3rd Jagiellonian Sympo. on Fundamental and Applied Subatomic Physics,
23-28 June 2019, Collegium Maius, Jagiellonian Univ., Krakow, Poland

Recent topics on Mesic atoms and Mesic nuclei

Satoru Hirenzaki (Nara Women's University, Japan)

24 June, 16:15 (25 (20+5) min.)

【0】Introduction

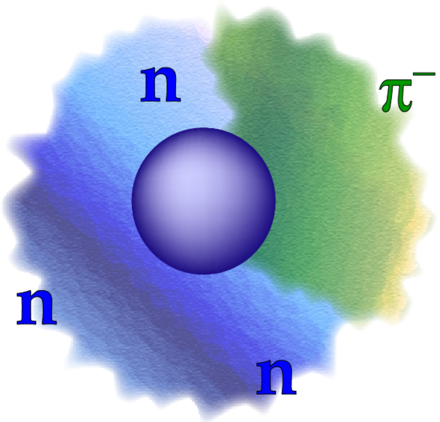
【1】$\eta'(958)$ mesic nucleus -- after GSI exp.--

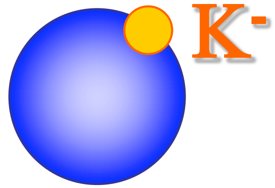
【2】$\bar{p}$: Hadronic systems from Anti-Protonic atom

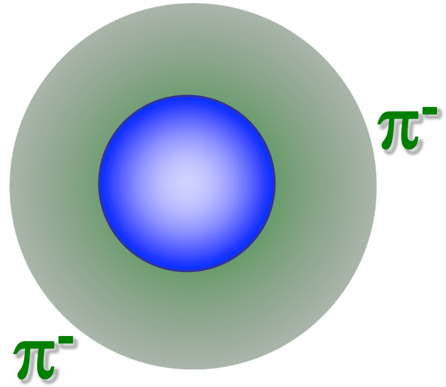
【3】η mesic nucleus

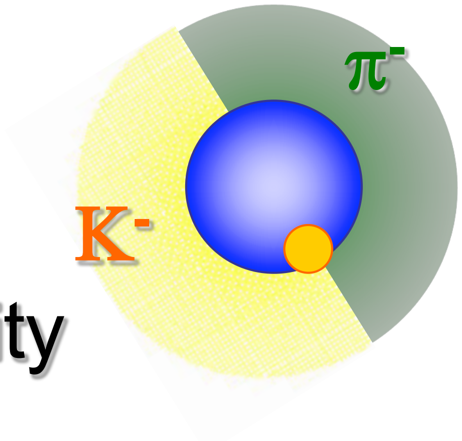
【4】Summary

(1) New exotic Hadron many body systems









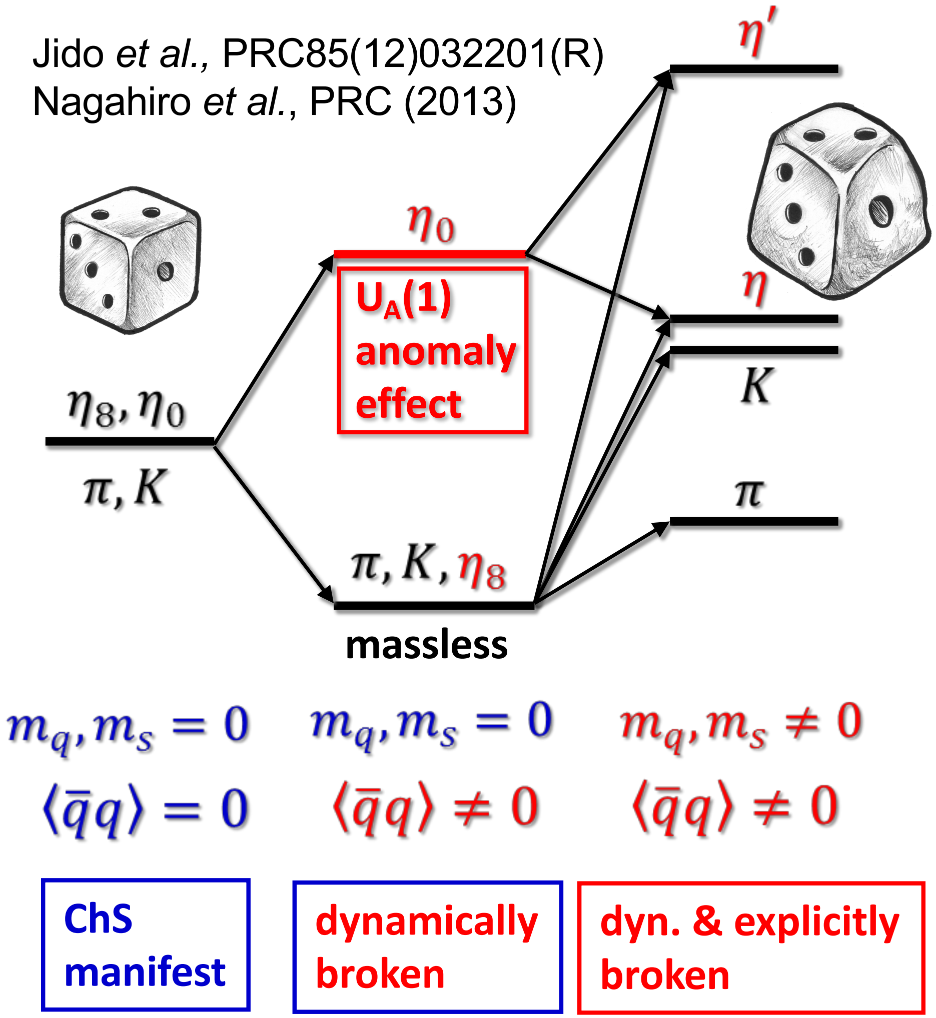
(2) Baryon resonances at finite density

$N^*(1535)$ 、 $\Lambda(1405)$ 、、

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

(3) Aspects of the Strong Int. Symmetry

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

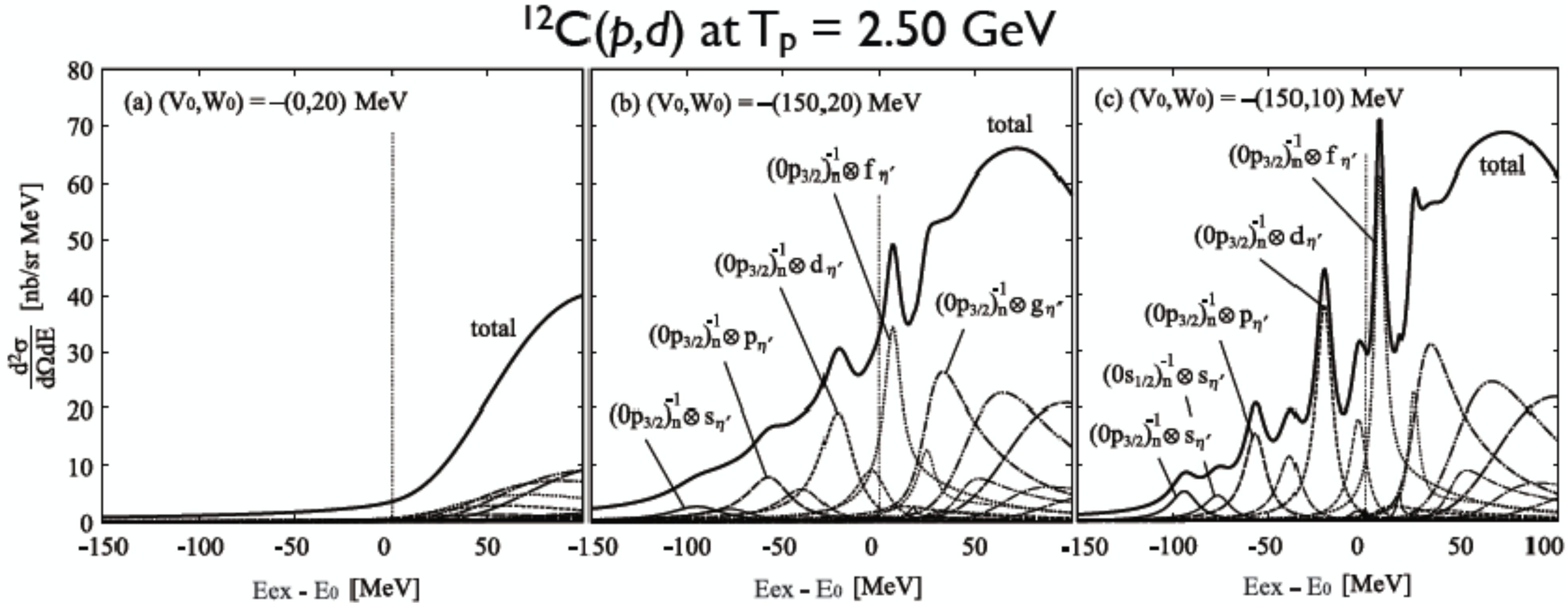


【0】Introduction

【1】$\eta'(958)$ mesic nucleus -- after GSI exp.--

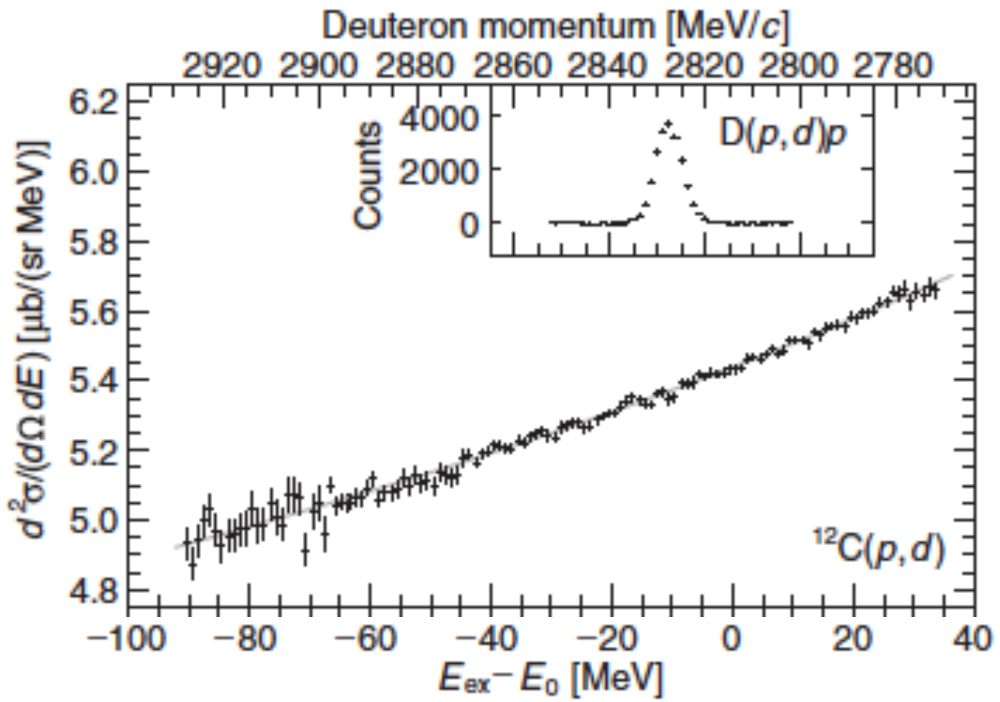
Theoretical predictions

$$V_{\eta'}(r) = (V_0 + iW_0)\,\frac{\rho(r)}{\rho_0}$$



Nagahiro et al., PRC87(13)045201.

Y. K. Tanaka, K. Itahashi, H. Fujioka, et al., PRL 117, 202501 (2016).



Experimental Results

FIG. 2. (Top panel) Excitation spectrum of ^{11}C measured in the ^{12}C(p, d) reaction at a proton energy of 2.5 GeV. The abscissa is the excitation energy E_{ex} referring to the η' emission threshold $E_0 = 957.78$ MeV. The overlaid gray solid curve displays a fit of the spectrum with a third-order polynomial. The upper horizontal axis shows the deuteron momentum scale. (Inset) Deuteron

Y. K. Tanaka, K. Itahashi, H. Fujioka, et al., PRL 117, 202501 (2016).

- mu – scale factor to theoretical spectra.

Contour on a potential parameter plane

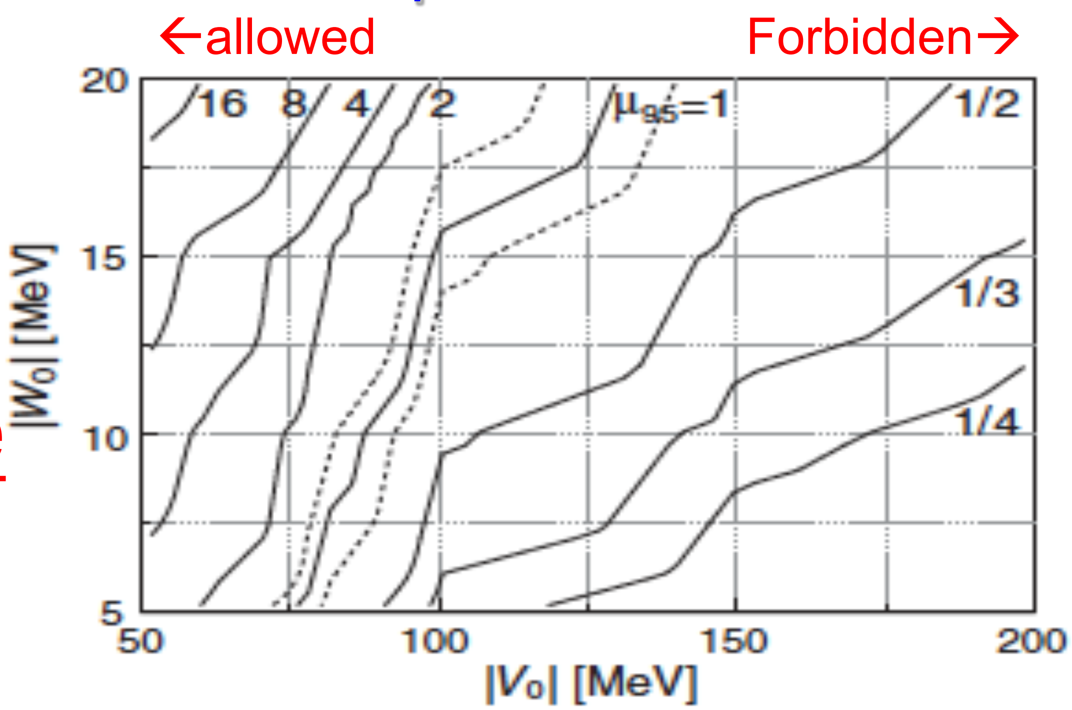


FIG. 4. A contour plot of μ_{95} (the solid curves), upper limit of the scale parameter μ at the 95% C.L., on a plane of real and imaginary potential parameters ($|V_0|, |W_0|$). The limits have been evaluated for the potential-parameter combinations (V_0, W_0) in $\{-50, -100, -150, -200\} \times \{-5, -10, -15, -20\}$ and $\{-60, -80\} \times \{-5, -10, -15\}$ MeV and linearly interpolated in between. Dashed curves show a band of $\mu_{95} = 1$ contour indicating the systematic errors. Regions for $\mu_{95} \leq 1$ are excluded by the present analysis.

- No clear peak. Upper limit is obtained.

- Aftre GSI exp., for further studies,
  - Theoretical eta(958)-N and -Nucleus interactions
  - Semi-exclusive exp. (p,dp) at FAIR/J-PARC

  - Self-consistent structure of eta(958)-nucleus
    => Possible Deformation (Compression) of Nucleus
    and Effects to the spectra.

    Meanings of the exp. upper limit may be changed.

Structure of η' mesonic nuclei in a relativistic mean field theory

Daisuke Jido[1,3,*], Hanayo Masutani[1], and Satoru Hirenzaki[2] Prog. Theor. Exp. Phys. **2019**, 053D02 (22 pages)

$$\mathcal{L} = \bar{\psi}\left[i\gamma_\mu\left\{\partial^\mu + ig_\omega\omega^\mu + ig_\rho\rho^\mu\frac{\tau^3}{2} + ieA^\mu\frac{1+\tau^3}{2}\right\}\right]\psi - \bar{\psi}(m - g_\sigma\sigma)\psi$$
$$+\frac{1}{2}\partial_\mu\sigma\partial^\mu\sigma - \frac{1}{2}m_\sigma^2\sigma^2 - \frac{1}{3}bmg_\sigma^3\sigma^3 - \frac{1}{4}cg_\sigma^4\sigma^4$$
$$-\frac{1}{4}\omega_{\mu\nu}\omega^{\mu\nu} + \frac{1}{2}m_\omega^2\omega^2 - \frac{1}{4}R_{\mu\nu}R^{\mu\nu} + \frac{1}{2}m_\rho^2\rho_{03}^2 - \frac{1}{4}F_{\mu\nu}F^{\mu\nu}$$
$$+\frac{1}{2}\partial_\mu\eta'\partial^\mu\eta' - \frac{1}{2}m_{\eta'}^2\eta'^2 + g_{\sigma\eta'}m_{\eta'}\eta'^2\sigma.$$

Table 4. Coupling constants of the σ–η' interaction. These are determined so as to reproduce the effective η' mass 80 MeV smaller than the in-vacuum mass at the saturation density.

No.	1	2	3	4	5	6	7	8	9
$g_{\sigma\eta'}$	2.21	2.51	2.94	2.17	2.44	2.82	2.13	2.38	2.70

∗ No width (absorptive process) for eta(958) states

* Large deformation (compression) for 1s eta(958)

Prog. Theor. Exp. Phys. **2019**, 053D02 (22 pages)

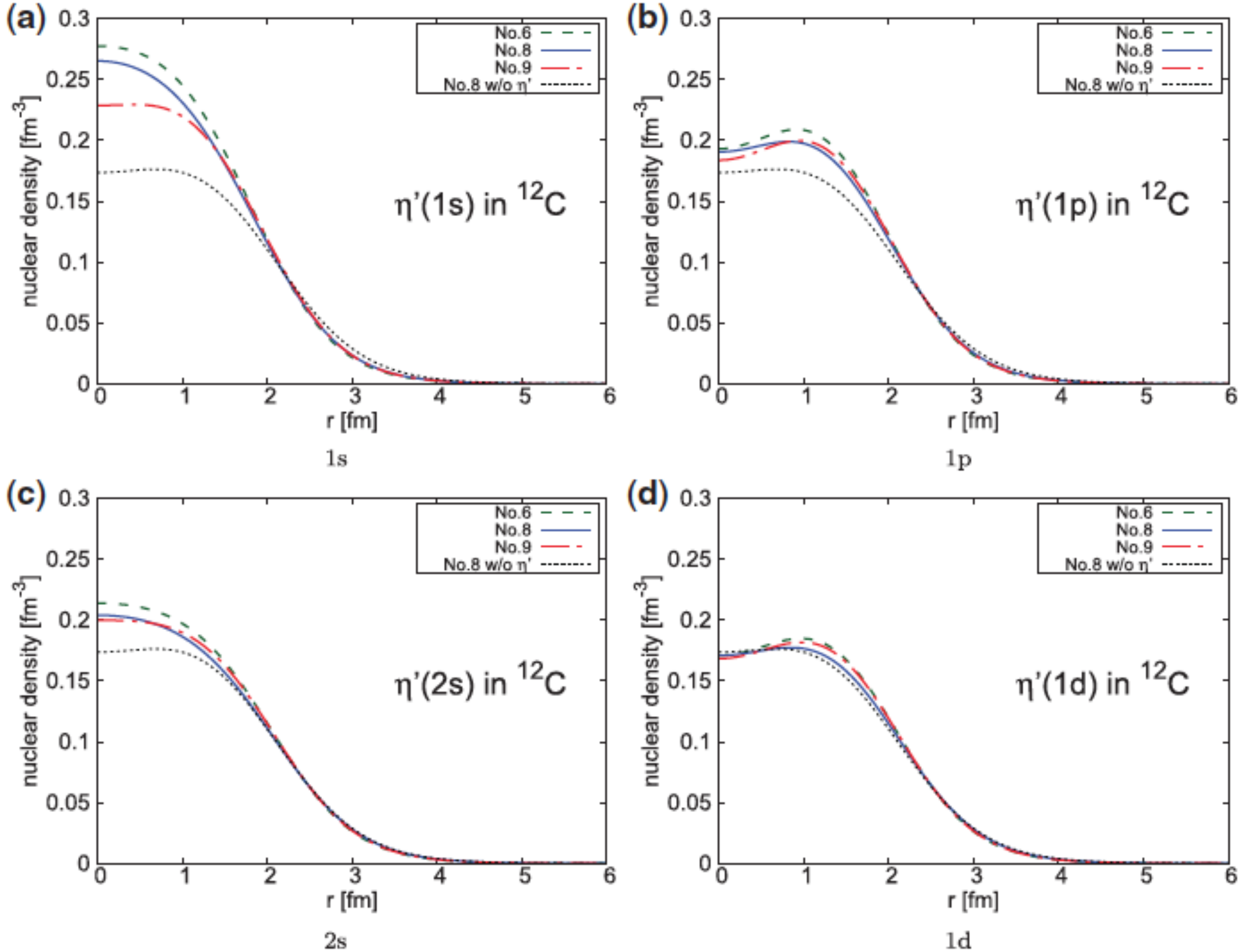


Fig. 8. Nuclear density profiles of the η' bound systems in ^{12}C obtained with parameter sets 6, 8, and 9. The dotted line stands for the density distribution of the normal nucleus ^{12}C without η' calculated with parameter set 8.

- No clear peak. Upper limit is obtained.

- Aftre GSI exp., for further studies,
  - Theoretical eta(958)-N and -Nucleus interactions
  - Semi-exclusive exp. (p,dp) at FAIR/J-PARC

  - Self-consistent structure of eta(958)-nucleus
    => Possible Deformation (Compression) of Nucleus
    and Effects to the spectra.
    Meanings of the exp. upper limit may be changed.

Suzuna Kinutani started some discussions
on Formation Spectra => Poster presentation

【0】Introduction

【1】$\eta'(958)$ mesic nucleus -- after GSI exp.--

【2】$\bar{p}$: Hadronic systems from Anti-Protonic atom

Hadronic systems from Anti-Protonic atom

- An idea proposed to JPARC

Letter of Intent for J-PARC

Double Anti-kaon Production in Nuclei by Stopped Anti-proton Annihilation

dated on 17 / 06 / 2009

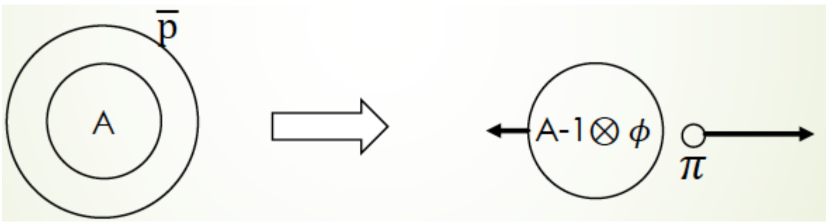
M. Iwasaki[1], P. Kienle[2,3], H. Ohnishi[1], F. Sakuma[1*], and J. Zmeskal[2]

- Other channels and/or Theoretical evaluation

based on the formula for hypernucleus formation by stopped K

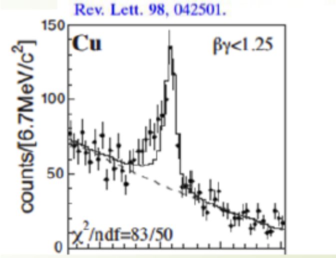
A. Matsuyama and K. Yazaki. NPA477 (1988) 673

Ex.) ϕ from $\bar{p} + N \rightarrow \phi + \pi$ by Mai Hirao and Suzuna Kinutani



cf.)

Muto, R., *et al.* (KEK-PS E325 Collaboration), 2007, Phys. Rev. Lett. 98, 042501.



- Based on A. Matsuyama and K. Yazaki. NPA477 (1988) 673

Probability to form bound states

$$P\left((nl)_{\bar{p}} \to \pi j_N^{-1}(nl)_\phi\right) = \frac{\Gamma\left((nl)_{\bar{p}} \to \pi j_N^{-1}(nl)_\phi\right)}{\Gamma_{\text{total}}\left((nl)_{\bar{p}} \to X\right)}$$

Numerator

$$\Gamma\left((nl)_{\bar{p}} \to \pi j_N^{-1}(nl)_\phi\right) = \frac{k_\pi \omega_\pi}{4\pi^2}\frac{1}{2l_{\bar{p}}+1}\left|t\left(\bar{p}N \to \pi\phi\right)\right|^2 \int d\Omega_\pi N_{\text{eff}}$$

$$N_{\text{eff}} = \sum_{m_{\bar{p}}M}\left|\int d\vec{r}\chi_\pi^*\left(\vec{r}\right)\left[\phi_\phi^*\left(\vec{r}\right)\bigotimes\psi_N\left(\vec{r}\right)\right]_{JM}\varphi_{\bar{p}}^{nl}\right|^2$$

Abs(t)^2 term – from experimental BR of elementary process.

$$B\left(N^{-1}\phi\right) = \frac{\sum_{N,\phi,\pi}\Gamma\left((nl)_{\bar{p}} \to \pi j_N^{-1}(nl)_\phi\right)}{\Gamma_{\text{total}}\left((nl)_{\bar{p}} \to X\right)}$$

- An Estimation by Hirao and Kinutani

BR

* ASTERIX collabo., PLB267 (1991) 299

$$B(\bar{p}+p \to \phi + \pi^0) = 40 \times 10^{-5}$$

$$B(\bar{p}+n \to \phi + \pi^-) = 51 \times 10^{-5}$$

For 12C, $(1s)_{\bar{p}} \to \pi s^{-1}_{1/2}(0s)_{\phi}$ case,

==> $P\left((1s)_{\bar{p}} \to \pi s^{-1}_{1/2}(0s)_{\phi}\right) = 5.7 \times 10^{-11}$

so small !!

∗ 2 origins for small P

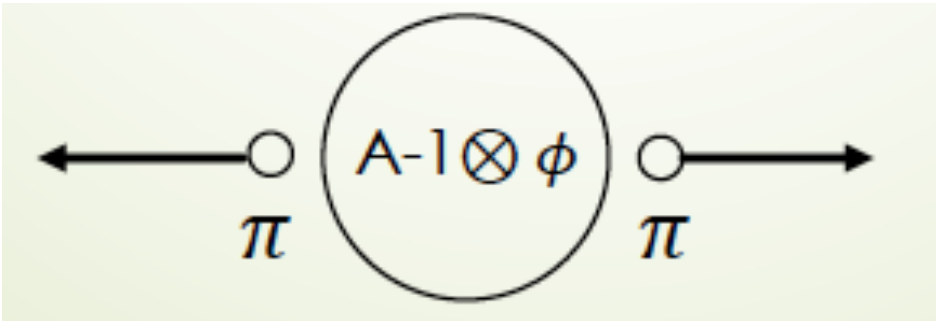
(1) Small BR,

(2) Large momentum transfer (~ 1GeV in this case)

Thus,

- Deacy modes with Relatively large BR

- Decay modes into 3 quasi-stable mesons with Back to back kinematics like



will be interesting.

Proton-antiproton annihilation and meson spectroscopy with the Crystal Barrel

Claude Amsler   Reviews of Modern Physics, Vol. 70, No. 4, October 1998

TABLE IX. Branching ratios for $\bar{p}p$ annihilation at rest into three narrow mesons. Mesons in parentheses were not detected.

Channel	Final state	B				Reference
$\pi^0\pi^0\pi^0$	6γ	6.2	±	1.0	10^{-3}	Amsler *et al.* (1995f)‡
$\pi^+\pi^-\pi^0$	$\pi^+\pi^-(\pi^0)$	6.9	±	0.4	10^{-2}	Foster *et al.* (1968b)
$\pi^0\eta\eta$	6γ	2.0	±	0.4	10^{-3}	Amsler *et al.* (1995e)‡
$\pi^0\pi^0\omega$	7γ	2.00	±	0.21	10^{-2}	Amsler *et al.* (1993a)‡
	$\pi^+\pi^-6\gamma$	2.57	±	0.17	10^{-2}	Amsler *et al.* (1994d)‡
$\pi^+\pi^-\omega$	$2\pi^+2\pi^-(\pi^0)$	6.6	±	0.6	10^{-2}	Bizzarri *et al.* (1969)
$\omega\eta\pi^0$	7γ	6.8	±	0.5	10^{-3}	Amsler *et al.* (1994c)‡
$\pi^0\pi^0\eta$	6γ	6.7	±	1.2	10^{-3}	Amsler *et al.* (1994b)‡
	$\pi^+\pi^-6\gamma$	6.50	±	0.72	10^{-3}	Amsler *et al.* (1994d)‡
$\pi^+\pi^-\eta$	$\pi^+\pi^-2\gamma$	1.63	±	0.12	10^{-2}	Abele *et al.* (1997a)‡
	$\pi^+\pi^-6\gamma$	1.33	±	0.16	10^{-2}	Amsler *et al.* (1994d)‡
	$2\pi^+2\pi^-(\pi^0)$	1.38	±	0.17	10^{-2}	Espigat *et al.* (1972)
	$2\pi^+2\pi^-(\pi^0)$	1.51	±	$^{0.17}_{0.21}$	10^{-2}	Foster *et al.* (1968a)
$\pi^0\pi^0\eta'$	10γ	3.2	±	0.5	10^{-3}	Abele *et al.* (1997e)‡
	6γ	3.7	±	0.8	10^{-3}	Abele *et al.* (1997e)‡
$\pi^+\pi^-\eta'$	$\pi^+\pi^-6\gamma$	7.5	±	2.0	10^{-3}	Urner (1995)‡
	$3\pi^+3\pi^-(\pi^0)$	2.8	±	0.9	10^{-3}	Foster *et al.* (1968a)
$\pi^0\eta\eta'$	6γ	2.3	±	0.5	10^{-4}	Amsler *et al.* (1994f)‡
$\pi^0\pi^0\phi$	$8\gamma(K_L)$	9.7	±	2.6	10^{-5}	Abele *et al.* (1997c)‡
$\pi^+\pi^-\phi$	$2\pi^+2\pi^-(K_L)$	4.6	±	0.9	10^{-4}	Bizzarri *et al.* (1969)
$\pi^0K_SK_L$	$3\pi^0(K_L)$	6.7	±	0.7	10^{-4}	Amsler *et al.* (1993d) [a]‡
$\pi^0K_SK_S$	$2\pi^+2\pi^-(\pi^0)$	7.5	±	0.3	10^{-4}	[b]
$\pi^\pm K^\mp K_S$	$\pi^+\pi^-\pi^\pm K^\mp$	2.73	±	0.10	10^{-3}	[b]
$\pi^\pm K^\mp K_L$	$\pi^\pm K^\mp(K_L)$	2.91	±	0.34	10^{-3}	Abele *et al.* (1998d)‡
ωK_SK_S	$3\pi^+3\pi^-(\pi^0)$	1.17	±	0.07	10^{-3}	Bizzarri *et al.* (1971)
ωK^+K^-	$K^+K^-\pi^+\pi^-(\pi^0)$	2.30	±	0.13	10^{-3}	Bizzarri *et al.* (1971)

[a]Using $B(\pi^0\phi)$ from Table VI and Eq. (47).
[b]Average between Armenteros *et al.* (1965) and Barash *et al.* (1965).
‡Crystal Barrel experiment.

【0】Introduction

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【2】$\bar{p}$: Hadronic systems from Anti-Protonic atom

【3】η mesic nucleus

* Constraining the optical potential in the search for η-mesic ^{4}He

M. Skurzok [a,*], P. Moskal [a], N.G. Kelkar [b], S. Hirenzaki [c], H. Nagahiro [c,d], N. Ikeno [e]

Physics Letters B 782 (2018) 6–12

=> $dd \to {}^3\mathrm{He}N\pi$ reaction (strong absorption) data

* Non-mesonic decay of the η-mesic ^{3}He via $pd \to (^3\mathrm{He}\text{-}\eta)_{bound} \to {}^3\mathrm{He}2\gamma(6\gamma)$ reaction

M. Skurzok [a], S. Hirenzaki [b], S. Kinutani [b], H. Konishi [b], P. Moskal [a], H. Nagahiro [b,c], O. Rundel [a]

=> η decay into photons. Not strong. Not absorption but decay.

* η momentum distribution

=> photon momenta simulation

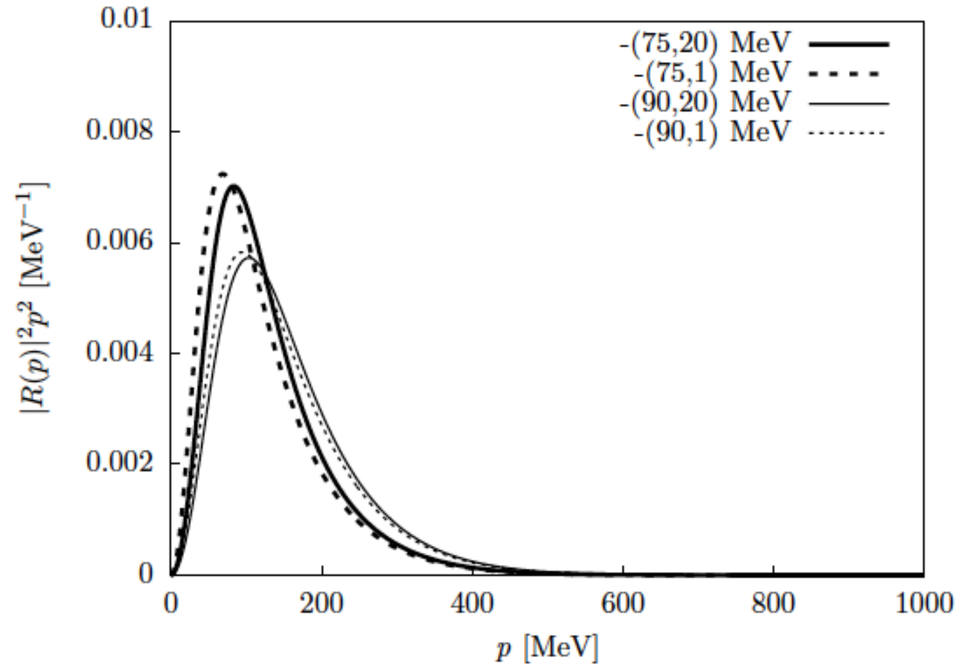

Figure 2: Fermi momentum distribution of the η meson in ^{3}He-η bound system estimated for $(V_0, W_0)=-(75{,}20)$ MeV (thick solid line), $(V_0, W_0)=-(75{,}1)$ MeV (thick dotted line), $(V_0, W_0)=-(90{,}20)$ MeV (thin solid line), and $(V_0, W_0)=-(90{,}1)$ MeV (thin dotted line). The distributions are normalized to be 1 in the whole momentum range.

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【4】Summary

Summary

* $\eta'(958)$: Deformation (compression) effects may change the meanings of the data (upper limit).

* $\bar{p}$: Hadronic systems production from Anti-Protonic atom may be interesting. Not only stopped but also in-flight.

J. Yamagata-Sekihara, D. Cabrera, M. J. Vicente-Vacas, S. Hirenzaki. Prog.Theor.Phys. 124 (2010) 147-162 (Formation by in-flight p-bar)

* η : Let's see what happen experimentally.
(Magda's talk.)

Suppose there is nuclear deformation, nuclear deexcitation should happen simultaneously. Something could be seen.