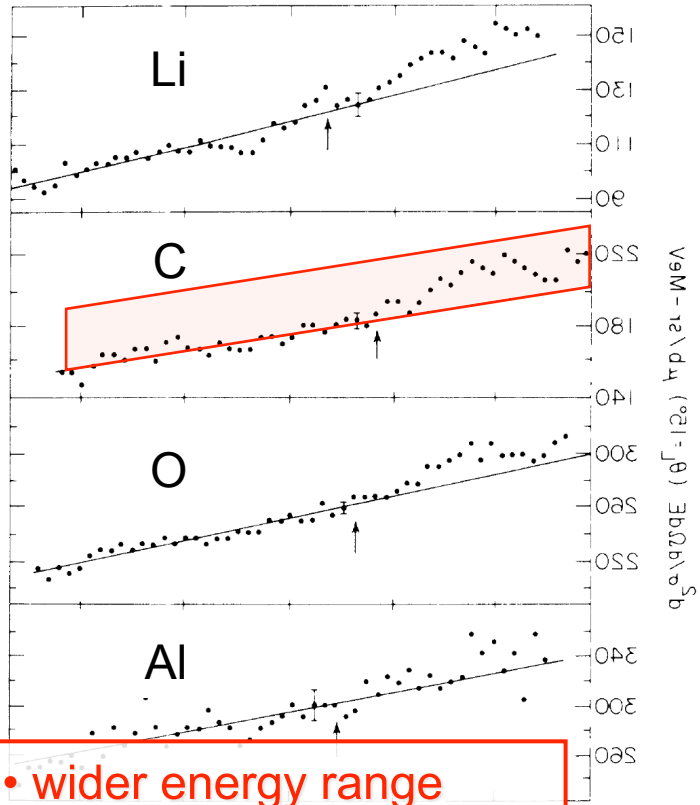
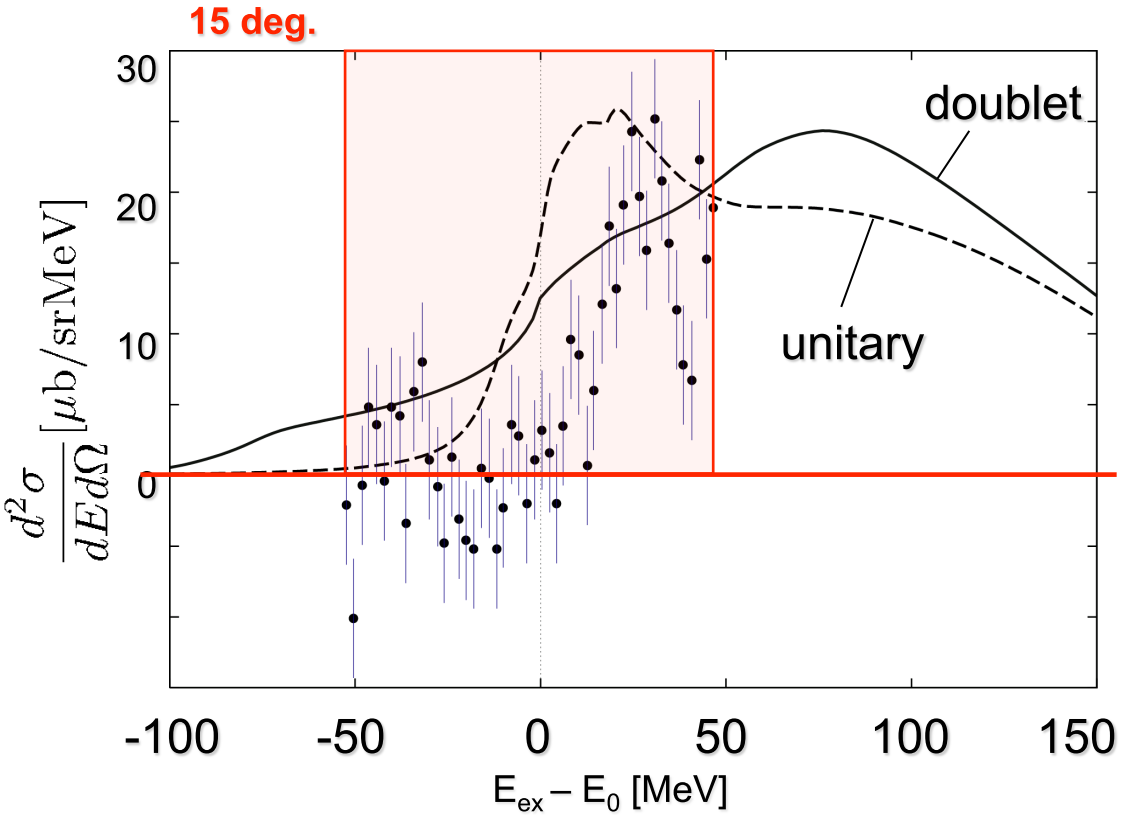


Chrien at al., PRL60(88)2595, Fig.1



- wider energy range
- proton angle = 0 degree



η mesic nuclei

- Formation of η-mesic nuclei

- Reconsideration of the experimental data at 1988 by Chrien *at al.*

  => We can consider more appropriate reaction conditions.

- **Possible observation in new experiments**

- **More talks in this session**

Kaonic Atoms

Very High precision Measurement (plan)
to investigate Kaon-Nucleus interaction

➔Study of Kaonic Nucleus,
Kaon in Nuclear Matter etc

Slide by S. Okada (RIKEN) at EXA2014 Very recent calc for K-^{4}He 2p level

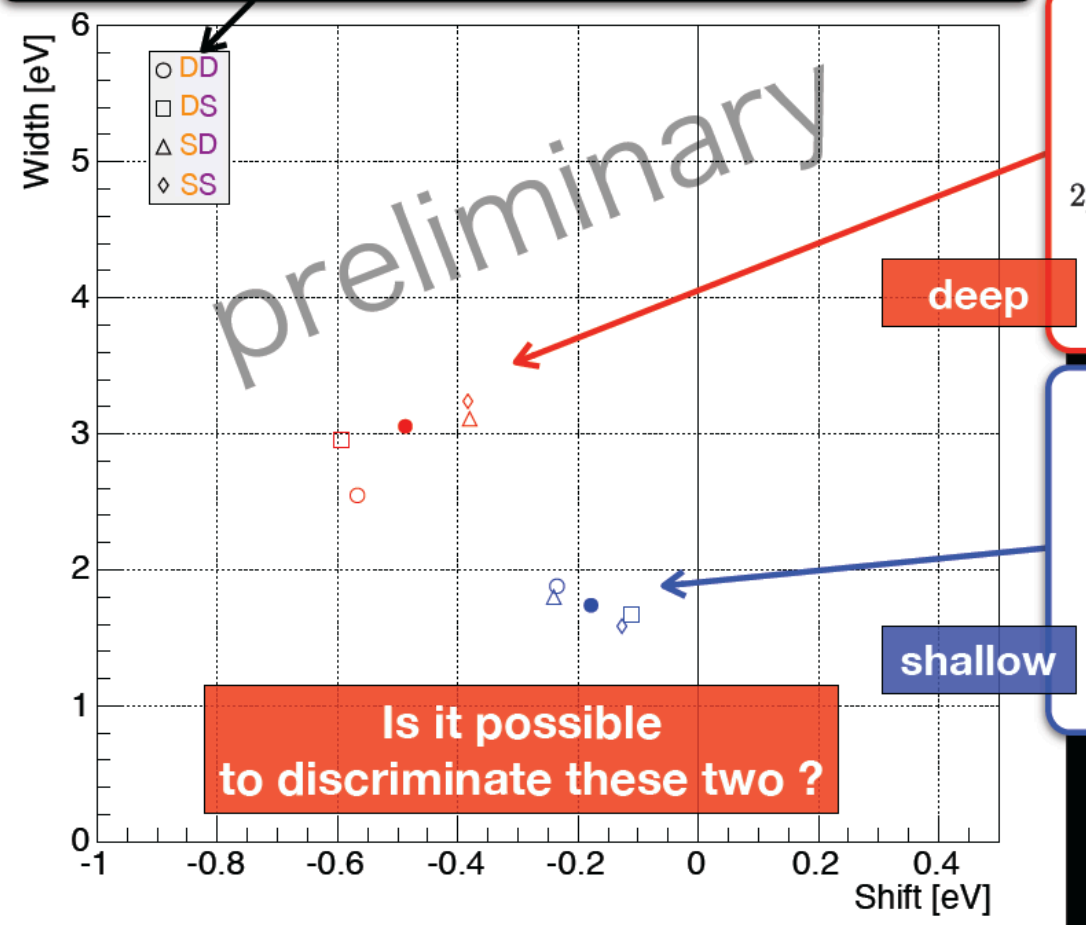
by J. Yamagata-Sekihara & S. Hirenzaki

Uncertainties of theoretical calc.

S D S D

Pheno : $V_{opt}(r=0) \sim -(170\text{-}187) - (70\text{-}75)i$ MeV … estimated with fit errors

Chiral : $V_{opt}(r=0) \sim -(36\text{-}44) - (50\text{-}60)i$ MeV … assuming 10% errors for each



Phenomenological model

Mares, Friedman, Gal, NPA770(06)84

$$2\mu V_{\rm opt}(r) = -4\pi\left(1+\frac{\mu}{M}\frac{A-1}{A}\right)\left(b_0 + B_0\left(\frac{\rho(r)}{\rho_0}\right)^{\alpha}\right)\rho(r)$$

$V_{opt}(r=0) \sim -(180 + 73i)$ MeV

Chiral unitary model

Ramos, Oset, NPA671(00)481

$$2\mu V_{\rm opt}(r,E) = \Pi(r,E)$$

$V_{opt}(r=0) \sim -(40 + 55i)$ MeV

Charge-density distribution for ^{4}He : Three-parameter Fermi model

Jager, Vries, Vries, Atom. Data Nucl. Data Tabl. 14(74)479

Summary

- Meson property at finite density,

  Mesic atoms and Mesic nuclei

- $\eta'(958)$: Anomaly effect at finite density

- η: Observation in new experiments ?

- Kaonic atoms, kaon-nucleus interaction

- Pionic atoms, New data at RIKEN